

Oxygen uptake rate test methodology: An assessment of data sensitivity to set up and test specific criteria

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Oxygen is required during gold cyanidation for its dissolution and, at considerable mass input, for the oxidation of sulphide minerals if beneficial for the gold recovery process. Oxygen uptake rate (OUR) values for specific ores form important base data for further computations towards sizing the oxygen plant on a mine site. Existing methods were reviewed, and the in-house procedure adapted to use the approach regarded as most valid. A series of testwork was performed to identify the test-specific parameters most liable to influence the produced data point. A flotation concentrate and two Run Off Mine (ROM) ores were used in the programme. The test data shows that grind (10-fold), temperature (a limiting factor due to intense oxygen uptake) and shear impact (+ 50%) are dominant factors, able to change the OUR value by factors. This would require more careful definition and application during tests. Sample ageing, often cited as a major concern, appeared to be of much less impact than anticipated.

INTRODUCTION

Determining the oxygen consumption of specific ores is an important aspect of the gold process before feeding into the extraction process. Oxygen is a required element in the cyanidation of gold to drive Elsener's equation (Equation 1) to the right, as well as oxidising other sulphidic and oxidisable constituents contained in the ore if beneficial to do so. The amount of oxygen needed for the above-mentioned aspects needs to be determined accurately to avoid either over- or under-sizing the oxygen plant. The design often relies on laboratory-generated oxygen uptake rate (OUR) numbers to enable further total mass computations using data related to the transfer efficiency of dispersion devices. Different methods involved in OUR determination were reviewed, incorporating the factors which may affect the determination.

In wastewater treatment and mining operations, oxygen is an important oxidising agent because of its high affinity to react with other elements. Although it has relatively low solubility in the aqueous phase, it is usually supplied in a gas phase (air or pure oxygen) for transfer into solution media. A critical mechanism before consumptive reactions start is the diffusion rate for the mass transfer of oxygen from the gas-to-the-liquid phase (water) into solids. The reaction between solids in a mining slurry and water-dissolved oxygen begins when there are enabling levels of dissolved oxygen (DO) in the liquid phase. Oxygen solubility is affected by the choice of gas (air or pure oxygen), temperature, pressure, and salinity. Once oxygen is available in the liquid phase of a slurry, the oxygen uptake may begin, depending on the consumers present. The rate of this is termed OUR and is usually expressed in *mg/L/min* or *g/ton ore/h*.

This paper aims to provide an understanding of critical factors affecting the produced OUR value. Two focus points were used in the approach:

- set-up specific definitions such as open/closed reactors, agitation energy, chosen head-space
- test-critical definitions such as ore/mineralogy type, grind, sample age, temperature choice, reagent additions (NaCN, lime), agitation/shear impacts and circuit phase (pre-oxidation or leach phase).

All these aspects affect the OUR value generated in a given system. It was observed from laboratory routine work and reviewing existing procedures, that clear definitions are often omitted and may lead

to disputable results. Laboratory-generated OUR values at Maelgwyn range from 0.05 to near 3.0 mg/L/h and a need to redefine and reconfirm the validity was identified.

The objective of the undertaken work was to assess which of the factors contribute most significantly to the error potential and how to incorporate the findings in practical applications.

It is hoped that the obtained results will provide information which will assist in generating OUR values of enhanced validity. This would improve the accurate sizing of oxygen plants on further computation. The use of basic data from an OUR determination towards mine site projected oxygen plants usually sees factors applied which amplify any errors in the OUR number. Such factors are related to the design of the plant and specified equipment. Transfer efficiencies of dispersion equipment, addition points, agitation and other factors affecting the k_{La} of a specific gas addition point all contribute to the final projected tonnage of oxygen. Consequently, this would define the capital and operational cost of the oxygen part of the gold extraction circuit.

Oxygen Need for Gold Dissolution

The main target of gold plants is to enable the gold dissolution and subsequent recovery at maximised and financially viable operating conditions, linking aspects such as comminution and reagent dosages to extraction time across a leach circuit. The overwhelming part of gold operations relies on the cyanide-based extraction process, even though other technologies using reagents such as thiosulphate, thiourea, halides or lately, glycine have been explored.

The first fundamental link to oxygen requirements on plants using this process can be found in Elsner's equation, well-known and accepted since 1846.



Whilst this equation represents an overall reaction, the individual cathodic steps are still seen as somewhat contested, (Bas, Gavril, Zhang, Ghali, & Choi, 2015) and (Bas, Ghali, & Choi, A review on electrochemical dissolution and passivation of gold during cyanidation in presence of sulphides and oxides, 2017). But numerous studies have dealt with the role of oxygen and cyanide and the resulting reaction rates. It is widely accepted that the molar ratio of CN to oxygen should be maintained at 8:1 to avoid retarding the diffusion-controlled reactions, (Rumball & Houchin, 2003) and (Kondos, Griffith, & Rara, 1995).

On mines sourcing ores where gold is classified as free milling (associated with quartz or at least not encapsulated by sulphides), the oxygen needs tend to be limited and can be satisfied using air; the 21% oxygen is sufficient for transfer to cover the gold dissolution needs. This is largely the case for South Africa's Witwatersrand mines, in contrast to many of the West African projects.

Even for this relatively basic need, it is observed that both agitation energy and temperature influence the reaction rates; elevating either of the two will increase them. A basic assumption, according to (Soto-Uribe, et al., 2023) is that for every 10°C the reaction rate increases by factor two or more.

Oxygen Requirements in the Presence of Sulphide Minerals

If the gold ores are sulphidic (and often refractory, where gold extraction is $\leq 85-90\%$) in nature, cyanide demand tends to rise due to many undesirable reactions. Based on gold only, a relatively minuscule amount of cyanide would be required for dissolution. But as is commonly known, often large excess amounts have to be applied to ensure an optimal degree of gold recovery. Where the gold ore is refractory due to sulphide minerals encapsulating or obstructing the target metal, these minerals have to be partially or fully oxidised to render the gold "leach amenable". Oxygen demand then follows the same path as cyanide, based on a multitude of possible reactions. However, the oxygen demand is often not as carefully determined during early testwork as the cyanide consumption.

Cyanide consumption on most ores will increase when using higher addition rates; the side reactions can be driven by higher NaCN reagent availability in the process. In practise, cyanide addition sensitivity tests are performed to determine where the additional gold recovery is in balance with the cost of raising NaCN addition. The same is true for the reagent oxygen, but only in more recent times has detailed attention been given to the application of excess oxygen and achievable potential gold

recoveries. The same reasoning would apply if the addition of excess oxygen achieves realisable higher gold recoveries; the consequential cost effects will have to be balanced against the materialised gold recovery increase. Oxidation of sulphides without benefits is in nobody's interest.

The sulphide minerals may be present mainly in the forms listed below (many more exist), in order of increasing liability to oxidative decomposition:

- Gersdorffite - NiAsS
- Pyrrhotite - $Fe_{1-x}S$ ($x = 0$ to 0.17)
- Marcasite - FeS_2 (orthorhombic)
- Arsenopyrite - $FeAsS$
- Pyrite - FeS_2 (cubic)
- Chalcopyrite - $CuFeS_2$

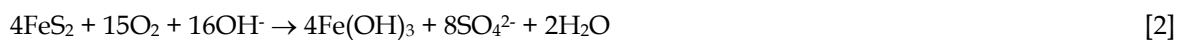
Depending on the degree of sulphide matrix oxidation required to liberate the gold, several options may be considered (listed in order of obtainable sulphide oxidation):

- Pressure oxidation (typically operated at 190 to 230°C and 350 to 700 kPa pressure)
- Roasting (single or two-step process at 500 to 800°C)
- Bioleaching (bacterial oxidation before cyanidation)
- Combinations of ultrafine grinding (UFG) and shear-reactor-based dissolution enhancement
- Direct cyanidation after ambient condition pre-oxidation.

OUR numbers are normally used to establish project design criteria in the last two process options.

Broadly speaking, sulphide minerals might be oxidised simply to elemental sulphur S^0 , sulphites or all the way to sulphate. Depending on oxidation conditions, variables such as prevailing oxidation potential, pressure and temperature, different sulphur-derived species might be generated from the corresponding minerals.

For pyrite, according to (Soto-Uribe, et al., 2023) the overall equation is generally assumed to be



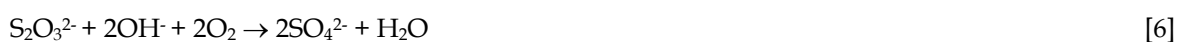
However, various intermediates are expected to form solution species further downstream to consume oxygen and cyanide. According to (Zhang, 2004) and (Breuer, Hewitt, Jeffrey, & Rumball, 2007) different species may form ranging from thiosulphate ($S_2O_3^{2-}$), polythionates ($S_xO_6^{2-}$, $x = 3-5$) or sulphite (SO_3^{2-}).



The much more reactive pyrrhotite follows similar reaction pathways.



In alkaline pre-oxidation (Kondos, Griffith, & Rara, 1995), the steps can progress via sulphides all the way to sulphate.



Therefore, depending on reaction rates, elevated oxygen demands can be expected which would report to the OUR quantification to a significant degree.

Currently Used Variations of OUR Methodology

A great deal of published methodology around OUR tests originates from the wastewater sector where OUR is used to monitor the oxygen uptake rate caused by biological microorganisms. These levels tend to be lower compared to metallurgical data values as no solids are involved.

Considerably less clarity is obtainable when the term OUR defines the oxygen consumption in mining where the aforementioned reactions may have to be considered. The range of OUR values obtained is bound to be wider and conditions more varied. Using ore samples during testwork projects, the determinations would be performed on a slurry batch (around 50% routinely, but not a given). The minerals listed as potential oxygen consumers may be present at low to percentage levels and commence reactions straight upon oxygenation. It must be borne in mind that at the plant circuit level there could be phases of differing OUR values materialising:

- During pre-oxidation (commonly the highest demand)
- At leach start once cyanide and other reagents are added (still significantly elevated)
- In all following Carbon In Leach (CIL) tanks, but normally in a regressing intensity (unless pre-ox was omitted or insufficient).

There are several methods of OUR evaluation used in the metallurgical test environment. The testwork was started by reviewing six methods of OUR. None of these methods are known approved standardised methods (ASTM or ISO) but products of gas suppliers or commercial laboratories. Results are usually further processed without differentiation. They were scrutinised for questionable practices or undefined, but critical test parameters of influence. These could lead to the invalidation of the OUR value. It was observed that they share inconsistent definitions and specifications relating to

- Set-up: closed or open system, headspace zero or undefined
- Set-up: agitation (only rpm given, not blade type choice of shear application)
- Test specific: air or oxygen use,
- Test specific: maximum DO for OUR test start and time allowed to reach this (up to 45 minutes)
- Test specific: pre-oxidation phase or leach period applicability
- Test specific: number of cycles, hours of test time
- Test specific: temperature specification (leach temperatures up to 60°C and more are possible).

The influence of these variables was taken into consideration to define the testwork scope.

Interpretation of the OUR cycle data

All the methods mentioned utilise a similar technique to interpret the results and calculate the OUR value. The rate of change of DO in the solution phase as it decays – termed a dynamic method – is illustrated by Equation 1. As the OUR test progresses, the DO meter is continuously measuring the DO in the aqueous phase and data can be plotted as seen in Figure 1 along with the OUR slope value.

The solids present in the slurry in the continuous stirred tank reactor will withdraw oxygen at a specific rate and this consumption rate is termed the volumetric oxygen uptake rate. The dynamic method for the measurement of OUR describes the oxygen uptake rate and oxygen transfer rate (OTR) mathematically according to Equation 7.

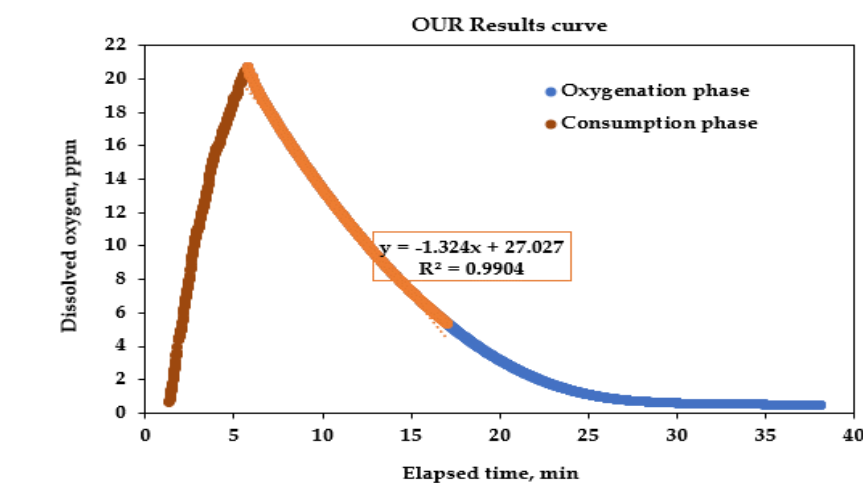


Figure 1. DO profile during OUR measurements.

$$\frac{dC}{dt} = k_L a (C_{O_2}^* - C_{O_2}^t) - OUR \quad [7]$$

Equation 7 above can be only applied during the oxygenation phase; the components are defined below:

$k_L a$: volume mass transfer coefficient
(The measure of the aeration capacity of the system for a given set of operating conditions).

$[O_2]^*$: set point DO

$[O_2]$: DO at any given point/time

$\frac{d[O_2]}{dt}$: rate of change of DO during the oxygenation phase

$$OUR = - \frac{d[O_2]}{dt} \quad [8]$$

During the decay phase, the rate of change of DO is negative since the volume mass coefficient is zero due to no O_2 transfer during the decay phase. The OUR determinations are done during the oxygen withdrawal phase of each cycle, and it is determined as the slope of the oxygen concentration decay. There is no oxygen transfer during this phase, thus Equation. 7 can be rewritten according to OUR decay equation as Equation 8.

The oxygenation and decay cycles are repeated several times, the slopes determined, and the resulting mass (g/t/h) may be used in an accumulative fashion or averaged from all the tests to arrive at a full plant leach CIL or Carbon In Pulp (CIP) tank circuit allocation excluding transfer efficiency factors or losses to the atmosphere.

Laboratory Test Result in Relation to Oxygen Plant Sizing

As described, metallurgy-oriented OUR tests normally cover around 6-9 hours; tests carrying on for longer are exceptional. Total needs and subsequent allocation to specific plant sections can be difficult to reassess. Past experience has shown that the computation of laboratory-supplied OUR values may be widely different from one engineering entity to another. Two of the obvious factors contributing to the conversion of a laboratory figure are differences resulting from:

- the tank surface-based loss factor upon re-equilibration of solutions exceeding air-relevant levels where oxygen is used
- the efficiency or k_{LA} of the entire system (gas dispersion equipment, agitators, addition points and more).

These two factors are not scalable between a 4L laboratory test reactor set-up and, for example, a 2500 m³ leach tank. A laboratory-generated OUR value should be virtually free of loss factors and the final computation including these significant moderators left to engineering sections able to base these calculations on validated models.

OUR THEORETICAL FUNDAMENTAL BASE

To attempt the generation of useful OUR values and assess their validity, it merits considering some of the fundamentals leading to observed DO values.

Reachable DO levels in water are modelled, supported by an equation based on Henry's Law where

$$DO = (P \times S \times \%) / (R \times T) \quad [9]$$

The fundamental elements are

P = partial pressure of oxygen in air or gas phase (atm)

S = oxygen solubility in water (mg/L/atm)

% = solubility of dissolved oxygen in %

R = is the Henry's Law constant (0.0821 L·atm/mol·K)

T = water temperature in Kelvin

Considering the role of oxygen partial pressure, it will be obvious that the use of relatively pure oxygen (99.5%) instead of air (21% O₂) would lead to DO levels almost five times higher.

To measure DO levels, several commercial sensor-based instruments are available if this route is chosen, rather than wet-chemistry methods (Winkler method).

Two mainstream sensing routes are used to measure DO concentrations:

- Electrochemical sensors (further differentiated into galvanic and polarographic types)
- Optical sensors (which can be further divided into intensity- or lifetime-based systems).

The electrochemical sensors based on both principles consist of a cathode and an anode situated in an electrolyte-filled cavity separated by a membrane from the measured solution. Oxygen molecules dissolved in the sample will diffuse through the membrane, the rate of which is proportional to the pressure difference across the cell. The reduction of the oxygen molecules then generates the electrical signal that the instrument then further processes, considering temperature and altitude (pressure).

Optical sensors, which have gained widespread acceptance due to their near maintenance-free operation, rely on entirely different systems. Some suppliers call their systems luminescent dissolved oxygen, optical dissolved oxygen or rugged dissolved oxygen but the functions are the same. The principle relies on a physical rather than a chemical phenomenon: luminescence. Here the intensity and lifetime of a blue LED-generated luminescence (red) emanating from a dye layer will be reduced when oxygen is present. The quench rate coefficient is used to generate the precise value.

These sensors have a few distinct advantages. They do not require a warm-up period and generally much less maintenance. They are also not agitation/membrane flow dependent.

MSA used a YSI Professional ProOdo instrument with the associated probe.

EXPERIMENTAL

The main aim of the study was to develop a method to accurately measure the OUR of specific ore samples which can be used with confidence in calculations to scale up the oxygen needed at the plant level. After reviewing the various methodologies and considering the potential importance of generated low OUR values, it was decided to conduct all work using ore samples in a closed system with near zero headspace. The oxygenation phases to reach test start DO levels were kept to a minimum by the use of stainless steel spargers. Agitation input (shear) was deemed a choice option and impacts were investigated.

Different raw materials were tested for different aspects of the project, with a focus on setup specifics and test variable criteria requiring specification.

Tap water was used for some setup specifics tests using acid-washed silica sand to simulate a 50% solids slurry. The silica sand was acid-washed to remove iron (Fe) species which generated low-level OUR values. The Fe content of the *silica sand* before acid wash was analysed at 0.34% and reduced to 0.07% Fe after a series of nitric acid washes.

Sample 1: a flotation concentrate containing 26% Fe, 19% S and 0.93% As with trace amounts of Cu and Ni with a solid density of 3.1 g/cm³.

Sample 2: a ROM ore containing 9% Fe, 7% S and 463 ppm As with a solids density of 2.98 g/cm³.

Sample 3: a ROM ore containing 15% Fe, 4.37% S and 0.45% As with a solids density of 3.62 g/cm³.

Set up specific aspects in the absence of oxygen consumers

The loss factor on a fully open system is observable when solutions with DO levels higher than the air equilibrium start to release oxygen to the atmosphere on re-equilibration. Even closed systems can have a very small loss factor remaining around stirrer shafts and other gaps, as the system is not supposed to be fully sealed and pressurised.

The setup was validated by evaluating the OTR and OUR at different tank volumes, utilising different impellers at varied agitation speeds and different water temperatures. The loss factor was seen differing at low levels with all setups tested. Low slurry volumes result in gas buildup forming a headspace which can lead to a delayed OUR value determination (feed from the headspace to the oxygen-consuming slurry). This can lead to unreliable results at low OUR values as the DO decay will only be visible once the gas stored at the headspace is fully utilised.

The loss factor associated with the tested closed system was required to be below 0.1 mg/L/min OUR since low-consuming ores also generate OUR values drifting around these levels; it can be an area of dispute. The setup-specific results with the resultant loss factors are shown in Table 1. It was observed that for those samples not requiring a high shear impact simulation, using the ringed propeller at 700 rpm in a full reactor with no gas headspace in the closed-circuit setup led to loss factors of <0.1 mg/L/min. This will represent at this stage the identified quantification limit of this setup since no clear deduction can be made whether the number is related to oxygen consumption by an ore or the loss factor of the associated setup.

Table 1: Loss factor compared between new and old MSA closed OUR setup

Sample ID	Revised setup (improved seal)	Original setup
	OUR, mg/L/min	OUR, mg/L/min
Silica sand based slurry, 50% solids before acid extraction of Fe	0.09	0.13
Silica sand based slurry, 50% solids after acid extraction	0.00	0.09

Aspects of OUR Value Generation in the Presence of Oxygen Consumers

With some of the setup-specific questions clarified, the project focused on the more test-specific variables. This included % solid content, sample ageing, sample grind, shear/agitation, reagent addition, temperature and mineral type.

The impact of varying % solids slurry is of importance as often limited amounts of sample mass are made available. These tests aimed to assess whether deviations in solid content could be tolerated. The OUR was evaluated at different % solids ranging from 30 to 50% solids. The results shown in Table 2 illustrate that low solid contents will return lower OUR values but the relation to solid mass levels the outcome to a degree. It is advisable to determine the ore OUR at the solid content applicable to plant operations. The value, if expressed in relevance to solid mass rather than solution-based levels, might still be of use.

Table 2. Test-specific criteria testing: % solids using Sample 2

% Solids	OUR, mg/L/min	g O ₂ /t ore/hr
30	0.13	18.09
40	0.18	16.10
50	0.26	15.63

Sample ageing was regarded as capable of impacting the OUR determination testwork, hence its influence was also investigated. Most samples spend months in transit depending on where the plant is situated. Some of these samples are obtained from a point in the process after comminution and could be subject to deterioration. Ageing might lead to surface passivation and result in lower OUR values obtained, compared to freshly milled samples. Sample 1 as received was milled to the target grind of 20 µm and evaluated for OUR. More samples were milled in parallel and stored for later evaluation, depending on the set time frames. The results are shown in Table 3, from which it is evident that storing the sample for some time after milling can potentially affect the OUR value. The one-month sample storage reduced the OUR value by ~0.1 mg/L/min from the fresh sample tested. Whilst further evaluation of methods used to store samples might be necessary, the value reduction is not seen as significant in the wider context (~3% for this sample).

Table 3. Test-specific criteria testing: Ageing of Sample 1

Age	OUR, mg/L/min	g O ₂ /t ore/hr
Fresh	2.50	225
1 Week	2.47	223
1 Month	2.43	219

Sample grind was investigated as it was expected to contribute significantly to the elevation of the OUR value of ore with high sulphide mineral content. Sample 1 as received was evaluated for OUR which was levelled at 0.23 mg/L/min suggesting 20.72 g O₂/t ore/hr is required to achieve the target DO at the plant level (before applying inefficiency factors). The OUR increased 10-fold in a UFG-based sample

of 20 µm grind size from the as-received grind. Thus sample grind has a significant impact on OUR value and requires to be clearly defined and best milled to size prior to OUR determination. OUR values in Table 4 demonstrate the multiplication factor of the values' dependence on particle size.

Table 4. Test-specific criteria testing: Sample grind/PSD using Sample 1

Grind size	OUR, mg/L/min	g O ₂ /t ore/hr	Comments
D80 63 µm	0.23	20.72	As received
D80 53 µm	0.45	40.33	Polished
D80 45 µm	0.61	54.47	UFG milled
D80 20 µm	2.50	225	30-minute decay time

Temperature and its effects were tested to evaluate whether the influence on the OUR is significant enough to include this criterion as a test-specific definition. Before using the oxygen-consuming samples, tap water was used to check on the measured DO in relation to elevated temperatures. The water temperature was increased up to 60°C, and the resulting DO levels and OUR were measured and then compared to the theoretically expected DO levels of freshwater for the specific temperature, pressure and salinity. The values are altitude-corrected.

Table 5. Water-based DO checks for different temperatures

Temperature	Expected DO	Reached DO	OTR	OUR
°C	ppm	ppm	mg/L/min	mg/L/min
30	31.0	28.0	2.34	0.04
40	26.0	24.0	4.62	0.02
50	22.0	18.0	3.65	0.01
60	19.0	16.0	1.91	0.01

The oxygen transfer and consumption rate in tap water were not significantly affected by a change in temperature. The reached DO levels were under-reporting when compared to calculated concentrations based on temperature and altitude. The reasons are not clear.

Sample 1, being the high sulphidic ore with a grind of 80% passing 20 µm was used for OUR tests at elevated temperature levels. Even at ambient temperature, the oxygen was faster consumed than transferred; a slope could not be derived for higher temperatures. Whether a high-efficiency device for the transfer of oxygen could overcome this remains to be tested. With the current OUR setup, the highest achievable DO during transfer was 3.5 ppm at 40°C. The natural DO concentration of the test slurry was below 1.0 ppm. Table 6 compares the highest achievable DO levels as a function of temperature. The levels dropped to zero immediately as the oxygen flow was stopped; no OUR value could be derived.

Table 6. DO levels achieved using Sample 1 at UFG grind as a function of temperature

Temperature	Expected DO	Reached DO
°C	ppm	ppm
20	37.5	19.7
40	25.9	3.5
50	21.9	2.5

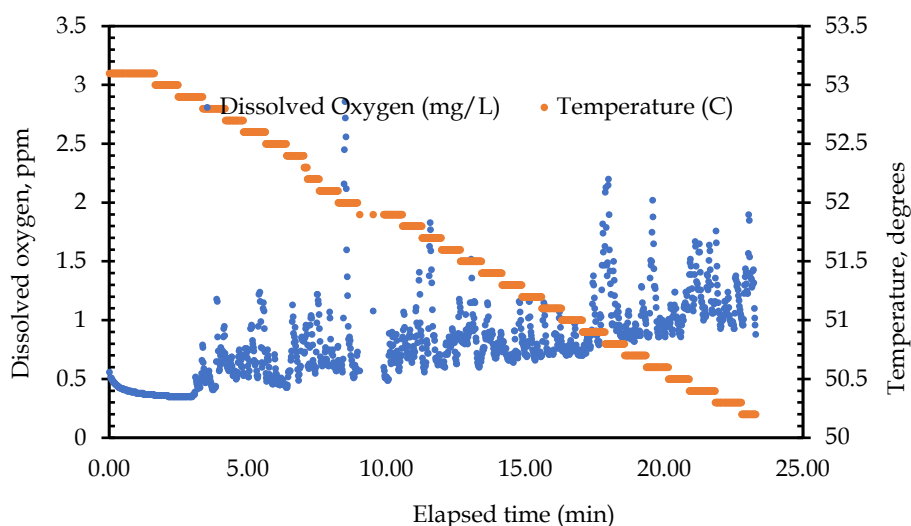


Figure 2. Sample 1 temperature OUR test, 50 degrees.

The oxygen demand of individual gold ores is largely dependent on the sulphide mineral content. Samples of known Fe and S content were tested for OUR to evaluate their oxygen demand and relation to sulphide content. The OUR values contained in Table 7 illustrate the range of OUR values that might be generated from different ores.

Before assessing the OUR of sulphide-containing ore, acid-washed silica sand at a P80 of 75µm was used as a blank sample and compared to those samples with a known concentration of Fe and S. A quartz sand sample should depict little to no oxygen consumption as silicates are classified as oxide minerals which will not undergo further oxidation by oxygen in aqueous solutions; this was confirmed as evident in Table 7. Sample 1 has shown to be a highly oxygen-consuming ore which is supported by analytical analysis of high Fe and S content as compared to sample 2 and 3.

Table 7. Test-specific criteria testing: Mineralogy influence

Sample ID	% Fe	% S	OUR, mg/l/min
Silica sand (Blank)	0.07	-	0.00
Sample 1	26	19	2.53
Sample 2	9	7	0.26
Sample 3	15	4.13	0.29

Sample 1 was further evaluated before and after reagent addition, to assess the OUR value change as a function of leach circuit position. Thus, a series of tests were performed at pre-oxidation level, at cyanide addition and lastly after carbon addition for the extended CIL phase. Operating plants using pre-oxidation at Tank 1 level before cyanide addition see this as essential to satisfy oxygen-consuming species ahead of the gold dissolution stage. This helps to reduce cyanide consumption and gold recovery losses due to retarded leach kinetics by rate-limiting DO levels downstream in the CIL circuit. In addition, intense pre-oxidation often leads to increased gold recovery due to sulphide minerals being oxidised along grain boundaries.

The results are shown in Table 8, illustrating how the OUR of Sample 1 is affected in each stage of Au dissolution. Whilst the pre-oxidation based OUR cycles reflect relatively high oxygen demand, after reagent addition the uptake slows down rapidly towards a steady state consumption. With the addition of carbon, the cycles show little change but remain at a level slightly higher than after the end of the cyanide-based cycles.

Table 8. OUR values showing the effect of reagent addition after a pre-ox stage, mg/L/min

Cycle	Pre-oxidation	Pre-oxidation + NaCN	Pre-oxidation + NaCN + Carbon
Cycle 1	2.36	1.69	0.74
Cycle 2	2.09	0.66	0.73
Cycle 3	1.98	0.57	0.73
Cycle 4	1.80	0.54	0.73

Mechanical agitation inside the reactor serves to homogeneously mix the reactor contents, maintain the solids in suspension and support the dispersion of gas bubbles. This will substantially improve the OTR. Elevated agitation may also enhance reaction rates due to reduced film boundary layers. Where high-shear reactors are intended to be deployed, simulation using suitable agitators might have to be considered.

Different agitation speeds were tested with both radial and high-shear impellers to evaluate the OTR and OUR values (Sample 1). Data reproduced in Table 9 illustrates the enhanced transfer rate and increased OUR. High-shear agitation can thus advance the reactions and lead to elevated OUR values for a period in the system. This can be beneficial, but a link to the gold recovery must be attempted. Some plants make use of high-shear reactors for oxygen dispersion; OUR tests should simulate this environment as it would lead to higher values at Tank 1 and 2 levels in the circuit.

Table 9. The effect of impeller type during transfer and consumption phase, mg/L/min

Agitator type and speed	OTR, mg/L/min	OUR, mg/L/min
Radial agitator at 500 rpm	1.09	2.36
High shear agitator at 1500 rpm	5.08	3.70

CONCLUSIONS AND RECOMMENDATIONS

The work conducted has shown that a single sample if tested for OUR, could generate values differing by factor 10 or more depending on the conditions chosen. This would have severe impacts on further processing and ultimately on oxygen plant size-based capital expenditure. Gold recovery-based revenues if oxygen is under-supplied could be negatively affected.

The various methodologies in use often lack clear definitions of OUR applicability to the leach circuit (pre-oxidation or leach phase). This should be specified and separate tests conducted for both locations as the values will differ significantly and should be used accumulatively.

Furthermore, where high-shear reactors are used at plant level, the OUR system utilised agitators and applied shear should simulate this environment as values generated under such conditions have been shown to rise by 50%.

The preferred setup-specifics were defined as a closed system with near-zero gas headspace and a choice of agitator type for either standard or high-shear oxidation simulation.

The low-level OUR type of ores generate values at or below the loss factor of an open system; a closed system is preferred to avoid confusion (open system around 0.3 mg/L/h, closed systems <0.1 mg/L/h). Scalability between laboratory OUR data and plant mass-need of oxygen should be left to competent facilities.

The OUR test system could benefit from the inclusion of oxygen flow metering during cycles and temperature-controlling ability. Further reduction of the loss factor down to near zero is targeted.

Apart from set-up typical influences on generated OUR data, the test-specific influential parameters in order of significance are:

- Grind (factor 10 elevation between standard and UFG type Particle Size Distribution (PSD) in this work) requiring definition and exact matching of plant or project specification
- Temperature (limiting test execution due to consumption rate exceeding the feed rate of O₂) but seen as a massive influence by a mere 20°C lift with many mines in Africa operating at temperatures at or above 50°C
- Agitation/shear input with elevations on values of 50%
- Matching solid content to project or plant specification and lastly, sample ageing are of relatively minor significance.

Thus, before undertaking OUR tests, the reagent additions, relevant mine site temperatures, grind and OUR relevance in the circuit (pre-oxidation or leach phase) must be integrated into the test programme and agreed on with engineers and mine process staff.

More investigative work is needed to evaluate the dependence and validity of the OUR value generated at elevated temperatures, shear and for a wider range of sulphide-containing samples.

Further work should also validate the data generated at laboratory level to plant-based consumptions through the integration of the scalability factors linked to loss factors and plant-level k_{La} amongst potential other contributors.

The relation of generated OUR values to certain sections of the extraction circuit and the impact on computations towards mine-based oxygen plant sizing needs to be further assessed.

Considering that oxygen plants on mining sites often range from 5 to 50 tonnes, this can have significant financial implications if utilised incorrectly. Most plants known to Maelgwyn have over time increased their oxygen tonnage fed into the system rather than reduced it.

Improving on the correct OUR value generation, further processing of the data and correlating the results to the gold recovery is seen as of high importance and will be further focused on.

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