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Gold-PM Keynote

POX – HAS IT REACHED ITS FULL POTENTIAL, OR IS THERE STILL ROOM FOR IMPROVEMENT FOR TREATING REFRACTORY GOLD ORES?

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ABSTRACT

As many will already know, pressure oxidation (POX) is an oxidative pre-treatment of refractory (sulphide hosted) gold ores and concentrates prior to leaching and recovery of gold typically by cyanidation and recovery onto activated carbon. Commercial gold POX operations use one or more horizontal multi compartment pressure vessels lined with a corrosion barrier and layers of protective masonry. Agitators in each compartment to provide mixing and most importantly mass transfer of gaseous oxygen for the aqueous oxidation of the sulphides and their reaction products such as iron and arsenic. Operating temperatures typically range from 200°C to 230°C at pressures of between 25 bar.g and 35 bar.g. The high pressure allows for an increase in dissolved oxygen concentration to drive mass transfer and the high temperature significantly increases reaction rates and consequently process intensity. For example, at these elevated conditions the reactions may be complete within less than 60 minutes in comparison to leaching at atmospheric conditions which may require 20 hours or more for the same oxidation extent.

The characteristics of high process intensity, efficient oxygen utilisation, high gold recovery and robust process performance have made POX the technology of choice in recent year for major refractory gold projects. These include the Copler Sulfide Expansion Project in Turkey, the Mansourah & Massarah Project in Saudi Arabia, the Amursk and Petropavlovsk POX Hubs in Russia, and Pueblo Viejo in the Dominican Republic. Closer to home, the POX operations at Porgera and Lihir in Papua New Guinea and Macreas in New Zealand have each been operating for more than 20 years.

In spite of this commercial success the author contends there is still room for improvement, but having said this, what do we understand by the term "improvement"? This could simply be seen in a process context, improved extractions, reduced residence times, improved oxygen utilisation and so on. Alternatively, there are issues of reliability such as the life of vessel linings, severe service control valves and agitator impellers. In an overall sense however, the author's view is that the three key areas for improvement in the control of the designer and operating company can be captured in terms of improved safety, reduced capital cost and increased operating time. Low operating costs inputs such as labour and power costs are obviously beneficial, but these are generally a function of the site location and do not represent an improvement to design or operation. That said if the three suggested improvements are addressed these will naturally lead to a reduced operating cost and thus to improved economic outcomes.

Operational safety provides a legal and ethical license to operate. Although historical performance has been adequate, avoidable incidents have occurred that potentially could have been more significant. In some ways understandably, many incidents and near misses have been downplayed by operating companies so the full picture is unclear, particularly in light of the geographic and corporate spread of operating sites and corporate offices. It is the author's contention that greater transparency and a better understanding of the potential risks is required whether by designers, operators or regulators given the contained energy of these systems and the potential consequences of failure.

The process efficiency of POX technology is well established but the technology is complex and together with the associated oxygen production facility are the most capital-intensive areas of the process plant. An oft voiced criticism of POX is its capital cost, and certainly compared to less sophisticated processes this is a step up from what some may be used to. The capital intensity of the technology demands additional diligence in terms of project definition and engineering to ensure that the ultimate design is pragmatic and fit for purpose, in other words not wastefully over designed or under designed to the point that the project is unsuccessful. In principal this is no different for any other project but given the high capital intensity the negative consequences

of poor project definition, excessive design margins or errors are significantly magnified. Once in service, changes to the design are generally challenging to execute and impose a significant cost burden not only for the modification itself but also in terms of the opportunity cost of the interruption to production.

Maximising operating time is another means of increasing plant throughput for a given plant capacity. In other words, for a given nominal plant capacity a smaller plant is required resulting in lower capital and operating costs if properly defined, designed and operated. Consistent operation with a sustainable increase in operating time is indicative of improved safety performance and lower maintenance costs.

This keynote invites a review of the past, the present, and more subjectively a look to the future of the technology. The items for improvement suggested above together with some purely technical opportunities will be discussed in the context of the title of this paper.

Keywords: Refractory Gold, Pressure Oxidation, Improvement

INTRODUCTION

Pressure oxidation (POX) is an oxidative pre-treatment of refractory (sulphide hosted) gold ores and concentrates prior to leaching and recovery of gold typically by cyanidation and recovery onto activated carbon. Commercial gold POX operations use one or more horizontal multi compartment pressure vessels lined with a corrosion barrier and layers of protective masonry. Agitators in each compartment to provide mixing and most importantly mass transfer of gaseous oxygen for the aqueous oxidation of the sulphides and their reaction products such as iron and arsenic. Operating temperatures typically range from 200°C to 230°C at pressures of between 25 bar.g and 35 bar.g. The high pressure allows for an increase in dissolved oxygen concentration to drive mass transfer and the high temperature significantly increases reaction rates and consequently process intensity. For example, at these elevated conditions the reactions may be complete within less than 60 minutes in comparison to leaching at atmospheric conditions which may require 20 hours or more for the same oxidation extent.

The characteristics of high process intensity, efficient oxygen utilisation, high gold recovery and robust process performance have made POX the technology of choice in recent year for major refractory gold projects. These include the Copler Sulfide Expansion Project in Turkey, the Mansourah & Massarah Project in Saudi Arabia, the Amursk and Petropavlovsk POX Hubs in Russia, and Pueblo Viejo in the Dominican Republic. Closer to home, the POX operations at Porgera and Lihir in Papua New Guinea and Macreas in New Zealand have each been operating for more than 20 years.

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This paper provides context to the discussion by firstly summarising the history of POX, then discussing aspects of the technology at a high level before addressing the issue of the potential for improvement.

GOLD POX HISTORY

The development of the technology that would ultimately lead to the flowsheets that we in the gold industry understand as pressure oxidation or POX as we commonly call it, is founded in the base metals industry. Once well established in base metal refineries treating concentrates or mattes the technology attracted the attention of those interested in the on-site extraction of gold from sulphide hosted refractory ore bodies, either as concentrate or whole ore. As confidence in the technology grew operating temperatures and pressures increased as did the physical sizes of the vessels. With the laterite boom in the last decade of the last century technologies developed for the gold industry were incorporated into the new autoclave circuits whose own trials and tribulations led to improvements that we now see in the latest generation of POX circuits.

For those interested in a detailed history of pressure leaching technology up to the early 1960s, W. Martin Fassell Junior’s paper “Hyper-Atmospheric Extractive Metallurgy, its past, present and future” provides an excellent summary. More recently in 2018 Mike Collins from Sherritt published an excellent history of the technology “Development of autoclave technology”.

I have taken the liberty of extracting and summarising some significant events in the development of the technology relevant to gold pressure oxidation. Note this does not include the former USSR and the PRC as at the time of these developments the cold war was real and limited information was and is still available from these countries in the West.

Some of the key developments that lead to the acceptance of POX for refractory gold ores included,

- The invention of the Bayer Process for the use of caustic for bauxite digestion in 1888
- The 1927 patent for the leaching of sulphide minerals using oxygen by Henglein and Neimann.
- The announcement in 1952 of the development of the Chemico Process by the Chemical Construction Company (Chemico) for the leaching of base metals. Three operating plants were planned, one for Sherritt Gordon (in Alberta, one in Missouri and a third in Utah for the Calera Mining Company).

Fassell spends some time elaborating on the difficulties that the first of the plants had as it was the pioneer and the first of its generation. These difficulties may strike a chord with anyone involved in one of the more recent start-ups.

He concludes his excellent review with a summary of the pressure leaching operations in North America including examples of acid, base and ammonia leaches. One key observation is that only air rather than tonnage oxygen was recorded as the oxidant in sulphide systems. By the time of the review (1961) the feed sources for pressure hydrometallurgical process included Cu, Ni, Co concentrates, laterite ore, Cu scrap, Cu, Zn concentrates, bauxite ore, U ore and cobaltite concentrate.

In 1957 Sherritt acquired Chemico's patent rights and other intellectual property from its parent company American Cyanamid. Over the next twenty years pressure hydrometallurgy for base metals became an established technology with growth in the number of base metal refineries using Sherritt technology such as the Kwinana Nickel Refinery, built for concentrate but ultimately used for treatment of matte from the Kalgoorlie Nickel Smelter. Combined pyrometallurgical and hydrometallurgical flowsheets such the Yabulu Nickel Refinery in Townsville and the Surigao Nickel Project on Nonoc Island. By 1980 over sixty autoclaves using Sherritt's technology were in operation around the world including applications in PGM treatment as well as the new Zn direct leach operation at Trail, British Columbia. By this time the use of cryogenically produced tonnage oxygen had been adopted as standard for POX applications.

In the West other base metals companies such as the International Nickel Corporation (INCO) were pursuing their own versions of the technology but at that time Sherritt was the clear leader in terms of the international commercialisation of POX technology for the treatment of base metals.

Whilst the application of the technology for base metals treatment in refinery applications would continue, the next key development was the start-up of the of the McLaughlin Mill for Homestake in California in 1985.

In the early 1970s the US finally abandoned the gold standard which led to a rapid increase in the gold price from a low of US $65/oz in 1973 to a peak of nearly US $ 700/oz in 1980. This spurred the re-examination of technologies for the treatment of refractory gold ores by a number of mining companies including Homestake who in 1979 initiated development testing examining a number of pre-treatment options for the McLaughlin ore including pressure oxidation. Reserves were reported as 20 Mt at approximately 5 g/t Au.

Gold was associated with pyrite and marcasite and the ore exhibited variable poor to moderate recoveries when subjected to direct cyanidation. In 1981 Sherritt Gordon started testwork including pilot testing at their facility in Fort Saskatchewan, Alberta. Pressure oxidation lifted cyanide recoveries consistently above 90% at the design operating conditions of 160°C and 1,700 kPa.g with a nominal residence time of 90 minutes.

Once pressure oxidation was selected, Davy Mckee started the engineering design of the 3000 t/d mill and whole ore POX circuit in June 1982, with construction starting just over a year later. Ore was fed to the mill in January 1985 and the first gold was poured that March.

The design contained many of the elements that one would expect in a modern-day flowsheet including,

- Carbonate destruction by fresh and recycle acid followed by thickening ahead of POX
- Heating of feed slurry using flash steam and HP steam
- Multiple trains of horizontal multi-compartment POX autoclaves
- The use of cryogenic oxygen
- CCD washing of POX residue
- Neutralisation and thickening of CCD wash liquor
- Leach / CIP of washed POX residue
- Gold recovery by elution and electrowinning followed by smelting in an induction furnace

Whilst significant changes have been made to the design and capacities individual equipment items the overall flowsheet remains remarkably familiar.

The success of McLaughlin led to a rash of new POX installations for refractory gold treatment over the next fifteen years that included the following operations,

Table 1. POX Operations (i)

Original Owner	Property	Country	Commissioned
Homestake	McLaughlin	USA	1985
Genmin	Sao Bento	Brazil	1986
Barrick Gold	Mercur	USA	1988
First Miss Gold	Getchall	USA	1989
Barrick	Goldstrike Phase I	USA	1990
Placer	Campbell Red Lake	Canada	1991
Porgera JV	Porgera	PNG	1991
Nerco	Con	Canada	1992
Barrick	Goldstrike Phase II	USA	1992
Barrick	Goldstrike Phase III	USA	1993
Santa Fe Pacific	Lone Tree	USA	1993
Santa Fe Pacific	Twin Creeks	USA	1997
Rio Tinto	Lihir	PNG	1997
GRD	Macraes	New Zealand	1999

POX Operating temperatures ranged from 190°C to 225°C gradually increasing over that period in line with the experience gained by the various operating companies and engineers. Likewise, POX operating pressures increased to approximately 30 bar.g.

In 2000 the same forces that had driven the rapid adoption of the technology reversed with the gold price plunging to less than US $ 260 $/oz. This put an understandable chill on development and it would be more than ten years before the next installation.

This hiatus overlapped with the start-up of the nickel laterite high pressure acid leaching (HPAL) plants in Western Australia. The engineers involved in these projects all had relevant and recent experience in POX technology and many of the features of the of the gold projects were applied, albeit at significantly higher pressure and temperature of approximately 50 bar and 250°C respectively. Some of these features included the use of,

- High pressure piston diaphragm autoclave feed pumps
- "Splash and flash" heat recovery and transfer
- Brick lined flash vessels
- Horizontal multi-compartment autoclaves with mechanical agitators
- Metal seated severe service ball valves, and
- Severe service pressure letdown valves with ceramic trims

Conversely some chose to employ technologies from the alumina industry with disastrous results such as the use of upflow choke letdown systems for the Murrin Murrin flash letdown train.

As oxygen addition and mass transfer was not required all three operations (Cawse, Bulong and Murrin Murrin) used metal clad titanium autoclave linings and internals. Each operation had its own combination of issues with the erosion and sometimes corrosion of the titanium cladding, as well as mechanical damage to the welded joints (batten straps) between separate clad plates.

The severe conditions experienced by this generation of HPAL plants drove the development of mechanical equipment including the,

- Metal seated severe service ball valves
- Severe service pressure letdown valves
- Hydraulic valve actuation
- Autoclave feed pumps, cooling "drop legs" and valves
- Centrifugal high-pressure pumps
- Flash and heater vessel design, and
- Agitator mechanical seals and seal water supply systems

This experience permeated through the various engineering houses and the equipment vendors often as hard-won lessons. This was seen in the next generation of HPAL autoclaves built for Coral Bay, Ravensthorpe and Taganito. These were succeeded by the HPAL operations at Ambatovy and Goro that targeted operation at 260°C and 270°C respectively with mixed success.

As well as influencing the development of HPAL autoclave technology POX technology was applied by Phelps Dodge at Bagdad in 2003 for the high temperature leaching of chalcopyrite concentrate, and later by Freeport McMoRan for medium temperature leaching at Morenci. In 2006 autoclaves from the former operation at Getchell Gold in Nevada were relocated to Zambia for treatment of chalcopyrite/bornite concentrates at the Kansanshi Operations of First Quantum Minerals. In 2008 Vale started the Carajás Hydrometallurgical Copper Plant using a 2.1 m diameter Cu POX autoclave fabricated from Grade 12 titanium plate although the operation has subsequently been shut down. No issues were reported with the integrity of the autoclave vessel.

Also at this time a POX circuit was supplied to Dundee Precious Metals operation at Chelopech in Bulgaria for the leaching of enargite/pyrite concentrate although ultimately the circuit was never installed due to permitting issues.

A gradual increase in the gold price provided the impetus for new gold POX projects and from 2008 onwards there has been a reasonable steady number of projects coming on line all benefiting from the experience gained in period of HPAL development.

These projects included,

Table 2. POX Operations (ii)

Original Owner	Property	Country	Commissioned
Agnico Eagle	Kittila	Finland	2008
AngloGold Ashanti	Córrego do Sítio	Brazil	2012
Polymet	Amursk	Russia	2012
Barrick	Pueblo Viejo	Dominican Republic	2012
Newcrest	Lihir Expansion	PNG	2012
Anagold	Copler	Turkey	2018
Petropavlovsk	Pokrovskiy	Russia	2018

Although the pressures and temperatures for this series of projects were comparable with the previous generational improvements in the understanding of vessel and lining design allowed a significant increase in vessel size to almost 6 m in diameter and 45 m tan to tan.

In addition to these POX projects, engineering is underway for the Mansourah and Massarah project in Saudi Arabia as well as an expansion at Amursk (Russia).

THE BENEFITS OF POX TECHNOLOGY

As one of the established technologies for the pre-treatment of refractory gold ores POX is used to liberate occluded and solid solution gold from host sulphide minerals for subsequent recovery, typically by cyanidation. Historically POX has competed against roasting, bacterial oxidation and ultra-fine grinding in this duty.

POX has demonstrated the ability to achieve very high (> 99%) sulphide sulphur oxidation if required with short residence times, typically between 40 and 90 minutes. The process chemistry is extremely robust and has the ability to treat both labile and highly refractory sulphides. Problem elements such as arsenic are easily handled and converted to scorodite for co-disposal with the circuit tails.

With appropriate design, POX can achieve these high oxidation extents at high oxygen utilisations (>90%) and with suitable washing POX Residues typically exhibit low cyanide consumptions due to the lack reactive sulphides and elemental sulphur. Whole ore POX provides the ability to treat low sulphide sulphur grade ores without flotation recovery loss.

Due to its intensity the equipment is relatively compact and can be installed in remote locations as demonstrated at Porgera and most recently at Copler where the autoclaves were delivered in sections for welding and pressure testing on site.

Since the lapse of various Sherritt patents such as on the oversized first autoclave compartment, the technology has become openly available without restriction and requirements for royalty payments.

Feed Materials for POX

For the purposes of the paper the various potential POX feed sources have been allocated to the following categories,

- Whole ore – This is ground and thickened run of mine ore typically blended to achieve target feed characteristics for sulphide sulphur, gangue minerals such as carbonate and acceptable metal grade. This is selected when the sulphide sulphur grade is sufficient for autothermal operation and avoids a recovery loss associated with flotation. The increased volumetric flow also increases the size of the ancillary equipment and to a lesser extent the size of the autoclave(s).
- Concentrate – Flotation allows the upgrade of target sulphides minerals as well as the potential rejection of gangue minerals such as carbonate. Typically, the sulphide sulphur grade is set to maximise gold recovery at an acceptable grade for the heat balance. Concentrate grades up to 25% sulphide sulphur can be practically treated although concentrates in the range 10% - 14% sulphide sulphur are recommended from the perspective of heat balance and autoclave chemistry. Higher grades are favoured if the concentrate has to be transported from the minesite to an off-site POX circuit. Concentrates can be economically reground to improve oxidation kinetics.
- Double Refractory ores and concentrates– Sulphide gold ores that are also associated with pre-robbing organic carbon can be successfully oxidised using carefully controlled POX conditions as per the relevant Newmont patent. Ground limestone is used to control autoclave chemistry due to its low cost although this negatively impacts oxygen utilisation due to the CO2 generated and precipitated anhydrite requires frequent de-scaling.
- High carbonate ores and concentrates - Sulphide gold ores can be treated although this typically requires either carbonate rejection by flotation or carbonate destruction by recycle of acidic autoclave discharge solution (often called acidulation). Exceptions to this approach include the Barrick Mercur operation that managed to achieve acceptable oxidation kinetics under alkaline conditions. This allowed the use of cheaper materials of construction reducing capex. More recently Barrick Goldstrike has converted three of their six autoclaves to run at alkaline conditions to treat high carbonate ore albeit with reduced sulphide oxidation and gold recovery.

The most common gold bearing sulphide minerals treated using POX are pyrite (including arsenian pyrite) and arsenopyrite but other mineralised sulphides such as enargite and chalcopyrite can also be treated along with gangue sulphides such as stibnite, galena sphalerite and pyrrhotite.

For gold only circuits, base metals sulphides such as chalcopyrite and sphalerite are rejected if possible as they provide no economic benefit, in fact usually the opposite due to their role as cyanicides. In general POX feed is targeted to maximise the ratio of gold to sulphide sulphur to reduce oxygen consumption and neutralisation requirements, in turn improving capex and opex.

POX Conditions for Refractory Gold Pre-treatment

With the exceptions of the Barrick Mercur Operation and the more recent conversion at Barrick Goldstrike all current POX circuits are operating under acidic conditions.

Due to the detrimental effect of elemental sulphur on cyanidation POX circuits tend to be run under highly oxidising conditions with high oxidation extents and partial oxidation of sulphides to elemental sulphur is avoided. Operation is therefore typically at higher temperature (210°C to 230°C) although some operations such as Porgera have been limited by their pressure vessel design and operate below this (190°C – 200°C).

Good water quality (<50 ppm Cl^-) is a requirement for gold POX operation. Chlorides inhibit sulphide oxidation and may form complexes under oxidising conditions which is particularly problematic with double refractory ores and concentrates as the gold chloride complexes precipitate on carbonaceous solids.

HT POX Chemistry

Typical reactions for acid POX based on the oxidation of pyrite and arsenopyrite are summarised in the table below. Although the key purpose of the POX circuit is to liberate gold from refractory sulphides it is not considered in this chemistry which is dominated by sulphur, iron and potentially carbonate and arsenic.

Table 3. Simplified Acidic HT POX reactions

Reaction	Equation
S^{2-} oxidation	$2FeS_2 + 7O_2 + 2H_2O \rightarrow 2FeSO_4 + 2H_2SO_4$
Fe^{2+} oxidation	$4FeSO_4 + O_2 + 2H_2SO_4 \rightarrow 2Fe_2(SO_4)_3 + 2H_2O$
S° oxidation	$2S + O_2 + 2H_2O \rightarrow 2H_2SO_4$
As oxidation (i)	$4FeAsS + 11O_2 + 2H_2O \rightarrow 4HAsO_2 + 4FeSO_4$
As oxidation (ii)	$2HAsO_2 + O_2 + 2H_2O \rightarrow 2H_3AsO_4$
As precipitation	$2H_3AsO_4 + Fe_2(SO_4)_3 \rightarrow 2FeAsO_4 + 3H_2SO_4$
Jarosite precipitation (Me = Na, K, Ag etc.)	$Me_2SO_4 + 3Fe_2(SO_4)_3 + 12H_2O \rightarrow 2MeFe_3(SO_4)_2(OH)_6 + 6H_2SO_4$
Alunite precipitation (Me = Na, K, Ag etc.)	$Me_2SO_4 + 3Al_2(SO_4)_3 + 12H_2O \rightarrow 2MeAl_3(SO_4)_2(OH)_6 + 6H_2SO_4$
Hematite precipitation	$Fe_2(SO_4)_3 + 3H_2O \rightarrow Fe_2O_3 + 3H_2SO_4$
Gangue leaching	$MgCO_3 + H_2SO_4 \rightarrow MgSO_4 + CO_2 + H_2O$

The extent of hematite and jarosite formation is dependent on the acid base balance with hematite being favoured at low levels of free acid (less than 30 g/L FA). Free acid levels can be manipulated by the addition of base such as limestone. This is used in Newmont's patented technology for the treatment of double refractory ores and concentrates. Silver in the feed will be dissolved and reprecipitate as argento-jarosite making POX less suitable for high silver ores and concentrates. Lead and mercury behave in a similar manner.

The extent of oxidation can be adjusted to suit the relationship between gold liberation and sulphide oxidation although the conditions for the discharge chemistry such as the formation of scorodite for arsenic stabilisation should be maintained. Likewise, care should be taken to control elemental sulphur formation for the reasons stated above.

Arsenic enters solution from the oxidation of minerals such as arsenopyrite or enargite and needs to be oxidised from As(iii) to As(v) in the presence a sufficient excess of Fe(iii) to precipitate as scorodite. Note that this requirement contributes to the oxygen. Residual arsenic is precipitated along with ferrihydrite during neutralisation downstream of the POX circuit.

The sulphide oxidation reactions are exothermic and this is used to maintain the operating temperature. Depending on the feed density, feed sulphide sulphur grades above 6% S are autothermal, whilst below this grade heat recovery and recycle is required until approximately 3% sulphide sulphur after which live steam is required to maintain the heat balance but this becomes a significant operating cost. Live steam is however used to bring the autoclave up to temperature before the introduction of oxygen.

Tonnage oxygen (GOX) is supplied by either cryogenic or VPSA technology at purities of greater than 95% v/v. Cryogenic supply has improved economics at larger scale, say above 200 t/d, and allows for the on-site production of liquid oxygen (LOX) which can be used as a backup in the event of an interruption in GOX production. Cryogenic plants with a capacity of 2000 t/d contained GOX are currently in service. GOX is supplied at a suitable pressure above the steam temperature for the operating pressure to provide the overpressure (typically 300 – 700 kPa) for oxygen mass transfer.
Non condensable gasses such as CO_2 from the decomposition of carbonates and N_2 associated with the GOX supply contribute to the overpressure and have to be vented continuously to maintain a constant autoclave operating pressure.

Autoclave temperature control is achieved by the direct injection of cooling water (Quench Water) although cooling coils can be used for indirect cooling. Flash cooling, that is flashing a portion of the slurry in the first autoclave compartment and recycling the flashed slurry to the feed is not currently practised in gold POX although it is an established method of heat removal for base metal autoclaves.

Mechanical Equipment

This section provides a brief overview of the key equipment commonly used in POX circuits. Although equipment size, capacity and ratings have increased over the past 60 years, the circuit configuration and basic equipment types remain recognisable. The autoclave is typically an agitated horizontal multi-compartment pressure vessel protected by an internal membrane and acid brick lining. The acid brick protects the membrane beneath from effects of the operating temperature of the process as well as from mechanical damage. Historically membranes were panel then homogenously bonded lead, but specialised organic membranes and hard rubbers are also used. Bricks are installed over the membrane set in specialised mortars for the process conditions. Typically, two or three courses are used to achieve a suitable thickness for the thermal and stress requirements. The various vendors make claims for the unique properties of their bricks as well as their mortars and membranes.

Autoclave feed slurry is typically introduced by high pressure piston pumps, in the case of circuits with heat recovery a cooling leg is fitted to reduce the temperature at the pump which may either be flat diaphragm or an elastomeric sleeve in a duplex or triplex configuration. A centrifugal pump is normally used a “boost pump’ to ensure sufficient suction pressure for the piston pump. Strainers are fitted to protect the piston pumps check valves from mechanical damage. The design of cooling legs has improved significantly over the years with the original design temperature for McLaughlin Homestake pumps of 155°C to the current generation of pumps rated to 220°C. This has a commensurate benefit for thermal efficiency due to the potential to reduce the temperature difference between the autoclave feed and discharge with low sulphide sulphur feed grades.

Autoclave agitators are fitted with impellers suited to gas liquid mass transfer such as Rushton and Smith Turbines or their proprietary equivalents. Agitator shafts are fitted with double mechanical seals to retain autoclave pressure. Super duplex stainless steel stub shafts are commonly fitted above the titanium shaft and impellers to reduce the likelihood of a metal oxygen fire. A high-pressure seal system (or systems) ensures a reliable supply of high-pressure seal barrier fluid as well as water for cooling and seal flushing. Seal suppliers offer are a number of configurations but a common feature is the ability to maintain seal pressure for a nominal time period in the event of a loss of power or control. Agitators for gold POX with 400 kW drives are now in service. Likewise numerous agitators are operating at over 50 bar.g in HPAL service reflecting the level of improvements in mechanical design.

Titanium anti-swirl baffles set into the brickwork maximise power transfer. Walls between compartments are typically fabricated from titanium although historically these were also fabricated from brick.

Metal seated ball valves are used to isolate the autoclave upstream and downstream typically arranged in pairs that can be used to form a block and bleed or in a primary / secondary configuration. Historically autoclave discharge was let down to lower pressure and temperature through a fixed ceramic choke. Cold water could be injected to attemperate the flow, changing the enthalpy of the slurry and thereby affording a limited means of flow control. In the 1990’s Steve Chipman then at Valtek (now Flowserve) developed a severe service ceramic lined angle valve which allowed continuous flow control over a broader range providing significantly greater operational flexibility. Steve went on to found a new company Caldera, with his friend and colleague Jeff Robinson and the two companies continue to compete in the POX industry.

Temperature control uses high pressure ‘quench water’ injected into each compartment as part of temperature control loop using thermocouples set in submerged thermowells. The autoclave is continuously vented via a severe service angle valve to maintain pressure control using redundant pressure transducers. A pressure safety valve (PSV) protects the autoclave from overpressure. Depending on the design this may be supplemented by SIL rated supervisory control logic. Vent from the pressure control valve is cooled and scrubbed together with the other low-pressure vents before being discharged to atmosphere. Some operations require dedicated scrubbing circuits for mercury removal.

Slurry is letdown from autoclave conditions in one or more flash vessels depending on the configuration. The flash vessels are vertical membrane and brick lined cylindrical pressure vessels that allow the separation of flash overheads (mostly steam) and flashed slurry. The flashed overheads are either directly scrubbed discharged to atmosphere or are recycled to an upstream splash condenser or heater for energy recovery. In multi flash circuits the flashed slurry from the high-pressure stage gravitates to the next stage where the slurry is letdown to the next pressure. Up to three stages of flashing are used for POX operating temperatures.

Heaters are vertical cylindrical vessels that may operate at temperature depending on their duty. They are typically fabricated from corrosion resistant alloy although historically they were fabricated from carbon steel with a membrane and brick lining.

Piping and valving around the autoclave is typically fabricated from titanium with the exception of oxygen and some vent piping. Super duplex and duplex stainless steels are used at lower temperatures. Oxygen piping requires non-reactive metals and so austenitic and super duplex stainless steels are typically used depending on their place in the circuit. These materials are obviously less resistant to corrosion and so are considered as consumable items. Alloys such as niobium stabilised titanium have been tried in oxygen service but have not been found to be reliable.

GOLD POX FLOWSHEETS

Some simple examples are presented to illustrate the incorporation of POX in two alternate flowsheets.

Gold Only POX

A block flow diagram for a conventional POX circuit is shown below, the circuit could be whole ore or concentrate. After POX the acidic residue is washed in a counter current decantation (CCD) thickener circuit to remove free acid and cyanicides such as ferrous and cupric ion. The cooled, washed and thickened solids are typically neutralised and diluted to achieve an acceptable feed for the downstream leach/CIL circuit.

CCD Overflow also containing any residual As in solution is neutralised before tailings disposal. If carbonate destruction (acidulation) is required prior to POX acidic wash solution can be recycled for this although as the solution contains levels of dissolved Fe, Al and possibly Cu the resulting chemistry can be complex.

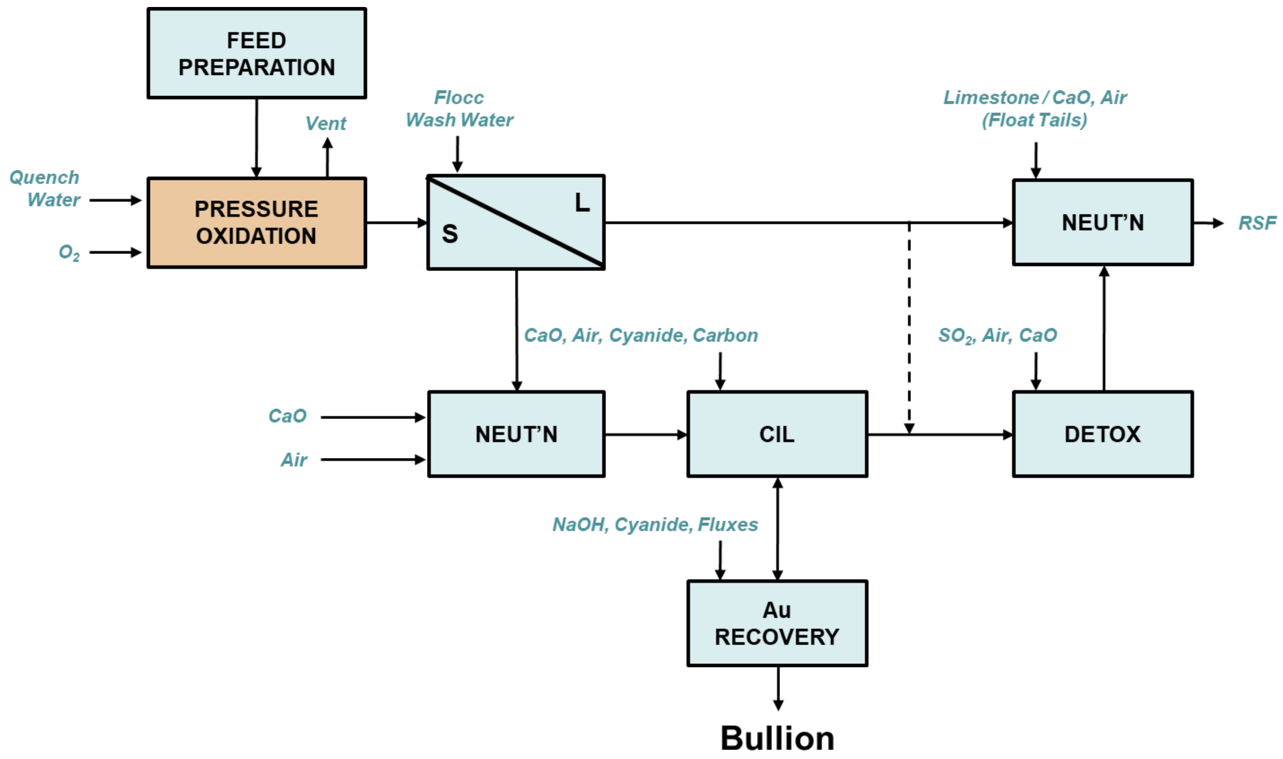


Figure 1. Typical Gold POX Circuit

In the West the use of resin for gold recovery is limited. Penjom Gold Mines in Malaysia have been using resin in leach (RIL) to treat a double refractory ore since 1999 and from 2014 Barrick Goldstrike has been recovering gold downstream of their POX circuit using calcium thiosulphate as the lixiviant in their RIL circuit.

Green Gold Technology applies resin in an innovative circuit for the recovery and recycle of cyanide at the Mirah Gold project in Indonesia. The use of resin for gold recovery has found greater acceptance in Russia (and the former USSR) although the technical details and economic considerations are poorly documented.

Mixed Gold / Copper POX with Copper Heap Leach

Mixed gold copper concentrates can be processed with the soluble copper in the CCD overflow recovered in a downstream SX/EW circuit after suitable solution preparation. This has the benefit of providing a sink for acid generated in the EW circuit in the associated copper heap leach circuit.

The gold recovery circuit is similar to the gold only circuit previously described although additional CCD washing is required both for copper recovery as well as to limit the bleed of soluble copper to the leach / CIL circuit.

The circuit has the benefit of maximizing flotation recovery by not requiring differential flotation of the gold bearing and copper sulphides.

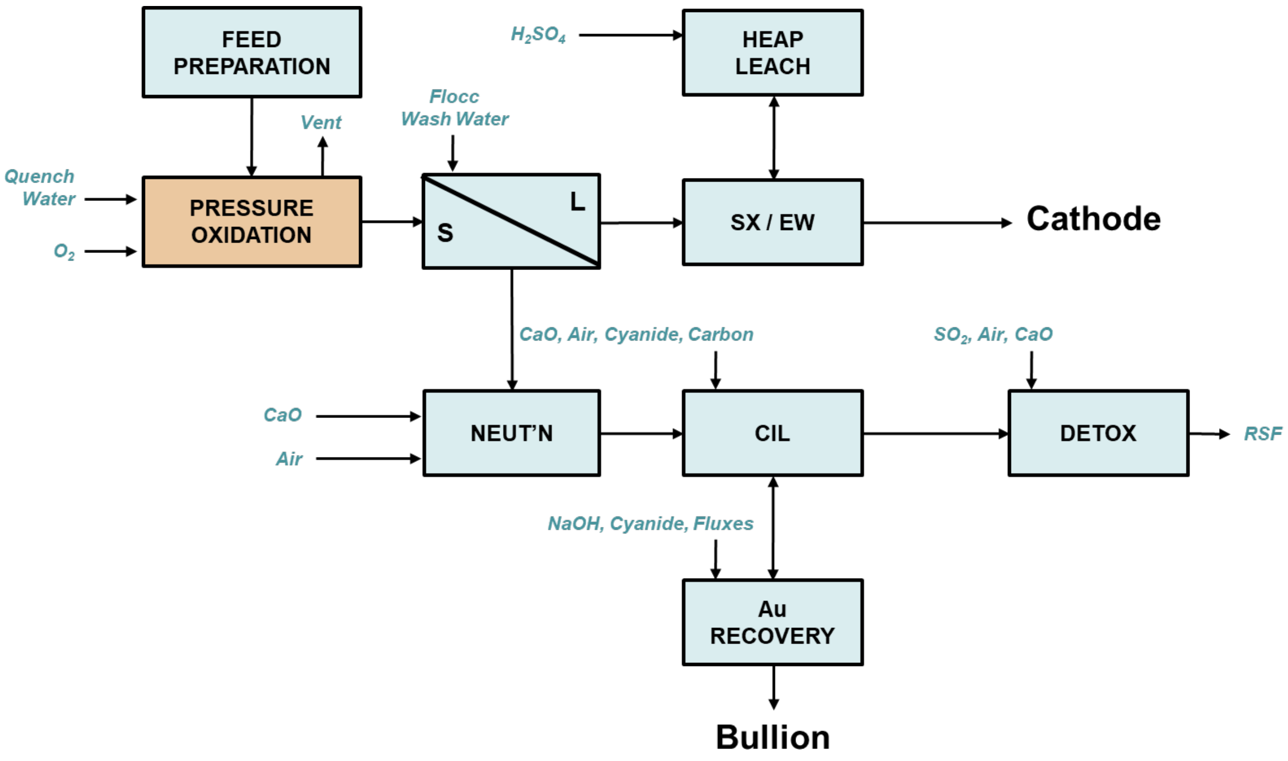


Figure 2. Typical Gold / Copper POX Circuit

OPPORTUNITIES FOR IMPROVEMENT

The preceding sections have outlined the history of the technology as well as describing its practical application. The question remains "has POX reached its full potential, or is there still room for improvement?".

The question could simply be seen in a process context, improved extractions, reduced residence times, improved oxygen utilisation and so on. Alternatively, there are issues of reliability such as the life of vessel linings, severe service control valves and agitator impellers. In an overall sense however, the author's view is that the three key areas for improvement in the control of the designer and operating company can be captured in terms of improved safety, reduced capital cost and increased operating time.

Reduced operating costs inputs such as labour and power costs are obviously beneficial, but these are generally a function of the site location and do not represent an improvement to design or operation. That said if the three suggested improvements are addressed these will naturally lead to a reduced operating cost and thus to improved economic outcomes.

Safety

To misquote Leonard Henry Courtney, 1st Baron Courtney of Penwith, 'the price of safety is eternal vigilance'.

Safety - Potential hazards

POX Circuits are characterised by a number of potential hazards,

- **Loss of Containment.** The energy stored within an autoclave at operating conditions is significant. If we assume the following autoclave characteristics,
  - Total volume 400 m^3
  - Live volume 340 m^3
  - Fluid Water
  - Operating conditions 220°C, 31 bar.a
  - Ambient conditions 20°C, 1 bar.a

  Ignoring the contained energy of the compressed vapour space the energy change of the fluid from operating to ambient conditions if released explosively is equivalent to over 50 tonnes of TNT. In the more realistic scenario where the contained energy of an autoclave is released over a number of hours as a result of a leaking flange the release is still significant with the potential for personal injury and certainly mechanical damage to equipment.

  Fortunately, catastrophic autoclave failure is a highly infrequent. In the past 20 years in the HPAL industry there have been a number of failures of high-pressure autoclave slurry lines, but the most significant recorded incident was the titanium fire at Kidd Creek zinc sulfide leaching plant located in Timmins, Ontario[1]. In the incident a metal – titanium – oxygen fire was initiated by one of the autoclave agitators, the molten metal thrown off the agitator resulted in the failure of two titanium insert pipes, one a thermowell and the other containing the nuclear source used for autoclave level control. Fortunately, neither the shell nor the brick lining were damaged, repairs were affected, operating procedures updated and the autoclave was returned to service.

  By publishing the details of the incident in an open and timely manner, Kidd Creek Mines have made a significant contribution to the industry and have most likely prevented the occurrence of similar incidents. Design concepts resulting from analysis of the incident such as the use of non-titanium stub shafts in autoclave agitator mechanical seals are now common in the industry.

  Other mechanisms for a loss of containment include,
  - Corrosion of pressure containing metallic components, typically piping,
  - Erosion of pipework (most are unlined) or vessel protective linings, and
  - Bolted joint / gasket failure

- **Oxygen metal fires.** Titanium is a highly reactive metal; in fact, this is what provides its superior corrosion resistance in the form of the tenacious oxide layer that protects the parent metal beneath. If however the passivating oxide layer is removed, by for example mechanical damage in the presence of a sufficient oxygen overpressure, ignition may result. Significant effort is therefore made in preventing possible mechanical damage to titanium as well as limiting oxygen partial pressure. Other less reactive alloys are also susceptible to a metal oxygen fire and although less prone to ignition and therefore still require protection.

  Oxygen fires can be initiated by other means such adiabatic compression, poor oxygen cleanliness or incorrect materials selection.

  The incident at Kidd Creek described in the preceding section is a particularly severe example of a loss of containment due to an oxygen metal fire but other scenarios such as fires in piping and valves also occur, sometimes with a resulting depressurisation and loss of containment.

- **High Pressure Oxygen and Steam Supplies**. Although common utilities in many industries the use of high pressure (30 – 40 bar.g) utilities demand respect due to their contained energy and the potential consequences of uncontrolled release and depressurisation.
- **Corrosive or Toxic Materials.** The products of sulphide oxidation are typically acidic and may contain levels of dissolved salts such as arsenic or mercury. Construction materials such as lead based mortars for vapour phase brickwork are potentially toxic and require significant discipline in terms of occupational hygiene. Autoclave vent gasses are scrubbed including in some cases for mercury.

- **Radiation from Nuclear Sources.** Radiation sources are ever present in modern processing plants and POX circuits are no exception. Source sizes are typically larger due to the large vessel sizes and the attenuation of vessel lining systems. Nuclear sources have to be managed in the context of mechanical damage as well as personnel protection during vessel entry.
- **Confined Space Risks.** Maintenance work in brick lined vessels recently taken from service is often performed in conditions of high humidity and ambient temperature due to the thermal mass of the vessels and their lining systems. Safe isolation of inputs such as oxygen, steam, high pressure water and slurry is mandatory. Isolation from ionizing radiation from nuclear sources is required as discussed above.

Site operators successfully manage these potential hazards day in - day out, year in - year out on sites all over the globe relying on experience, operating and maintenance procedures. In the design process engineers put significant effort into designing out potential hazards as well as their mitigation, providing redundant levels of protection to reduce the expect risk to an acceptable level.

Despite of these efforts, incidents do occur, be they oxygen metal fires, uncontrolled rapid depressurisations, lining system failures or the more common and less dramatic incidents such as temperature excursions or passing flanges. Whilst uncommon, incidents such as these do periodically re-occur suggesting that there is room for improvement both in design as well as operational practice.

Safety –Opportunities for Improvement

In some ways understandably, incidents and near misses have been downplayed by operating companies so the full picture is unclear, particularly in light of the geographic and corporate spread of operating sites and corporate offices. The incident at Kidd Creek is the exception rather than the norm, both in terms of its severity but also in terms of the transparency of the operating company.

In recent times the issue of process safety has most notably championed by Trevor Kletz, the former safety advisor for ICI. Although focussed on the chemical process industries (CPI) rather than the extractive industries, on a practical level many of the safety related issues overlap and there are commonalities in terms of human and organisational behaviour.

It is encouraging that many of the CPI practices pioneered by Kletz and his colleagues and successors have migrated to the mining industry to assist with the identification and mitigation of potential hazards. Examples include,

- HAZID (Hazard Identification Studies),
- HAZOP (Hazard and Operability Studies),
- LOPA (Layer of Protection Analysis), and
- QRA (Quantitative Risk Assessment)

It should be remembered that these practices are simply tools used by individuals using their experience to the best of their abilities, but no individual is infallible. No study can capture all possible eventualities but the real-world experiences of the team members and their knowledge of the state of the art will help to reduce the gap between the known and the unimagined. As a cautionary note these tools can be misused and need to be applied appropriately and with care for their output to be productive. Performing the tasks to satisfy a corporate requirement or as a bureaucratic exercise adds no value, perhaps just the opposite by instilling an unrealistic sense of complacency in the project team.

In another migration from the CPI, new POX designs are also seeing the adoption of supervisory systems and SIL rated control loops for critical shutdown functionality in place of the simple but effective hardwired electromechanical relays used previously. Again, these need to be used judiciously, using a supervisory system is no substitute sound engineering and basic process control system (BCPS) implementation. Additional complexity does not inherently increase integrity, often the simplest design decisions can have the greatest impact on reducing the risk of failure. An example is the selection of conservative (but not too conservative) piping classes in place of additional instrumentation and safety loops.

In an operational environment the importance of change management cannot be understated. Seemingly innocent changes to interlocks or control setpoints to address short term operational or maintenance problems can undermine the various layers of protection that ensure safe operation. This calls for an informed workforce also armed with the tools to help them make necessary changes safely without negatively impacting system integrity. This applies to maintenance of P&IDs, control system configuration, application of ‘temporary’ control system bridges and even the procurement of spare parts. The supply chain should not be in a position to deviate away from previously specified components without engineering approval and a suitable specification to ensure that spares are fit for purpose.

One of Kletz's repeated concerns relates to the publication of incident / accident reports and the dissemination of the relevant learnings[2]. POX plants share a number of common hazards as discussed above, and likewise can share in the methods for their elimination or mitigation. In making the case why operating companies should publish accident reports Kletz proposes four reasons which are paraphrased below,

- **Moral**. We have the opportunity to prevent harm to others who may be in a position to benefit from our experiences.
- **Pragmatic**. It is reasonable (although sometimes optimistic) to expect others to reciprocate and in so doing help us to avoid potential incidents and accidents.
- **Economic**. If we publicly 'raise the bar' and lift industry standards then others may also be obliged to do so for example to demonstrate the application of best practice to staff, shareholders or regulators. This potentially reduces the investment differential for the implementation of improved safety. (This is less of an issue the gold industry than in the CPI as POX operations are typically not competing directly against each other).
- **Reputational**. Safety is not a zero-sum game; a serious incident or accident amongst our peers not only adversely affects those directly involved but impacts our licence to operate as an industry. Whether it is our employees, our local community, the investment market or legislators, we rely on the good will of others to carry on our business. We need to earn their trust and part of this is transparency, so as an industry it is not good enough to simply believe we are doing the right thing, we should be seen to be doing so.

It would be unrealistic to expect operating companies to suddenly become forthcoming and shed their fears of criticism and loss of market value, but this does not change the potential benefits of greater transparency. A change in corporate behaviour requires a change in corporate culture which itself requires vision and courage from those with the ability to initiate change.

A good place to start would be with better investigation, analysis, reporting and education about significant incidents within individual operating companies. In his writings Kletz provides numerous examples where accidents repeat themselves either on the same operating site or in the industry at large because the institutional knowledge has been lost, often because it is not adequately recorded and just as likely because the information is not transmitted to succeeding generations of operations and maintenance personnel. Operating sites that experience high turnover are obviously more at risk of this loss of institutional knowledge.

Complacency is a common human failing and organisations are no less susceptible. Managers who may previously have made budget cuts to maintenance and training in less critical operations may fail to appreciate the risks they take. Historically, failures as a result of these cuts may have impacted production temporarily but did not pose a risk to life and limb, let alone corporate reputation. These risks are similarly real in the project design and execution phase where cuts to budget, but most critically schedule have the potential to significantly impact design integrity and project ramp up.

In terms of the implementation of process safety it is the author's experience that behaviour varies widely from site to site, typically as a function of corporate or managerial culture. Some sites appear to do as little as possible to incur the wrath of their regulators appearing comfortable with sailing close to the wind. At the other extreme, site culture rewards those for finding reasons not to do something or to simply find fault, with individuals hiding behind bureaucratic layers of collective decision making. That said, individuals need to be empowered to raise real concerns and for those concerns to be dealt with in a professional manner, this especially important in countering groupthink or the insidious effects of unrealistic schedules or cost cutting.

Fortunately, most sites have a pragmatic culture understanding the strengths of individual responsibility, transparent decision making and a realistic management of risk. This culture is set from the top and is one of the fundamental responsibilities of leadership.

Opportunities to Reduce Capex

As described above the process efficiency of POX technology is well established but the technology is complex and together with the associated oxygen production facility are the most capital-intensive areas of the process plant. An oft voiced criticism of POX is its capital cost, and certainly compared to less sophisticated processes this is a step up from what some may be used to.

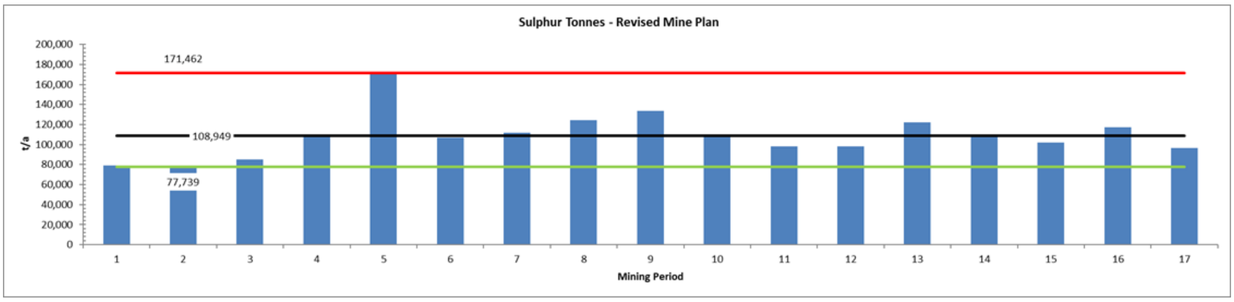
Recognising this it is essential that the design of any new installation is approached pragmatically neither under or over designed. This starts with a good understanding of the process requirements including,

- Throughput both as solids t/h and sulphide sulphur t/h
- Throughput constraints such as ore competency and feed density
- The relationship between oxidation and gold extraction
- Oxidation kinetics vs. grind size
- The deportment of impurities such as As, Sb, Pb, Hg
- Ore and mineral variability

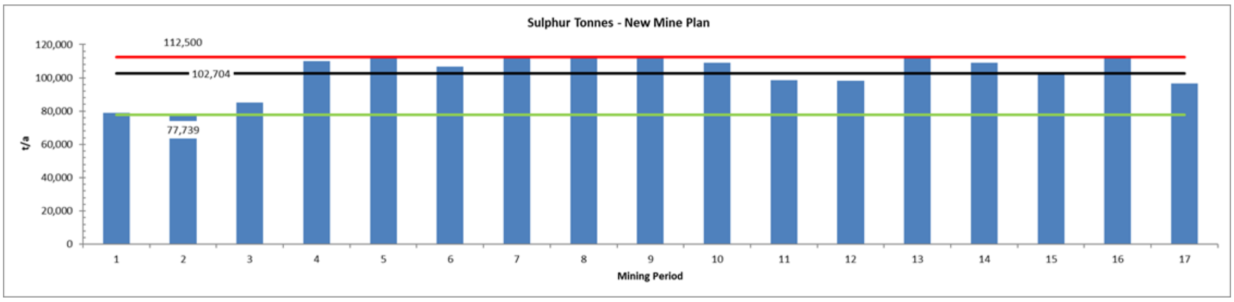
Interaction between the process design and the mine design is vital to optimise throughput with respect to the key process constraints typically,

- Comminution circuit power
- Feed thickener underflow density
- Autoclave volume
- Oxygen plant sizing

As an example, a client proposed the following POX feed schedule in terms of sulphide sulphur in feed and hence oxidation capacity.



After mine schedule optimisation the sulphide sulphur oxidation capacity of the proposed plant was reduced from ~170 kt/a to ~113 kt/a, a reduction of roughly a third with a commensurate reduction in capex and opex.



Appreciation of these constraints allows the clear definition of the overall plant operating window(s) and an alignment of overall business needs with design limitations.

In gold pressure oxidation the downstream circuit is generally more forgiving than for base metal circuits as the feed to neutralisation / cyanidation can be interrupted with little or no process impact apart from a loss of production. Typically, the downstream circuit as well as the utilities are conservatively designed so as to have a minimal operational impact on the capital-intensive comminution and POX sections.

It is a false economy to under design the less capital-intensive plant sections. An example might be the steam raising plant and associated water treatment for the autoclave start-up steam. If the steam supply is unreliable it will directly impact autoclave start-ups not only impacting short term production but having a long-term consequence in terms of the resulting increase in thermal cycling of vessels, linings and piping as well as actuation of metal seated ball valves.

A key component of cost-effective design is management of risk. This is a shared responsibility between the Owner and the Engineer, nothing comes for free. There is a perception that by employing a lump sum/fixed cost contract structure the Owner can transfer risk to the Engineer or Contractor. The only time this makes sense is when project definition is sufficiently mature to allow for it.

Typically, the Owner is in a rush to start production and either has insufficient testwork, an inadequate mine plan or Front End Engineering Design (FEED) to match the requirements of a lump sum contract. The Contractor has to allow for the risk in the proposed contract price which is then included in the tender to the project Owner. Forcing a Contractor to an unrealistic price benefits neither party to the transaction. It is cold comfort to successfully sue a Contractor if ramp up schedule is not achieved. To summarise, poor project definition adds cost and risk.

The best way to reduce the overall project cost is for the various parties to manage the risk they each best understand and in so doing minimise the overdesign required to compensate for uncertainty. It should be apparent that a steady and ordered project development path including adequate sampling, testwork, engineering will reap benefits in terms of overall cost and project ramp up. 'Fast Track' projects can be executed but they will typically cost more than necessary and carry greater risk of underperformance. This is also true for the introduction of novel technology as has been illustrated by Terry McNulty[3] in his survey mining project case histories.

Characteristics of the best performing (Series 1) projects included,

- A reliance on mature technology
- Equipment size and duty comparable to that used successfully in earlier projects
- Thorough pilot testing of potentially risky unit operations
- If licenced technology was used there were many previous licences

The Series 1 projects only included one POX circuit but '*an extraordinarily complete and professional was done of process development and engineering design'*. The less successful projects (Series 2,3 and 4) had a combination of some of the following characteristics,

- Newly licenced technology
- being a prototype of some sort
- Incomplete testwork
- Testwork performed on inappropriate samples
- Deficient engineering of 'simple' plant areas such as materials handling
- Poor understanding of variability and feed mineralogy
- Fast track engineering design and construction
- Equipment downsizing to meet capital expectations
- Unusually complex flowsheets
- Poorly understood process chemistry

McNulty also identified a number of compounding factors including,

- An overly aggressive or promotional attitude on the part of corporate management
- An ill-conceived rationale for the project
- Inadequate operator training and preparation
- Inexperienced supervisory staff
- Inadequate technical support during commissioning

It should be noted that quality is as important as quantity in ensuring a successful fit for purpose design and simply completing the steps laid out in the corporate project development manual such as piloting or even running a demonstration plant in no guarantee of success in itself as can be seen from the poor performance of some large-scale metallurgical projects.

Some practical means for maximising the value of capex are listed below. Many of these items are generic and have a greater applicability than to POX, but that does not diminish their importance or their potential impact on POX project viability.

- Ensure that contractual conditions between the Owner and the Contractor are consistent with level of project development and understanding of risk
- Assemble a suitably experienced Owner's team
- Ensure the Contractor's team has relevant and recent POX experience
- Allow a realistic schedule and budget
- Remember the schedule – cost – quality triangle
- Develop consistent definitions of ore and waste types between the disciplines of geology, mining and metallurgy
- Ensure that adequate testwork is available including for materials characterisation, corrosion and process variability
- Do not neglect or underestimate environmental permitting requirements or sample production for the characterisation of residues and effluents
- Agree on clear design criteria consistent with the proposed mine schedule and feed variability
- Consider water quality requirements for different plant areas
- Consider optimal oxygen purity for the expected chemistry
- Use modelling to explore and define process conditions
- Run model balances for each significant operating / feed scenario
- Develop well thought out operating windows using an optimised mine plan
- Define flow maxima in a dedicated document for use by all disciplines
- Autoclave (circuit) throughput is volumetric based, maximise POX feed density but be realistic
- Allow for appropriate feed storage and blending to control POX feed variability and to minimise the impact of upstream maintenance (e.g. mill relines) on POX operating time. (This is easier for concentrate treatment where it is not unusual to have several days of storage capacity).
- Consider opportunities for future expansion but be careful not to overcapitalise.
- Apply 'reasonable' allowances for scale build up on process equipment and pipelines
- Use risk-based design allowances
- Do not apply margins on design margins
- Ensure a clear understanding of design margins between disciplines
- Ensure services are fit for purpose and are sized not to negatively impact POX operating time.
- Minimise footprint whilst allowing for maintenance
- Use proven equipment and do not scrimp on quality for critical items
- Use hydraulic actuation for large valves and those in critical applications such as autoclave letdown
- Minimise nozzles on pressure vessels to reduce cost and mechanical stress, consider cluster nozzles
- For two autoclave trains replicate the layout rather than using a mirror image
- Minimise height, for example by using side entry for flash vessels than top entry
- Work cooperatively with specialist vendors to benefit from their extensive industry knowledge
- Consider alternative oxygen supply options such as vendor build own operate (BOO) and build own operate transfer (BOOT)

The capital intensity of the technology demands additional diligence in terms of project definition and engineering to ensure that the ultimate design is pragmatic and fit for purpose, in other words not wastefully over designed, or under designed to the point that the project is unsuccessful. In principal this is no different for any other project but given the high capital intensity the negative consequences of poor project definition, excessive design margins or errors are significantly magnified. Once in service, changes to the design are generally challenging to execute and impose a significant cost burden not only for the modification itself but also in terms of the opportunity cost of the interruption to production.

Opportunities to Increase Operating Time

Improved operating time is an effective means of reducing capex for a given plant capacity. The items for maximalising capex value listed in the previous section will also contribute to an improvement in operating time and an improvement in operating quality.

A well-executed POX design in a mature operation should have an annual availability of greater than 90% excluding long term outages for relining. Downtime for a given areas can be split into various categories, for example,

- Planned maintenance
- Unplanned maintenance
- Utilities interruptions
- Upstream and downstream process interruptions
- Process performance

The latter category is a reflection that it is not simply a requirement to have the area online but that this needs to be at the required throughput at the required process parameters. For POX this would typically be reflected in terms of sulphide sulphur throughput, oxidation extent, discharge chemistry and gold liberation.

Circuit complexity can play a significant role in plant performance, simple POX circuits with a downstream leach/CIL/CIP circuit are usually forgiving. For example, the Macraes POX circuit ramped up to full production in just two days. In contrast a plant that has a high carbonate feed with a significant acid recycle and carbonate destruction circuit is a more demanding challenge to maintain at steady state.

Disconnecting the grinding circuit from the POX circuit with a flotation concentrator incurs a recovery loss but helps to reduce the effects of upstream circuit performance and feed variability. POX Feed variability and circuit complexity will therefore impact intermediate storage and catch up requirements. These factors result in typical circuit design availabilities in the high 80 percent range.

As noted above it is a false economy to under design utilities that would otherwise impact POX operating time. It is not simply the utility downtime in and of itself but the consequences of a circuit trip which depending on duration and severity may require the autoclave to be put on hold, returned to temperature (requiring the steam utility) and the re-introduction of oxygen. A trip cycle involves the opening and closing of numerous valves, the temporary interruption of oxygen flow (which may have its own impact on the oxygen plant), as well as thermal cycling of vessels, lining systems and piping. Any damage caused by thermal cycling is cumulative and even if not apparent will affect long term equipment life. There is significant value in a balanced design.

Maintenance planning is also significant and applies to daily/weekly/monthly planned maintenance and the execution of major shutdowns. These often involve the use of specialist contractors, inspectors and consultants that have to be scheduled months in advance as do the necessary materials. The logistics and supply chain plays a key role in ensuring that the correct materials are available on site at the required time. This is even more critical if a shutdown is started opportunistically to take advantage of a breakdown.

It should go without saying that unplanned maintenance should be avoided but there is a balance between extending campaign durations to eke out every last possible operating hour and over maintaining the circuit. This balance can be adjusted once the start-up wrinkles have been ironed out and the behaviour of the new plant are understood.

For both design and maintenance planning, build-up of scale is particularly difficult to predict but a robust design and some operating history will successfully allow its management. The use of hydroblasting for descaling is common, although in brick lined pressure vessels scale removal is usually performed mechanically to limit damage to the lining system. Antiscalant additives have proven to be effective.

All lining systems require regular maintenance and repair. Brick lining systems will typically need a face course rebrick after approximately five years depending on the quality of the refractories and the severity of the operating conditions. This reline and the associated demolition of the old refractory will take several weeks and should be allowed for in the long-term production schedule. Repointing of eroded mortar joints is a normal shutdown activity. Likewise, it is not unusual to have to replace patches of brickwork in high wear areas.

Routine shutdowns are planned anywhere from each 3 months to 12 months depending on scale formation and the process conditions. Often shutdowns and split between internal (i.e. requiring vessel emptying and entry) and external shutdowns.

Technical Opportunities

The past twenty years has seen significant development in both the performance of specialised equipment for POX circuit operation both in terms of capacity and reliability. Examples include,

- Refractory and lining system design allowing for design of larger brick lined autoclaves up to 5.6 m internal diameter
- The replacement of litharge-based mortars with nontoxic alternatives
- Autoclave impeller design for reduced wear improving blade life and campaign duration
- More robust autoclave mechanical seals reducing unplanned outages
- A reduction in cost for variable speed drives allowing their cost-effective use for all autoclave agitators improving blade life and campaign duration
- Improvements in coating technologies for high wear areas such as impeller blades and valve balls and seats
- An improvement in ceramic materials design allowing larger and more reliable severe service control valves
- The introduction hydraulic actuation for severe service control and isolation valves. This also allows for valve partial stroking for scale removal and 'fingerprinting' for condition monitoring
- Improved severe service ball designs and coating leading to the use of up to 14'' autoclave isolation valves in the nickel industry.
- Improvements to autoclave feed pump valves, diaphragms and cooling leg design and maximum slurry temperature
- Improved condition monitoring including thermal imaging, vibration monitoring and shaft deflection monitoring
- On site autoclave and flash vessel fabrication on remote sites

It is likely that these items will continue to be improved. The industry will not stand still driven by an increasing gold price as well the drive to process more refractory lower grade ores. Improvements can be expected to include,

Instrumentation and control. The operation of POX circuits has historically been hampered by the lack of on-line data indicating process performance, for example discharge chemistry, solution and gas stream assays. This is an area ripe for development and may include,

- Direct vent gas analysis using suitably robust tuned laser diode spectrometers to allow better control of oxygen addition and overpressure with resulting improvements in efficiency and process safety.
- Direct vent gas mass flow measurement to assist in process control.
- On line measurement of pH and Eh in autoclave discharge allowing better control of autoclave chemistry.
- On line measurement of sulphide sulphur for feed and discharge streams for improved process control.
- The use of online models and expert systems to guide operators and to indicate deviation from safe operation

Mechanical equipment. Designers and equipment suppliers will continue to adapt and improve existing technologies as well as to develop new processes. Physical simulation software such as for finite element analysis (FEA) and computation fluid mechanics (CFD) will undoubtably improve allowing better design of physical components in terms of strength, performance and wear resistance. Particular items will likely include,

- The use of simulation for the analysis and optimisation flash letdown systems to reduce lining wear and carryover of slurry to the overheads lines.

- The use of either solid titanium or titanium clad autoclaves for gold POX has been the subject of debate for many years with concerns about wear and the potential for ignition with oxygen and subsequent loss of containment limiting its uptake. It is inevitable that someone will make accept the challenge in search for freedom from the constraints and costs of a traditional membrane and brick lined system.
- Equipment sizes will inevitably increase, probably as a compounding result of some of the developments in other areas such as metal lined vessels and the physical understanding of the flashing process.

Process understanding. The capability of modelling and simulation software is expected to improve as computational power increases allowing for improved understanding of existing processes as well as opening up new opportunities. Fundamental research in academia will continue. Process developments may include,

- Better manipulation of iron and sulphur chemistry such as the production of jarosite and basic iron sulphate (BFS). (Fundamental testwork on BFS chemistry is outdated and is based on batch testwork that does not reflect the reality of a continuous system).
- The use of additives to manipulate autoclave chemistry
- The application of flash recycle for heat balance control, especially with larger autoclaves.
- Controlled partial oxidation to maximise gold extraction for given sulphide sulphur extraction
- The use of downstream acid gold leaching processes (such as thiosulphate and thiourea) to reduce neutralisation requirements.

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