# IMPLEMENTATION OF SELECTIVE OXIDATION AT LIHIR GOLD OPERATIONS PAPUA NEW GUINEA


**Presenting Author**

**Johm O'Callaghan**
**Consultant**

stardustantares@gmail.com



## ABSTRACT

On 10 December 2014 Lihir Gold Operations changed from full oxidation of gold containing auriferous sulfides to selective oxidation.

Most of the gold at Lihir is contained in high-arsenic pyrite or arsenian pyrite and this pyrite is the target for preferential or selective oxidation. The installed and fixed cryogenic oxygen supply capacity is used to oxidise arsenian pyrite in preference to low-grade "barren" pyrite thereby maximising gold production.

This paper briefly describes the history of the Lihir process plant and the implementation of the selective oxidation process using the new operating strategy.

Specific lime, cyanide, and other reagent usage in the downstream Carbon-in-Leach gold recovery circuit has remained largely unchanged.

Other deposits of similar mineralogy may benefit from a selective oxidation approach.



***Keywords:*** *arsenian pyrite oxidation*


## INTRODUCTION

The Lihir Gold operation is located on the eastern side of Niolam Island in the New Ireland Province of Papua New Guinea (PNG), within the collapsed caldera of an ancient volcano. As Niolam Island is the principal island of the Lihir Group, it is generally referred to as Lihir Island see Figure *1* below. An aerial view of Lihir in Figure *2* shows the treatment plant in the foreground with the open-cut mine in the background.

Gold was discovered in 1982 and was followed by a major exploration program between Kennecott and Niugni Mining Limited. The first drilling occurred in 1983. Over 340 holes and 83,000m of drilling and associated metallurgical test work supported the final bankable Feasibility Study which was completed in 1992. Gold recovery using whole ore pressure oxidation was the selected treatment process. Construction of the mine, process plant and all related infrastructure commenced in 1995 and the plant was commissioned in May 1997.

In 1988, the RTZ Corporation (now Rio Tinto) acquired Kennecott from BP Minerals America, thereby taking over as the Lihir Joint Venture partner with Niugini Mining Limited. Lihir Gold Limited (LGL) was incorporated in Papua New Guinea in June 1995.

Newcrest Mining Limited (Newcrest) purchased Lihir Gold Limited following the merger of Newcrest and LGL in August 2010 and subsequently completed a major plant upgrade (Million Ounce Plant Upgrade – MOPU Project) that was already underway at the time. Additional crushing, grinding, pressure oxidation and carbon in leach (CIL) capacity as well as new support infrastructure was part of the upgrade. On 6 November 2023 Newmont Corporation completed the acquisition of Newcrest.

Considerable reserves remain at Lihir, and long mine life is expected.

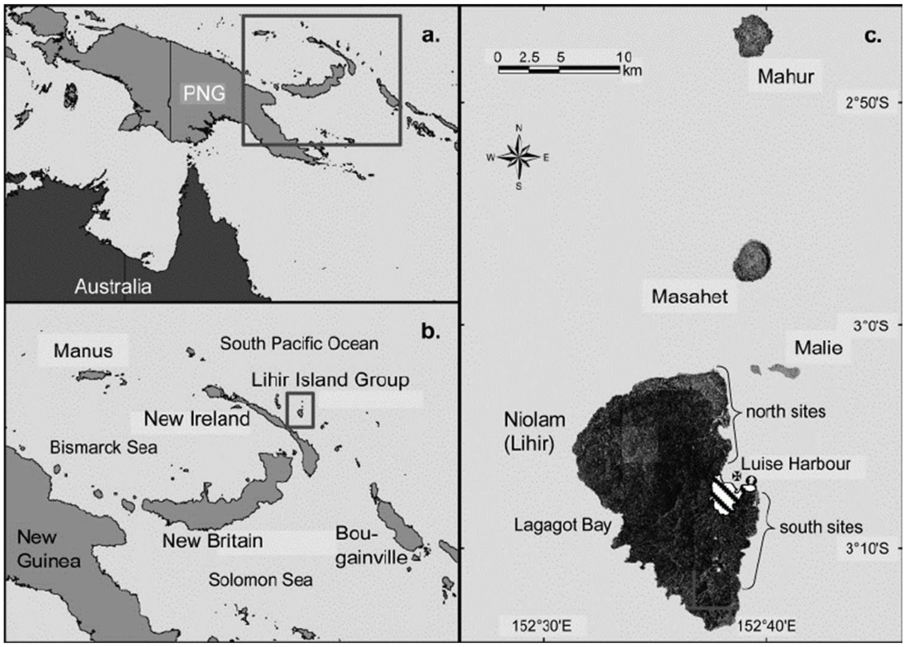


Figure 1 - Location of Lihir Island


Figure 2 - Aerial View of the Lihir Gold Mine

Sherritt Research Centre conducted the original Lihir pressure oxidation test work as a pre-treatment process ahead of gold recovery via cyanidation. There are several references documenting the process development for Lihir (Ketcham et al, Collins et al and Ketcham and O'Reilly). A key feature of the original process design was high sulfur oxidation for ores containing high gold and sulfur grades. The strategy for the original owners and then LGL for the MOPU project was to target the high gold and high sulfur "boiling zone" areas of the orebody. Initially a declining cut-off grade strategy was adopted which led to stockpiling of medium to low grade ores containing low Au:S ratio ores (mainly Argillics). Gardner et al describes the different ore types and domains at Lihir. (Note Au:S ratio = gold g/t and sulfur %w/w and all references to sulfur therein refers to sulfide sulfur).

Soon after purchase and faced with low gold prices, Newcrest took the value-based choice to adopt a lower gold grade processing feed cut-over strategy. Large scale stockpiling of medium grade ores was discontinued, and treatment of previously stockpiled "medium grade" ores commenced. The large Kapit Flat stockpile generated by the previous owners would be treated rather than relocated off the final major pit of the orebody - Kapit. In addition, future ROM grade ores from Kapit would be treated rather than stockpiled.

The new mining strategy required treatment of lower Au:S ratio and lower sulfur (sS) grade ores to maximise gold production.

On 10 December 2014 Lihir Gold Operations changed the plant operating strategy from "full oxidation" of gold containing auriferous sulfides to selective oxidation. As most of the gold at Lihir is contained in arsenian pyrite this is the target for *preferential* or selective oxidation. This allows increased throughput of lower Au:S ratio ores as only part of the sulfur needed to be oxidised. The installed and fixed cryogenic oxygen supply capacity is used to always oxidise arsenian pyrite in preference to low-grade "blocky" pyrite thereby maximising gold production.

## THE LIHIR PROCESS

At a pre-treatment process technology level, the Lihir process has not fundamentally changed over time. Pressure oxidation of gold containing auriferous pyrite remains the pre-treatment process prior to final gold recovery by Carbon-In-Leach (CIL).

The original overall block flowsheet for the Lihir process is shown in Figure *3* below (re-drawn from Collins et al). Chloride washing of autoclave feed slurry was practiced.

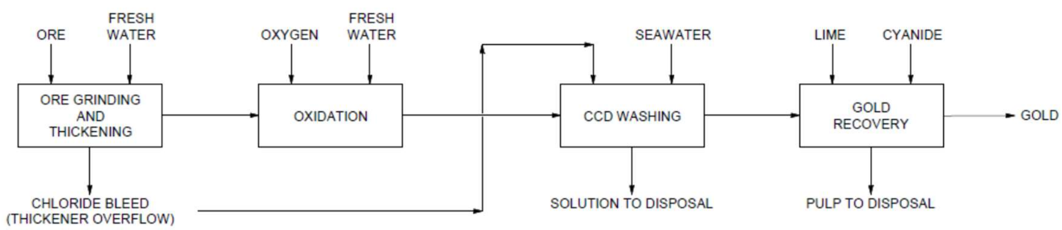



Figure 3 – Original Overall Lihir Flowsheet (Collins et al)

To accommodate declining sulfur grades over time, equipment additions, modifications, and enhancements were made. The decline in sulfur and gold grades over time (especially in the first 10 years of operation) is shown in the attached graphs (Figure 4 and Figure 5)

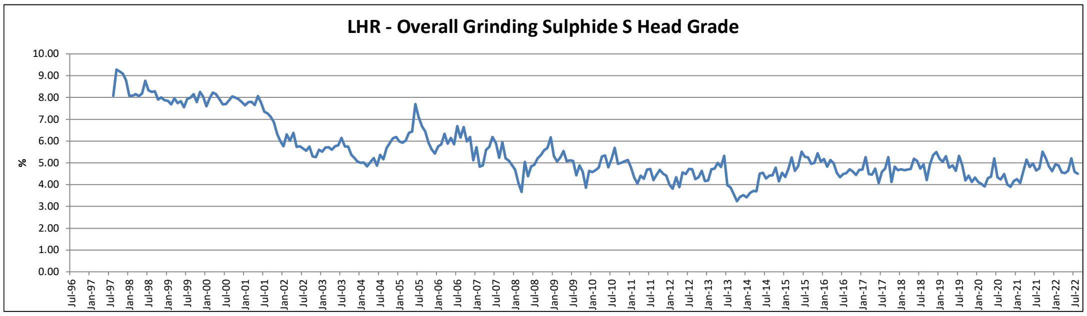


Figure 4 - Lihir Mill Feed Sulfide Sulfur, %S

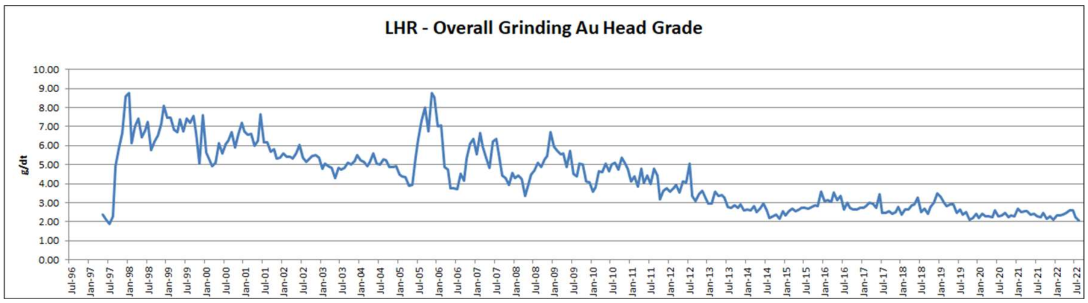


Figure 5 – Lihir Mill Feed Gold, g/t

With treatment of all ore types including those with lower grades of gold and sulfur the Au:S ratio has reduced to around 0.5 which is close to the Mineral Resource average for Lihir. Initially the Au:S ratio was higher at 0.8 to 1 (or higher) in line with the original declining cut-off grade strategy of targeting high gold and sulfur ores. This trend of Au:S ratio in mill feed is shown below in Figure 6.

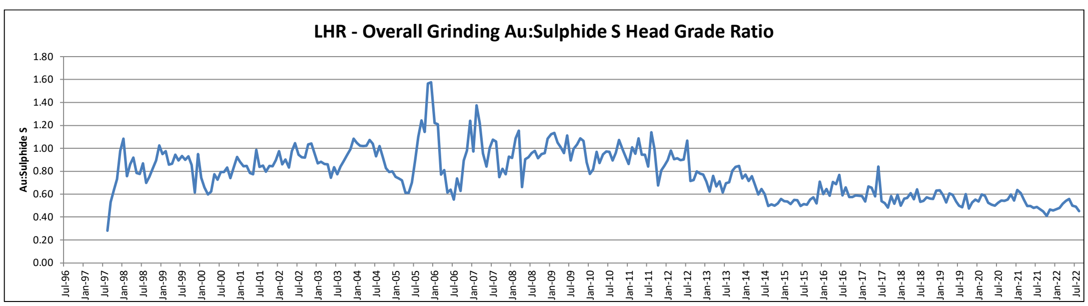


Figure 6 - Lihir Mill Feed Au (g/t):S (%)

Prior to 2015 with a fixed amount of oxygen available and in "full" oxidation mode then preference was given to high Au:S ratio ores, demanding proportionally higher mining rates to supply these ores.

Hence it was clear that "full oxidation" of low Au:S ratio ores (especially treatment of lower grade stockpiled ores) required a different approach as gold production would clearly be reduced with a fixed oxygen plant capacity.

After extensive mineralogy and gold deportment investigations (Gardner et al) it was verified that gold deports preferentially to micro-crystalline arsenian pyrite. Importantly this high-gold fraction is very reactive and oxidises rapidly in the autoclaves. The high-gold microcrystalline pyrite fraction occurs in all ore types at Lihir in varying amounts hence all ore types display some response to selective oxidation. Note that the low-grade “blocky” pyrite always oxidises to some extent however due to the slow kinetics it is preferentially present in autoclave discharge.

In early August 2014 a selective oxidation plant trial was completed which showed preferential oxidation of gold containing pyrite with high gold CIL recoveries after only ~ 70% oxidation. On 10 December 2014 the plant operating strategy was changed from ‘full” oxidation to selective oxidation. The gold within microcrystalline pyrite became the primary target for selective oxidation. The installed and fixed cryogenic oxygen supply capacity is now used to always oxidise arsenian pyrite in preference to low-grade “barren” pyrite thereby maximising gold production.

A minimum sulfide oxidation of 50% was set initially however some ores require higher oxidation and some less. In typical day-to-day operation the % oxidation varies as throughput and/or feed sulfur grade varies. This is discussed more later.

## Brief History of the Lihir Flowsheet

The flowsheet as installed in 1997 is shown below in Figure 7 . The main features were: -

Single stage crusher with a single SAB milling circuit
Fresh water ex Londolovit River
Three autoclaves with single stage flash and seawater flash steam quench
CCD wash for acid and soluble sulphates removal
1 x NCA (CIL) for final gold recovery
Whole ore feed only; no flotation and no pre-heating

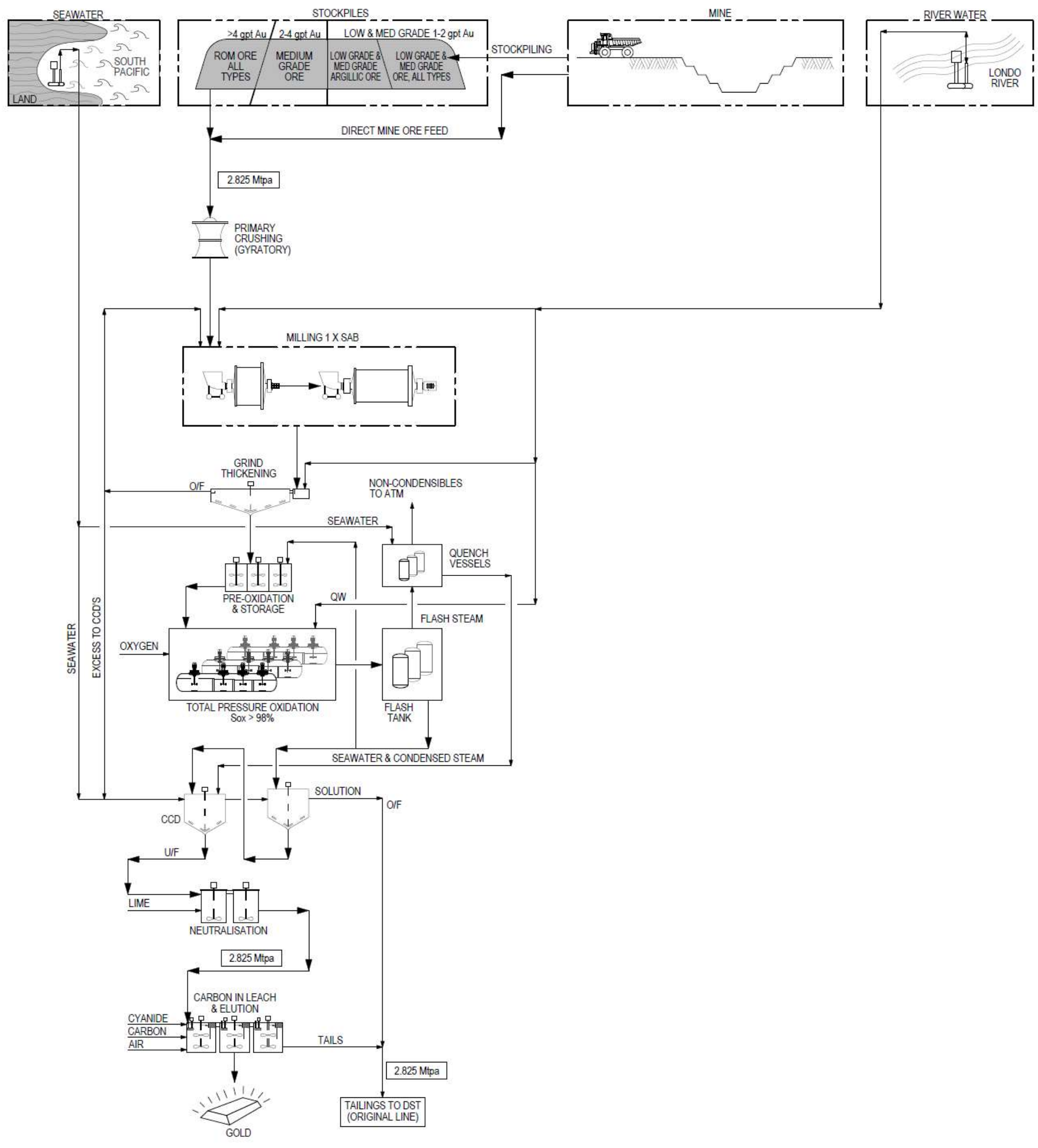



Figure 7 - Lihir Original Flowsheet circa 1997

In circa 2003, three direct contact heat exchangers and a pebble crushing circuit were installed. This allowed increased throughput with declining sulfur grades while ensuring the autoclaves were not restricted by autoclave temperature (McDonald).

After extensive piloting a flotation circuit was added in addition to a second grinding circuit in circa 2006 (the original flotation pilot plant has only recently been demolished). A dedicated concentrate thickener was also installed. The flotation plant was used on an as needs basis.

In 2010-2011 a major plant upgrade commenced associated with the addition of Kapit Ore Reserves. Known as the Million Ounce Plant Upgrade (MOPU) project the key equipment installed included:-

- Two jaw crushers and one additional grinding circuit SABC (HGO2)
- Two additional pre-oxidation tanks
- One additional autoclave roughly twice the size of the original three (AC4).
- Two additional flash/quench circuits for AC4
- Installation of a common Oxidised Slurry Tank system for all autoclave discharges
- Additional CIL capacity – NCA2
- New tailings disposal line
- Additional oxygen plant
- Other infrastructure

The design of the new MOPU autoclave is well described in Hewitt et al. Figure 8 shows flotation added to the overall block flowsheet.

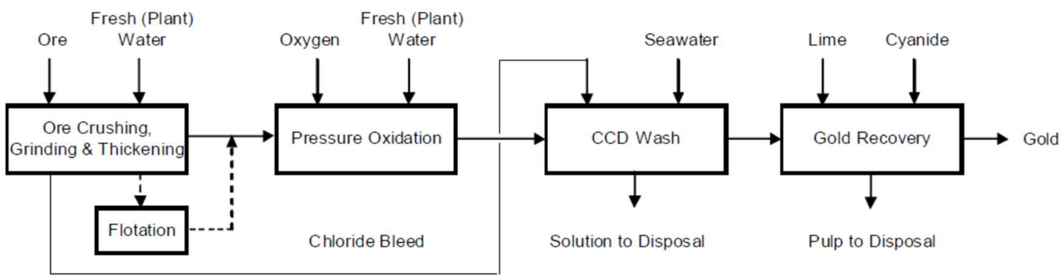



Figure 8 - Lihir Flowsheet with Flotation (after Hewitt et al)

The flowsheet with the MOPU equipment added is shown below in Figure 9

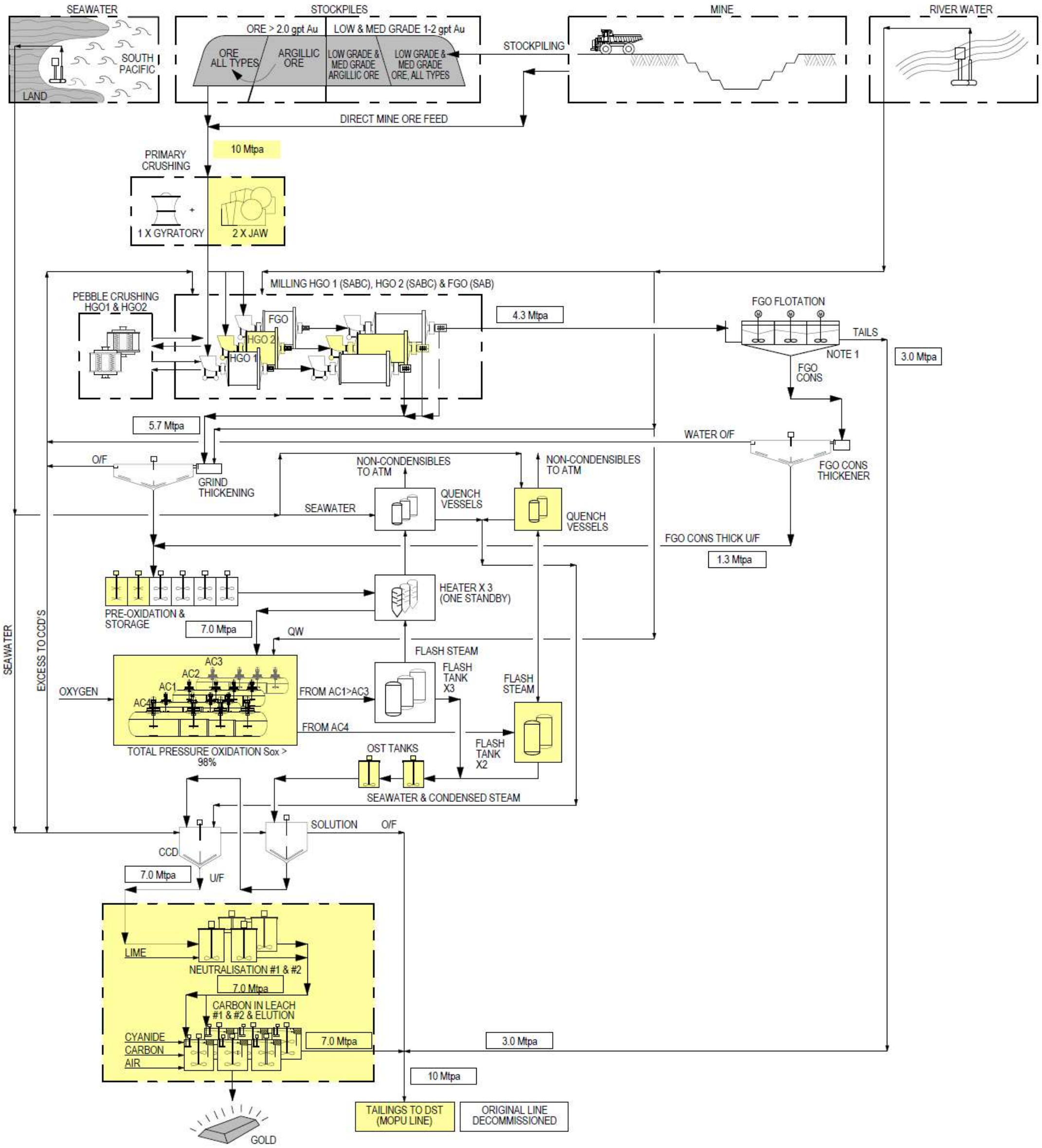



Figure 9 - Lihir Flowsheet post MOPU Upgrade

As the MOPU expansion project was nearing completion Lihir was acquired by Newcrest. To accommodate the new mining strategy requiring treatment of lower sulfur ores Newcrest installed a second and larger flotation circuit, considering recent processing lessons from its Cadia Mine.

From 1997 until the end of 2014 the pressure oxidation process was operated in nominally "full oxidation" mode.

With the change to selective oxidation of lower sulfur ores (and reduced Au:S ratio ores) on 10 December 2014 increased mill throughput was possible thereby maximising gold production.

As there was some latent grinding capacity available at the time this allowed an immediate increase in throughput. Excess mill capacity (above autoclave capacity) is sent to flotation which is now essentially a mass rejection process. Flotation became an integral part of the Lihir process rather than being used ad-hoc to upgrade low sulfur ores.

Sulfur oxidation is allowed to vary between 50 and 100% (subject to additional controls described further below) and hence autoclave sulfur throughput has increased substantially. While a slight reduction in CIL recovery has occurred, this is vastly offset by increased throughput.

Some limited recovery of gold from flotation tailings does occur. When floating partially oxidised stockpiled ores fine oxidised solids are recovered from flotation tailings using cyclones and the fines are sent to the CIL circuits directly. If fine sulfides are to be recovered these can be sent directly to the autoclave for oxidation.

The process plant flowsheet as it stands today is shown below in Figure 10.

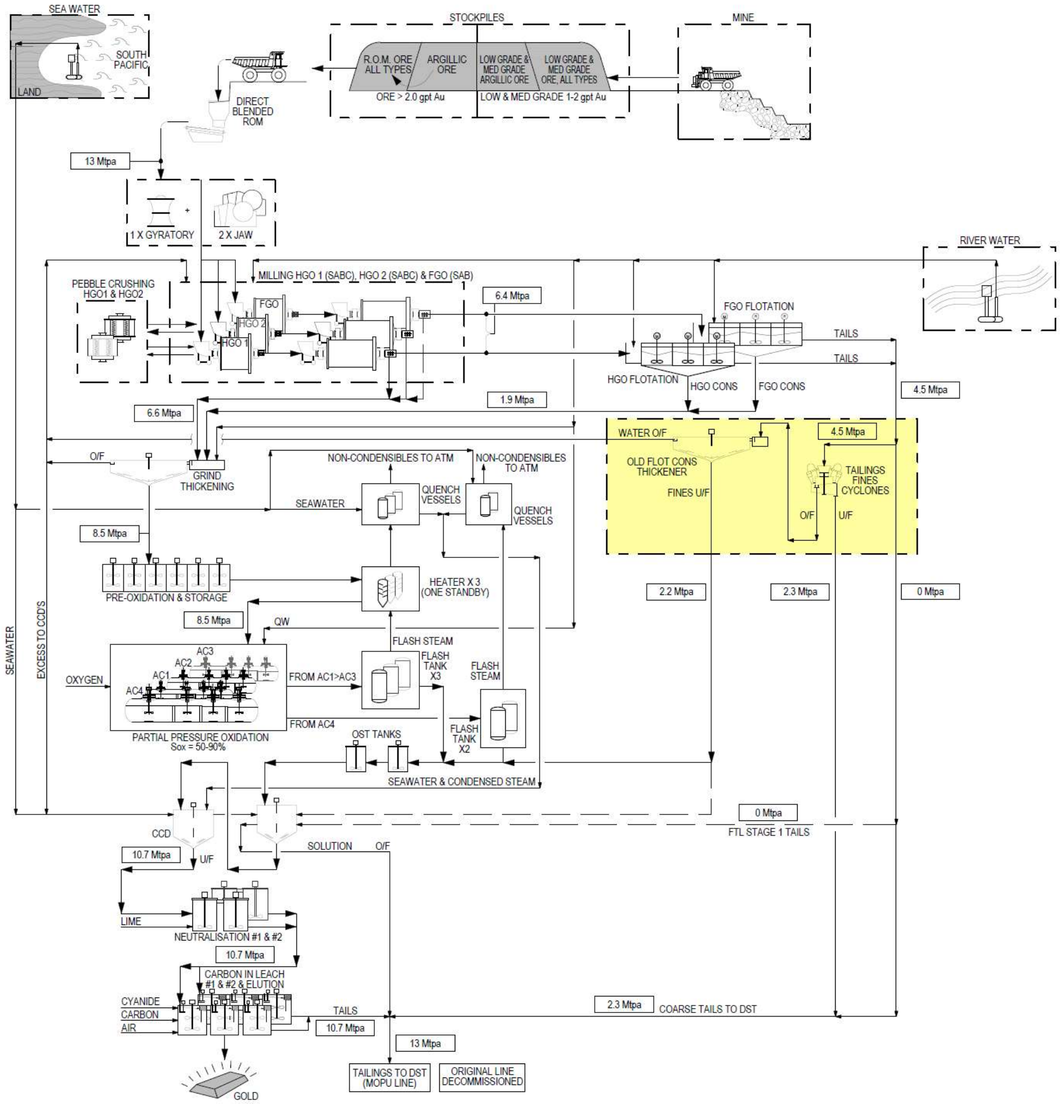
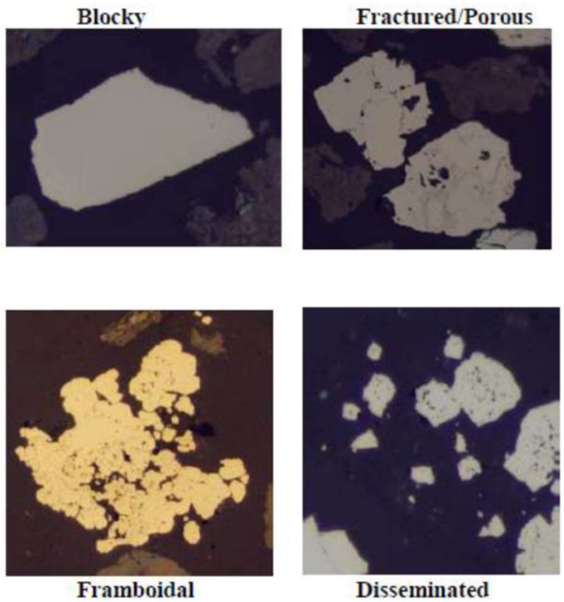



Figure 10 - Lihir Flowsheet Current

## Selective Oxidation at Lihir

On 10 December 2014 at roughly 3 pm in the afternoon the plant operation changed from nominally "full" oxidation to selective oxidation. Latent milling capacity was immediately used and over the next several years mill throughputs were progressively de-bottlenecked, and the milling circuits modernised.

Originally the descriptor "partial oxidation" was used for the new process and while technically correct – part of the sulfide sulfur is being oxidised - the term selective oxidation is more accurate since the plant is operated to ensure that liberated high-gold microcrystalline pyrite is oxidised preferentially to low-gold (blocky pyrite). Gardner et al describes the different pyrite species and some examples of the typical gold content of each of the pyrite types is shown in Figure 11 below.




| Pyrite Species | Au Content* |
|---|---|
| Blocky | 5.3 |
| Disseminated | 25.6 |
| Framboidal | 52.4 |
| Fractured/Porous | 11.7 |

(* ppm)

Figure 11 - Pyrite Speciation at Lihir (after Gardner et al)

The proportion of blocky and reactive pyrite varies throughout the orebody and operation down to 40 and even 30% oxidation is possible without significant gold loss. However, for future higher Au:S ratio ores it is likely that increased oxidation will be required. This is subject to on-going testing and analysis.

The optimum operating point for Lihir is to keep increasing sulfur throughput to the autoclaves such that all the available oxygen is used to oxidise the reactive microcrystalline arsenian pyrite only. At this point Lihir would be producing at the maximum gold production rate possible. However, for several practical reasons, operation occurs at just above the minimum ORP (oxidation reduction potential) or oxidation level. Of course, some blocky pyrite is always oxidised but at a much slower rate. Essentially inherent differences in pyrite oxidation kinetics are being exploited at Lihir.

Controlling the process plant to maximise gold production using selective oxidation is referred to as the Lihir Operating Strategy (LOS) and is described below.

## Lihir Operating Strategy (LOS)

The operating strategy at Lihir using selective oxidation is very different to the original design of "full oxidation" of high gold grade ores (and high Au:S ores). With a fixed oxygen supply capacity (currently 140 tph) the objective is to operate the autoclave facility such that all high gold arsenian pyrite is oxidised preferentially while minimising oxidation of blocky pyrite. This is achieved by maintaining high autoclave sulfur throughputs until either of the following conditions is met.

- Minimum total sulfur oxidised is 50% (can be lowered with Plant Manager approval)

  OR

- Minimum autoclave discharge slurry solution potential is 360 mV (ref Ag-AgCl, saturated)

Together these limits are described as the Lihir Chemistry Limit (LCL) and the objective is to always operate at the LCL.

Shown below in Figure 12 and Figure 13 are some typical daily trends for ORP and % oxidation. In this instance operation was close to the LCL. Compliance with the LOS is monitored continuously, and the process controlled to ensure gold production rate is always maximised.

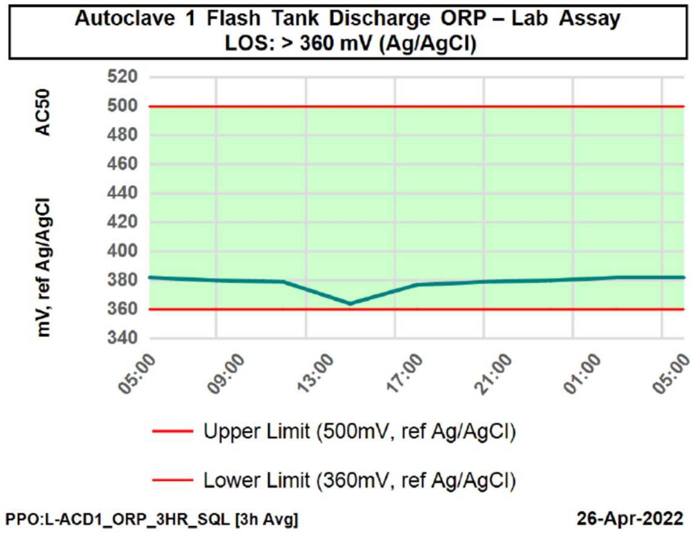



Figure 12 - Example ORP Trend - Autoclave 1

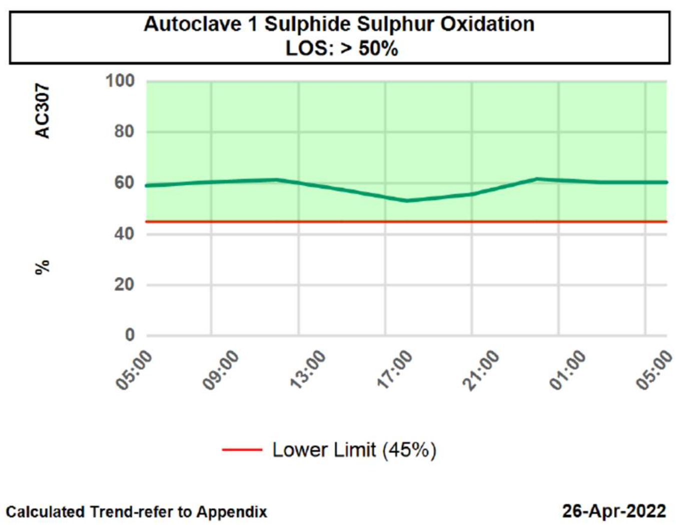



Figure 13 - Example Oxidation Trend - Autoclave 1

Other key aspects of the LOS are: -

Some ore blending should be practiced (not currently implemented)
Mill throughput is always maximised (with excess capacity sent to flotation)

- All available oxygen is used.
- Autoclave mass throughput is maximised (to maximise overall recovery by minimising the fraction of ore sent to flotation)
- Minimum and maximum autoclave feed sulfur grades are 5 and 12% (% w/w)
- The mill grind size maximum is P80 of 210 μm (see discussion later)
- Maximum oxygen utilisation is always targeted.

In theory autoclave mass throughput could continue to be increased while operating in selective oxidation mode. However, other constraints need to be satisfied including (but not limited to) autoclave feed pump capacity and final downstream carbon-in-leach (CIL) gold recovery circuit capacity. The most fundamental limit is that the autoclave energy balance must be satisfied, and the autoclave needs to be kept at the required operating temperature. For autoclave feed slurry densities typically encountered at Lihir roughly 4 to 4.5% sulfide sulfur must be oxidised to achieve this. Mass throughput is controlled to achieve minimum “front-end” temperatures. The LOS nominates a minimum of 5% sulfur grade in autoclave feed.

With the flotation circuits, milling of lower sulfur grade ores is possible and excess milling capacity over autoclave capacity is sent to flotation. High throughputs through the flotation circuits are possible and, often “full flotation” is achieved with only concentrate sent to the autoclaves. Gangue is rejected, and sulfur (and gold) grades are increased. However, on average the autoclaves receive a mixture of whole ore and flotation concentrate.

Importantly the split of milled ore to flotation is controlled by the level in the buffer storage (pre-oxidation) tanks between the grinding and autoclave areas. As level increases in the pre-oxidation tanks more ore is sent to flotation and more concentrate is treated in the autoclaves. When level drops, less ore is directed to flotation and effectively more “whole ore” is treated in the autoclaves.

The overall flowsheet showing LOS operation is shown in Figure 14 below.

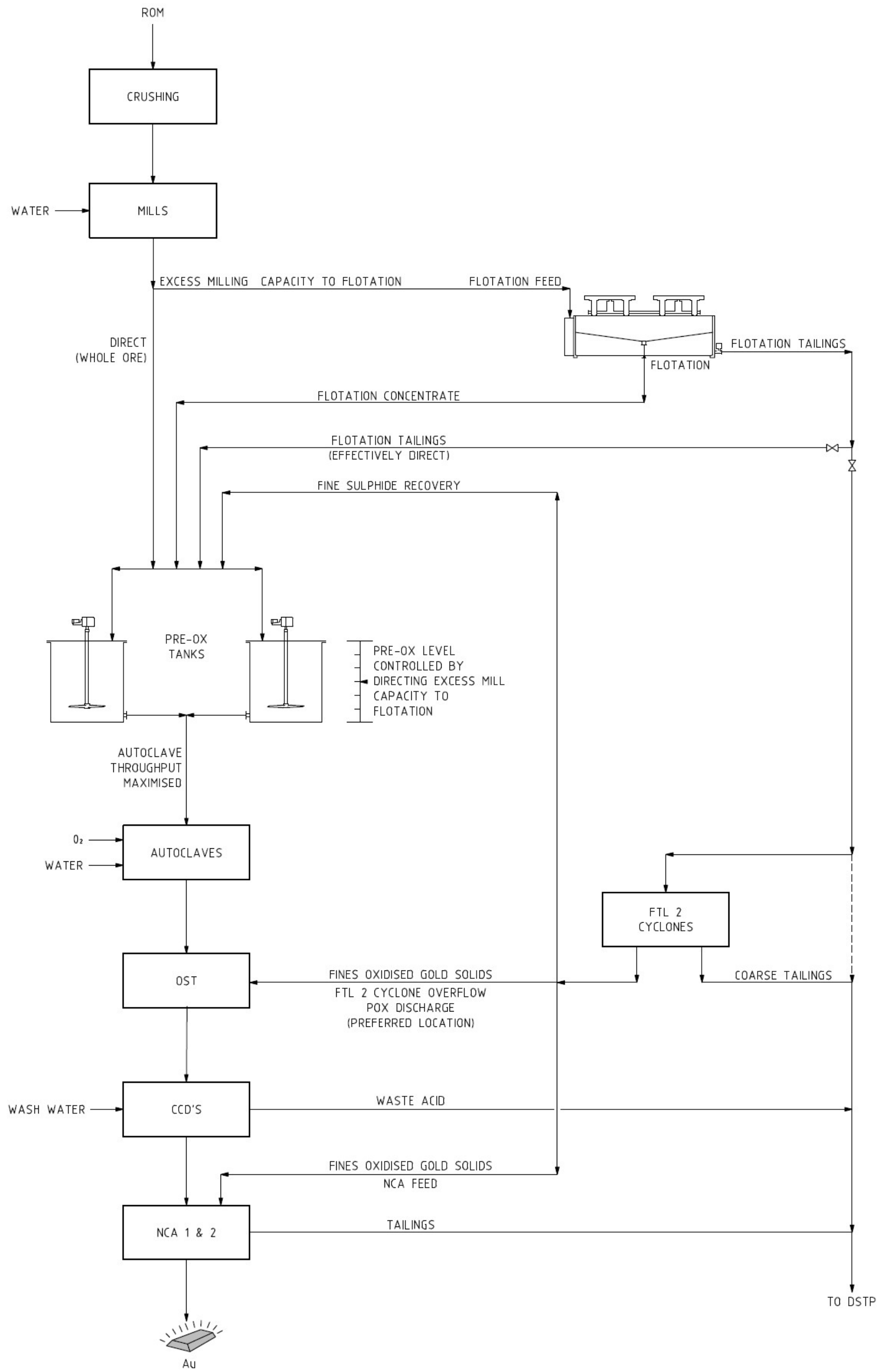



Figure 14 - Lihir Flowsheet showing LOS Operation

The four POX autoclaves at Lihir are horizontal pressure vessels with individually agitated compartments each with oxygen injection (the last compartment oxygen is now isolated). Cold water addition is used to control temperatures in individual compartments if and as needed. Cold feed slurry is introduced at the feed end of the autoclave ("front end") and slurry cascades over compartment walls until exiting under pressure from the last compartment. Feed slurry can be partially heated (to a maximum of 95 °C), however due to the nature of the reactor configuration there is almost always a gradient in the temperature profile and the front-end compartments are typically operated approximately 5°C lower than the target autoclave temperature (of 210 °C).

The LOS is an example of a self-correcting process. If "front-end" temperatures drop, then throughput is reduced. At a fixed mill throughput more ore is sent to flotation and the mix of whole ore and flotation concentrate changes and autoclave feed sulfur increases. "Front-end" temperatures increase as additional reactive microcrystalline pyrite is oxidised in the first few compartments with a higher oxygen utilisation (there is also a higher total concentration of sulfur as well). Oxygen utilisation is a strong function of feed sulfur grade at Lihir.

In theory, higher autoclave throughput is possible if operation closer to true autothermal operation could be achieved. Over the last eight years internal autoclave modifications like compartment wall removal and feed splitting between the first and third agitators have been made allowing higher mass throughputs at lower % sulfur oxidised and lower autoclave feed sulfur grade.

## Lihir Operating Performance – Before and After Introduction of Selective Oxidation

In the following figures, Lihir performance before and after the change to selective oxidation is shown and described.

### *Grinding and Flotation*

Total mill throughput rate (tonnes/operating hour) is shown in Figure 15. The increase with the second and third mill installation in 2006-07 and 2012 is clearly seen. From early 2015 to 2020 progressive mill de-bottlenecking work was completed. Higher throughput rates of lower Au:S ores and lower % sulfur ores can now be treated by selective oxidation with excess mill capacity over autoclave capacity directed to flotation (see Figure 14).

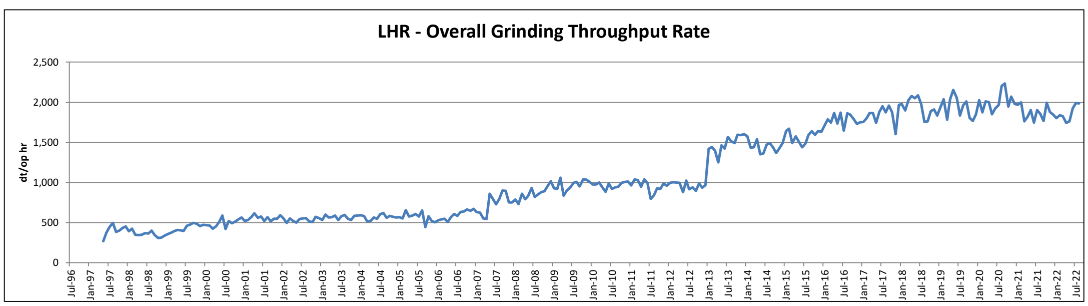



Figure 15 - Lihir Total Mill Throughput t/op.h

As installed mill power has not increased the average grind size has subsequently increased see Figure 16 below. The increase in average grind size has been partially offset by softer stockpile ores (Argillics mainly) being treated. The LOS allows grind size to vary up to a maximum of P80 of 210 µm beyond which mainly hydraulic issues with coarse particles start to occur in several parts of the plant. There is no grind size target at Lihir except to grind as fine as possible with the installed power. While some reduction in flotation and POX/CIL recovery occurs with coarser grinds the increased throughput and gold production vastly outweighs the incremental loss. Contributing to the relatively minor gold loss with grind size is likely preferential grinding of softer microcrystalline pyrites, although this requires further study. Note that some grind size information is missing in the trend below.

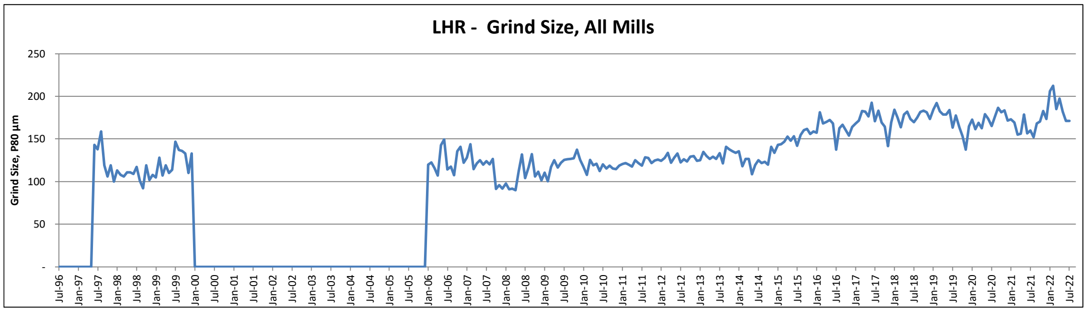


Figure 16 - Lihir Milling Circuit Grind Size, micron

Gold recovery in flotation is shown below in Figure 17 (note that recovery of sulfur is typically 2-5% higher). Flotation recovery is impacted by a combination of poor floating ores, oxidised stockpiled ores, high viscosities due to a high proportion of fines (mainly Argillics) and presence of smectites and a coarser grind. However, even with reduced recovery increased overall mill throughput using flotation for mass rejection leads to additional gold production at a lower unit cost ($US/oz). Note: there was no flotation at Lihir prior to approximately January 2007.

Work continues with optimisation of the flotation circuits at Lihir to minimise gold loss.

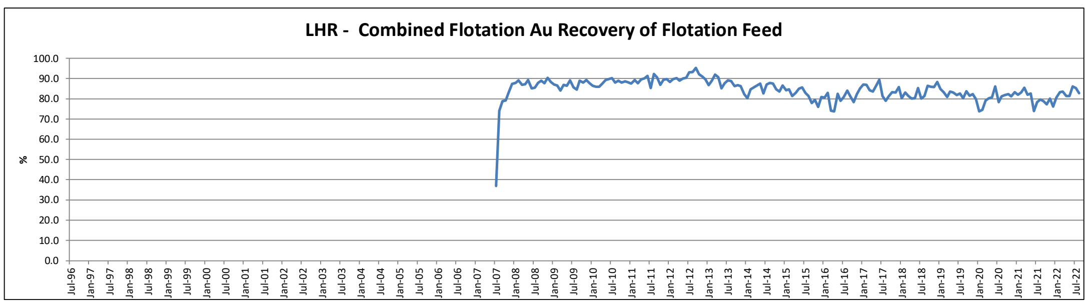


Figure 17 - Lihir Flotation Circuit Recovery

***Pressure Oxidation (POX)***

The autoclave feed sulfur mass flow in dry tonnes sulfur/month is shown below in Figure 18. The increase in sulfur mass throughput from 2015 is clear. From 2019 there was increased treatment of difficult stockpile ores with lower sulfur grades. Throughput through mills and autoclaves was impacted by smectite clays and excessive fines from Kapit Flat stockpile (mainly Argillic) ores. High and variable viscosity impacted milling rates and oxygen utilisation within the autoclaves.

However, as the operation moves into fresh ore from the third major orebody at Lihir (the Kapit orebody) then autoclave feed sulfur throughput (and hence gold production) is expected to increase.

Treatment of the residual Kapit Flat stockpile overlying the Kapit pit, is now essentially complete. While Argillic ores from the top of the Kapit orebody are to be treated, it is expected that fresh ore viscosity impacts will be lower in the near term.

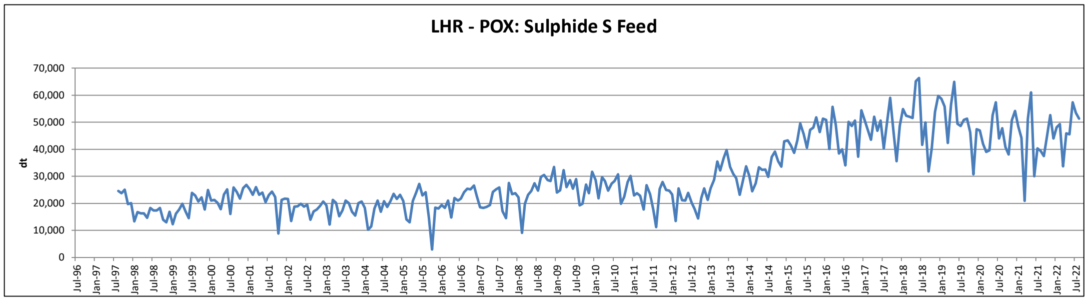



Figure 18 - Autoclave Feed Sulfide Sulfur Throughput

Autoclave availability Figure 19 also impacted sulfur mass throughput with erratic performance particularly evident during 2019-2021 (planned shutdowns are included in this trend).

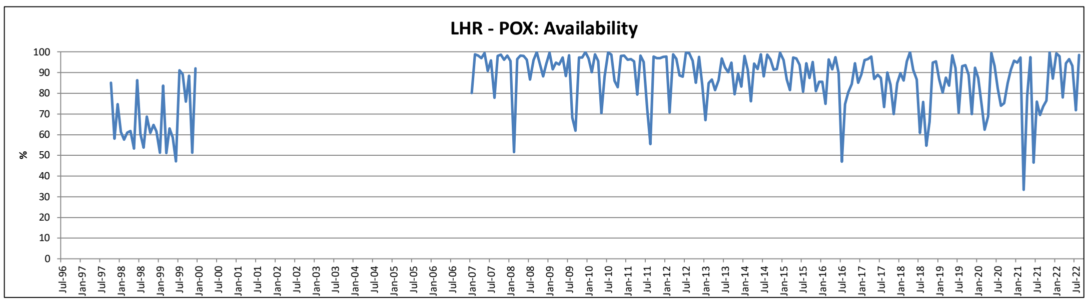



Figure 19 - Lihir POX Availability

Autoclave feed gold grade (g/dt) and sulfur grade (%) is shown below in Figure 20 and Figure 21.

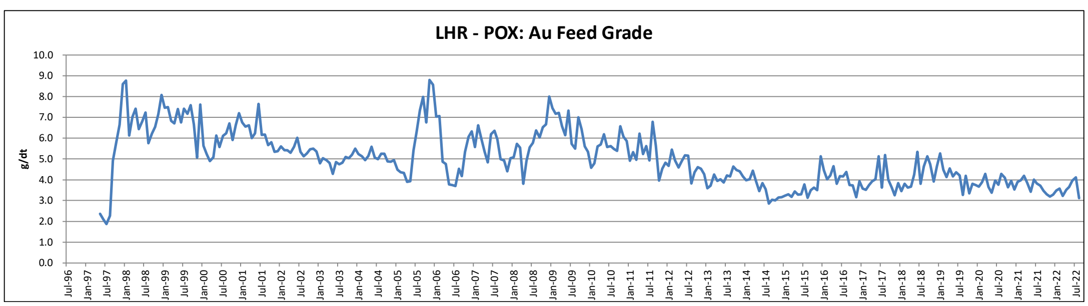



Figure 20 - Lihir Autoclave Feed Gold Grade, g/t

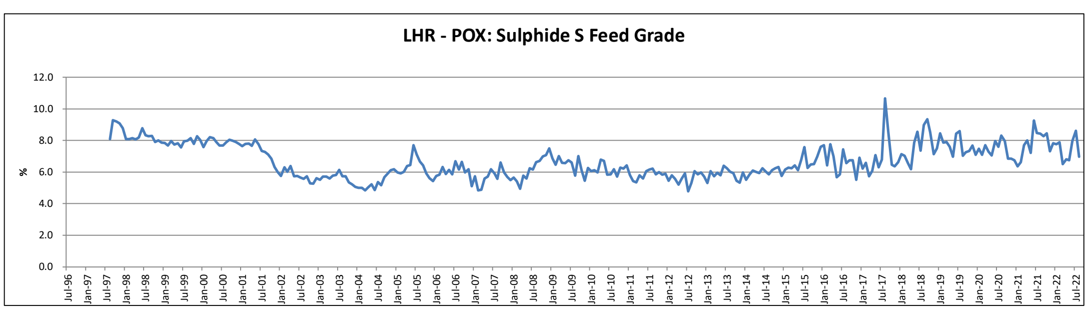



Figure 21 - Lihir Autoclave Feed Sulfide Sulfur Grade, %

The Au:S ratio in autoclave feed is shown below in Figure 22.  Generally reflecting the mill feed Au:S ratios.

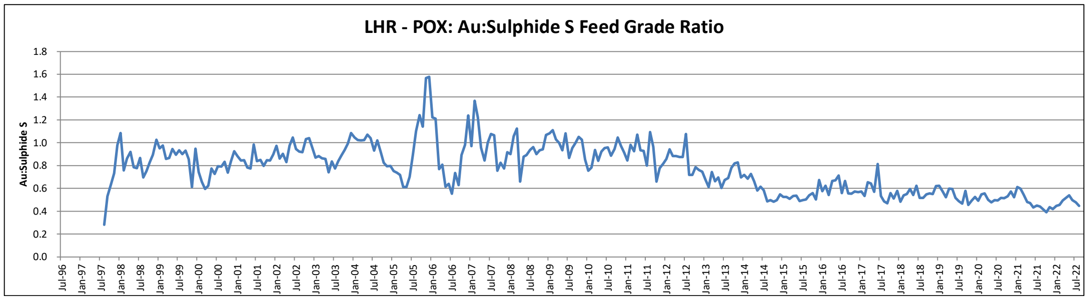


Figure 22 - Lihir Autoclave Feed Au:sS Ratio

POX sulfur oxidation is shown below in Figure 23.  Interestingly and importantly some “partial oxidation” was practiced as early as 2006.  Operators at the time empirically noticed that oxidation could be relaxed by increasing the amount of sulfur treated without a significant reduction in CIL gold recovery.  During this period of operation, the autoclave discharge % sulfide sulfur (sS) was targeted at a maximum allowable value of around 1.0 - 1.3%.  With the current LOS this is allowed to be much higher– see Figure 24.

The reduction in % oxidation from around Aug-Sept 2014 was due to selective oxidation plant trials and testing.  Then finally on 10 December 2014 the operation formally switched to selective oxidation.

There is no oxidation target at Lihir, and oxidation extent is allowed to vary.  The oxidation at any point in time is an outcome of the mine sulfur grade and the availability (and throughput) of mills, autoclaves, and oxygen plants.  For a fixed mill throughput and mine sulfur grade with an autoclave off-line then the total amount of oxygen that can be added in the POX circuit is lower and hence the % oxidation can be lower.  Conversely, for a fixed autoclave throughput and oxygen capacity and fixed mine sulfur grade then if a mill is offline the autoclaves can operate at a higher % oxidation.

While oxidation and autoclave feed sulfur grade can vary over the short term (often just a few hours) the oxygen flow to the autoclaves is fixed and the roughly same mass of sulfur is being burnt.  Autoclave temperatures remain relatively steady.  Depending on mine feed and plant equipment availability then oxidation may typically vary from 50% to 80%.

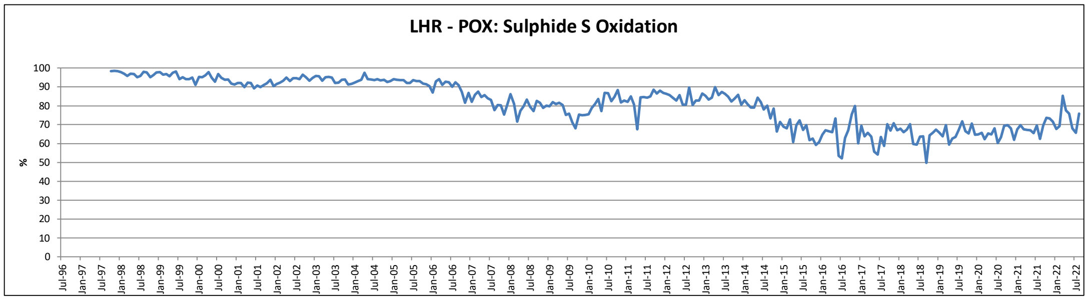


Figure 23 - Lihir Autoclave Sulfide Sulfur Oxidation

The impact of the LOS is more clearly seen in Figure 24 below where % sulfur in autoclave discharge slurry is shown. A value of 2.5-3% sulfur in autoclave discharge is now typical. While there is increased gold in autoclave discharge the autoclave feed sulfur and gold sulfur grades must increase since a minimum of 4 - 4.5% sulfur must be oxidised to maintain reaction temperature.

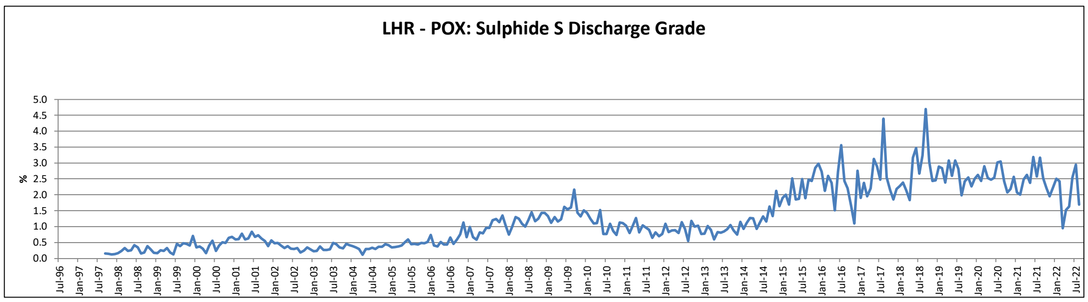


Figure 24 - Autoclave Discharge Solids, % Sulfide Sulfur

The autoclave oxygen:sulfur ratio is shown in Figure 25. The stoichiometric ratio for the oxidation of pyrite is 1.87 t oxygen/t sulfur. As clearly seen, operation well below this value (down to 1.2) has occurred since the introduction of selective oxidation as only part of the total sulfur is being oxidised. Note: some operational data is missing.

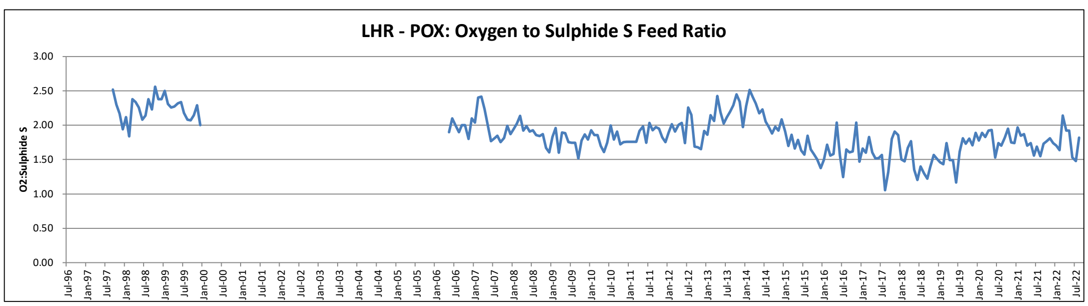


Figure 25 - Autoclave Oxygen : Sulfide Sulfur Ratio

***Gold Recovery***

Many controls are in place to ensure that all the high gold arsenian pyrite is burnt. One Key Performance Indicator (KPI) that is monitored daily is the gold in CIL solids to CIL feed % sulfur ratio. See Figure 26. Typically, this value is 0.10 - 0.2. Values >> 0.25 may indicate issues within the cyanide leach process itself or the presence of significant non-sulfide gangue containing gold like silicates or carbonates.

Note: NCA refers to Neutralisation, Cyanidation and Absorption. NCA uses CIL technology. A significant amount of neutralisation of autoclave discharge solids is required at Lihir.

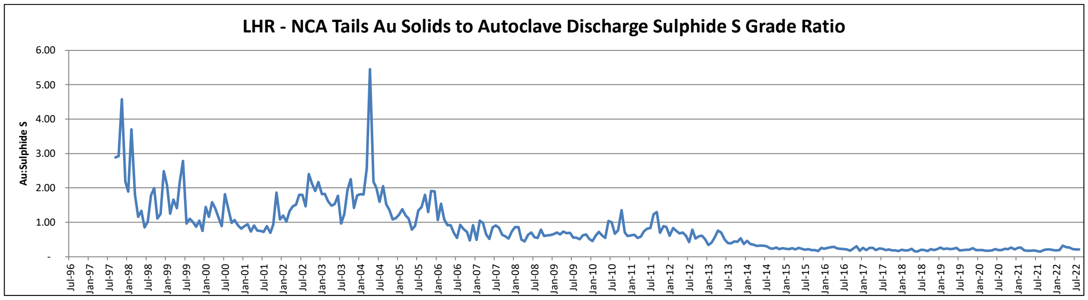



Figure 26 - Lihir NCA (CIL) Au:S Ratio

Interestingly neither CIL terminal gold grade nor overall extraction have changed significantly since 2015 despite reduced oxidation in the autoclaves. See Figure 27 and Figure 28 below.

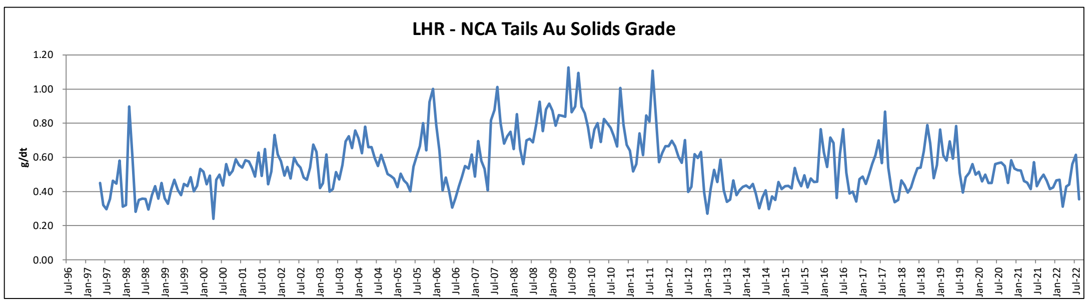



Figure 27 - NCA (CIL) Tails Gold Grade, g/t

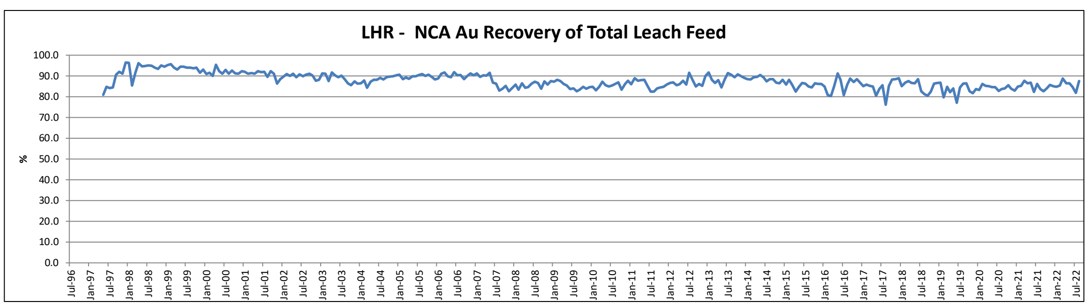



Figure 28 - Lihir NCA (CIL) Gold Recovery, %

A plot of gold extraction from solids vs oxidation is shown below in Figure 29 for the years 2015, 2016 and 2017. Hence this represents a wide range of ore types and variable mixtures of flotation concentrate and whole ore. For ore treated since 10 December the gold extraction vs oxidation is a reasonably flat line. Most oxidation since December 2014 has been in the region of 60 to 75%.

One reason for this is that the % oxidation has not dropped significantly despite much higher autoclave sulfur feed rates. This is due to the increase in autoclave oxygen utilisation as feed sulfur grade increases. More of the added oxygen is used for oxidation rather than being vented. An added benefit of the LOS.

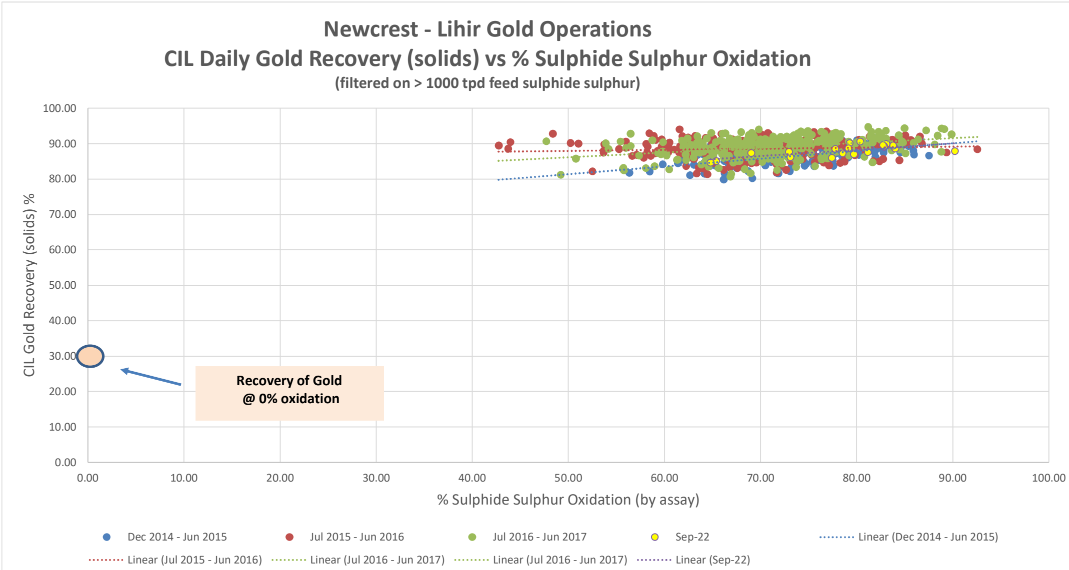



Figure 29 - CIL Gold Extraction (solids) vs Sulfide Sulfur Oxidation

***Cyanide, Lime, and Activated Carbon Usage***

Cyanide usage in terms of kg (NaCN)/d tonne of CIL feed as shown in Figure 30 has increased since 2017. In 2019-2021 a higher proportion of stockpile ore leading to viscous autoclave discharge necessitated increased dilution of CIL feed slurries and increased cyanide usage. Some increase in cyanide addition is also occasionally required when treating higher autoclave feed sulfur ores due to increased copper concentrations in solids. Copper as chalcopyrite is concentrated in flotation and some additional cyanide usage on CIL feed is expected. Residual sulfur from autoclave discharge may also partially consume cyanide and dissolved oxygen and to compensate the CIL circuits at have been converted to using oxygen rather than air. Work continues optimising cyanide and oxygen addition.

Note: some reagent data is missing in the following trends.

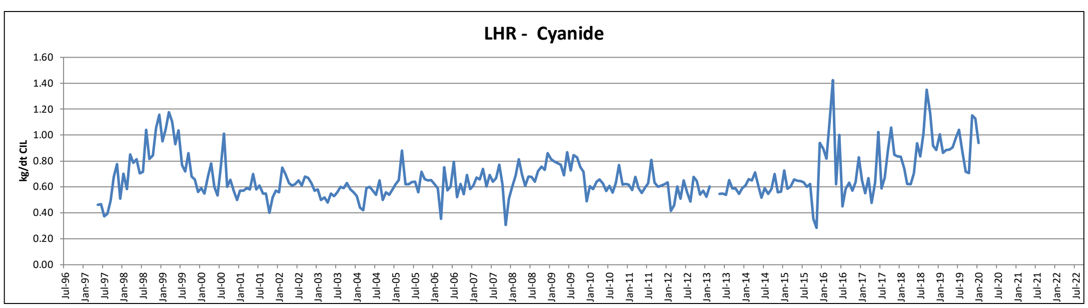



Figure 30 - Lihir Cyanide (NaCN) Usage, kg/t CIL Feed

Interestingly in terms of kg NaCN/dry tonne of mill throughput then usage is ~ 0.6 kg/t – in-line with the original design is shown below in Figure 31

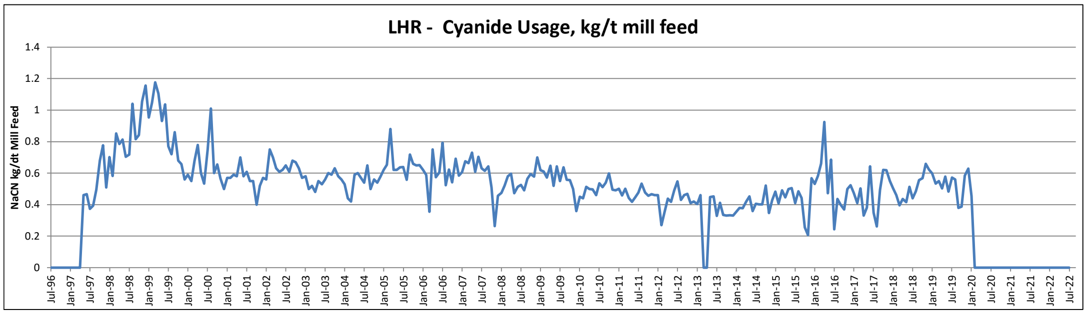



Figure 31 - Lihir Cyanide Usage (NaCN), kg/dt Mill Feed

Lime usage has been relatively steady (although considerable variation is often seen month to month). Consistent with cyanide, dilution (with seawater) in the CIL circuit since 2019 has led to slightly increased lime usage in terms of usage per to CIL feed, Figure 32.

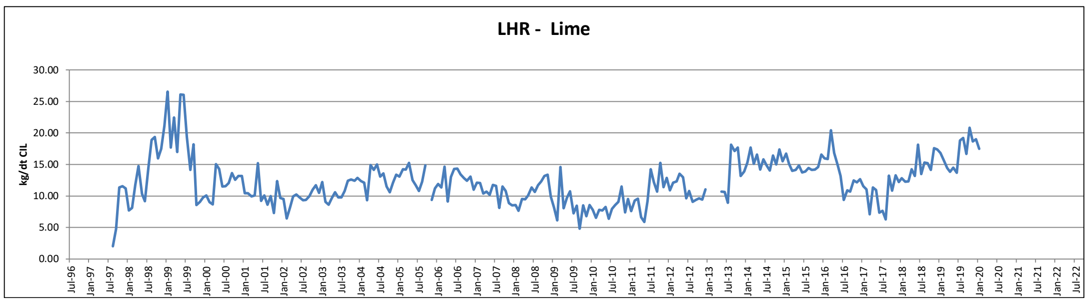



Figure 32 - Lihir Lime Usage, kg/dt CIL Feed

Again, expressed in terms of lime usage per dry tonne of mill feed, lime usage has not changed significantly during the period of selective oxidation at Lihir. See Figure 33.

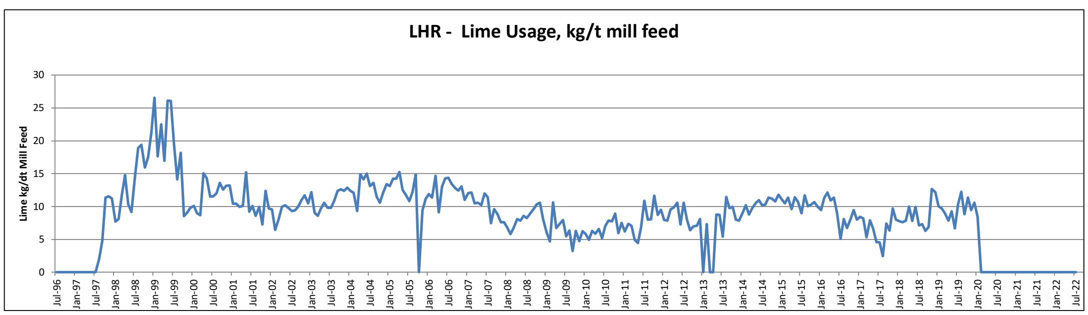



Figure 33 - Lihir Lime Usage, kg/dt Mill Feed

Activated carbon usage has increased in the last few years during treatment of the Kapit Flat stockpile. Work continues to optimise and reduce carbon usage.

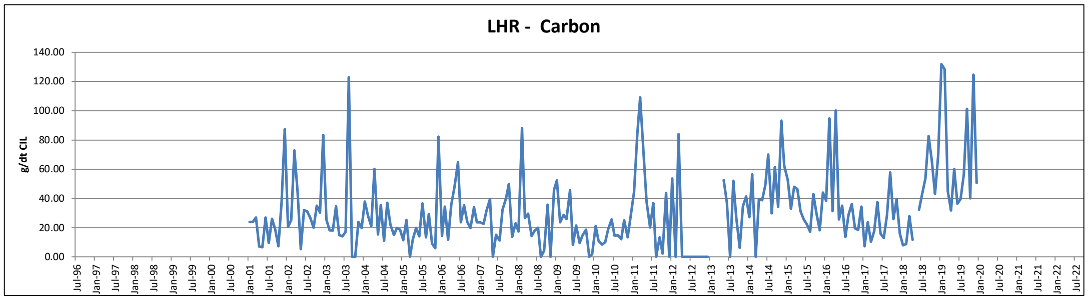



Figure 34 - Lihir Activated Carbon Usage, g/dt CIL Feed

## POTENTIAL APPLICATION TO OTHER REFRACTORY GOLD SULFIDE DEPOSITS

Selective oxidation may be applicable to other similar deposits. “Partial Oxidation” test work should always be completed to understand the relationship between recovery and oxidation for every refractory gold pyrite/arsenian pyrite/arsenopyrite deposit. High oxidation with commensurate high recovery is not necessarily the economic optimum for ores with a “flat” gold extraction vs oxidation profile as seen in Figure 29.

For example, the Lone Tree deposit in Nevada is another example of a POX project that utilised partial oxidation. Gold was deported into a fine-grained pyrite containing most of the gold and a coarse pyrite containing little gold. “Gold was concentrated in numerous fine-grained (< 10 µm) aggregates of porous pyrite, marcasite and arsenous pyrite mineralization. Coarse pyrite and arsenopyrite contained a very small portion of the total gold” (Simmons, p74). The papers of Cole, Janhunen and Lenz and G.L. Simmons give further description of the Lone Tree project.

The Lihir Operating Strategy and the use of selective oxidation has been patented (see references below).

## CONCLUSIONS

Selective oxidation at Lihir exploiting favourable pyrite-gold mineralisation has been successfully implemented at Lihir. Increased gold production has been achieved since December 2014.

As the major costs at Lihir are essentially fixed then the unit cost of production has been reduced.

Notably specific cyanide and lime consumption in the gold recovery circuit has not materially changed with the introduction of selective oxidation.

## ACKNOWLEDGEMENTS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