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RECENT DEVELOPMENTS IN THE METSO OUTOTEC BIOX® PROCESS

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ABSTRACT

RioZim selected BIOX® as the preferred technology for the treatment of the refractory gold concentrate for their Cam & Motor gold mine located near the town of Kadoma, approximately one hour's drive south-west of Harare, Zimbabwe. The BIOX plant was designed for an ultimate capacity of 200 tpd of concentrate, but the project will be implemented in two phases: phase 1 will have a capacity of 100 tpd, which will be expanded to 200 tpd in phase 2. The project is currently in construction and commissioning is expected to take place during Q2–Q3 of 2020.

The Fosterville mine is a high-grade, low-cost underground gold mine located 20 km from the city of Bendigo in the State of Victoria, Australia. The current operation was commissioned in 2005 and includes a BIOX plant. Fosterville has been evaluating the implementation of the Metso Outotec ASTER™ process for a number of years to improve the mine water balance by allowing treatment and then recycling of tailings dam water back into the process. In 2019 Fosterville decided to continue with the implementation of the ASTER plant, which will be the fourth application of ASTER technology.

Metso Outotec has developed and commercialised the MesoThem process, using a combination of mesophilic bacteria as the primary oxidation stage followed by thermophilic bacteria, operating at ~ 65°C, to complete the oxidation. The higher operating temperature in the thermophile stage allows for more complete oxidation of the sulphur in the concentrate, thereby reducing the cyanide consumption during the subsequent cyanidation step. Development of the process was done at Pan African Resources' Fairview BIOX plant, located near the town of Barberton in South Africa.

Development included operating the process at different scales, from a 120 l continuous pilot plant through 1 m^3 and 21 m^3 demonstration scale tanks. The final step in the development of the process included converting one of the secondary BIOX reactors at Fairview into a thermophile reactor. The results confirmed that the process was able to operate stably at the different reactor sizes and generate consistent results. Scaling the process up sequentially allowed for confirmation of the design equations and operating procedures at the different reactor sizes.

Keywords: RioZim, Cam&Motor, Obuasi, Fosterville, BIOX, ASTER, MesoTherm, Refractory, Gold, Fairview

INTRODUCTION

The BIOX® process for the treatment of refractory gold concentrates has been in commercial operation for 34 years following the commissioning of the first commercial operation at the Fairview Gold Mine in 1986. To date 12 successful BIOX plants have been installed in 10 countries spanning 4 continents with the 13th installation currently nearing completion in Zimbabwe. The process has been proven to operate successfully over a wide range of concentrate feed grades and mineralogies, climatic conditions and site altitudes. A hallmark of the technology has always been the continued development of the process and understanding of the operation of the BIOX bacterial culture and BIOX plants.

A complete list of the current and historical BIOX plants are given in Table 1. The successful commissioning and operation of the BIOX reactors at the Fairview Mine in South Africa was followed by the commissioning of three further plants in 1990, 1991 and 1993. But it was really the commissioning of the Obuasi (previously called Ashanti) BIOX plant in Ghana in 1994 and expanded in 1995, that proved the scalability of the process and the suitability of the process to operate in remote locations. The Coricancha BIOX plant in Peru, commissioned in 1998 confirmed the ability of the BIOX process to treat high arsenic concentrates, with concentrate feed arsenic concentrations reaching 20 % in the BIOX feed, and operating at high altitude, with the plant located at ~ 3 000 m above sea level.

Table 1: Current and historical BIOX Plants

Mine	Year commissioned	Capacity (t/d concentrate)	Reactor size (m^3)	Status
Fairview, South Africa	1986	62	340	Operating
Sao Bento, Brazil	1990	150	550	Care&Maintenance
Harbour Lights, Australia	1991	40	160	Decommissioned
Wiluna, Australia	1993	158	480	Care&Maintenance
Obuasi, Ghana	1994	1 000	900	Operating
Coricancha, Peru	1998	60	262	Care&Maintenance
Fosterville, Australia	2005	211	900	Operating
Suzdal, Kazakhstan	2005	520	650	Operating
Jinfeng, China	2007	790	1 000	Operating
Bogoso, Ghana	2007	820	1 500	Care&Maintenance
Kokpatas, Uzbekistan	2009	2 138	900	Operating
Runruno, Philippines	2016	404	1 300	Operating
Cam&Motor, Zimbabwe	2021	100 / *200*[1]	1 200	Construction

The Suzdal and Fosterville BIOX plants, commissioned in 2005 included the experience and learnings from the Generation 1 plants. A further three BIOX plants were commissioned in the period up to 2010 including the Kokpatas BIOX plant, currently the largest BIOX plant in the world.

The latest BIOX plant to be commissioned was the Runruno plant in the Philippines, commissioned in 2016. This was the first application of the BIOX generation 3 design principles. This was also the first plant to utilise the Generation 4 BIOX agitator design.

The BIOX design has evolved over the years with the incorporating of the knowledge and experience from every project into the design of the latest BIOX plant. This, coupled with focused research and development programs led to the launch of the Generation 3 BIOX design philosophy in 2013. The main focus of the Gen 3 design was delivering improved process robustness and ease of operation. It comprises of four main themes

- Increased robustness of the process;
- Process improvements;
- Improved BIOX service offering;
- Improved knowledge transfer.

A structured process was followed to collate all the information from the recent BIOX commissioning programs, BIOX audit reports and operating experience from the BIOX users. It was realised that there was a need to not only address the technical and process related issues but also to implement a more comprehensive service offering to the BIOX clients. This included a closer and more structured cooperation during the different phases of project implementation and a dedicated program to ensure effective knowledge transfer to all stakeholders during the execution of the project.

The Generation 4 design aims to achieve reduction in the cost structure of a BIOX project by addressing the main capital and operating cost items. The main capital cost items include the BIOX tanks, agitators and blowers while power and reagents are the two main operating cost items. The development of the dual impeller agitator system for the BIOX application has been reported on extensively, including the OKTOP 3105 design developed by Metso Outotec.

The bio-oxidation of refractory sulphide ore concentrates results in the liberation of the occluded gold for recovery via cyanidation. However, one of the side reactions is the reaction between residual cyanide and reactive sulphur species, resulting in the formation of thiocyanate (SCN^-).

In 2010 Metso Outotec introduced the ASTER process for improved water balances in commercial BIOX applications by supporting tightening environmental legislation on water usage and availability in both arid and tropical regions. Previously, a common challenge for BIOX plants was the inability to recycle thiocyanate containing water due to the low tolerance of the organisms. ASTER, a biological thiocyanate and cyanide destruction process, renders a non-toxic solution for re-use in BIOX. The ASTER circuit makes it possible to destruct cyanide tailings water at SCN- concentrations as high as ~ 4,000 mg/L down to level below 1 mg/L. This makes the treated tailings water suitable for recycling back to the BIOX process or the seasonal release to the environment.

Table 2 shows the three commercial ASTER plants are in operation currently. The fourth ASTER plant is currently in the final commissioning stages at the Fosterville Gold Mine in Australia.

Table 2: Current ASTER Plants

Mine	Year commissioned	Capacity (m3/d)	Design Feed [SCN^-] (mg/L)	Status
Consort, South Africa	2010	320	150	Operating
Suzdal, Kazakhstan	2013	528	1 200	Operating
Runruno, Philippines	2016	5 000	350	Operating
Fosterville, Australia	2020	792	5 000	Commissioning

In 2002, Metso Outotec commenced work using high-temperature thermophile micro-organisms as well, but this work focused on a combination mesophile–thermophile bio-oxidation process, which showed huge potential in reducing the cyanide consumption when compared with conventional mesophile biooxidation residues. This approach of utilizing mesophiles for the initial extent of sulphide oxidation is quite novel as it lowers the sulphide loading and duty for the subsequent thermophile stage, thus resulting in a less onerous mass transfer requirement at the higher thermophile temperatures.

This paper will describe the development of the MesoTHEM technology from laboratory scale to the first commercial application of the process at the Fairview BIOX plant in South Africa.

The development of the BIOX design program and implementation philosophy is a continues process and will continue beyond the successful roll-out of the Gen 3 and Gen 4 designs. The application of the Generation 3 design principles has resulted in an improved BIOX design and development strategy for new BIOX projects.

The rights to the BIOX, MesoTHERM and ASTER process are currently held by Metso Outotec (Finland) Oyj following the successful acquisition of Biomin Technologies S.A.

CAM AND MOTOR BIOX PLANT, ZIMBABWE

Location and History

The Cam and Motor Mine is situated 130km south west of Harare, 10km to the east of Kadoma, at Eiffel Flats (Figure 1). Mining in at the Cam and Motor mine dates back over 100 years on the site of the former Cam and Motor Mine. The mine was once the largest producer of gold in Zimbabwe and produced in excess of 150 tonnes of gold in its entire life. Three main ore bodies were mined by the Cam and Motor Gold Mining Company, the previous owners of the mine. These were the Motor Lode, Cam Lode and Petrol Lode. In 1968, the mine was closed with the gold price at US$35 per ounce and the mine operating at depths of 1,800 metres when operations were no longer viable.

At that stage, the mine cut- off grade was 8 grams/tonne and so it was considered likely that there could be significant resources adjacent to the old workings that would now be economic to mine. RioZim commissioned an exploration program to search for the expected lower grade zones surrounding the mined ore bodies.

RioZim limited commenced redevelopment of the mine with the installation of a new 2,000 tpd oxide processing plant at the Cam& Motor site. But the available oxide ores were always limited and planning for the sulphide plant expansion commenced simultaneously with the development of the oxide plant. This resulted in the installation of a flotation plant at the mine in 2018.

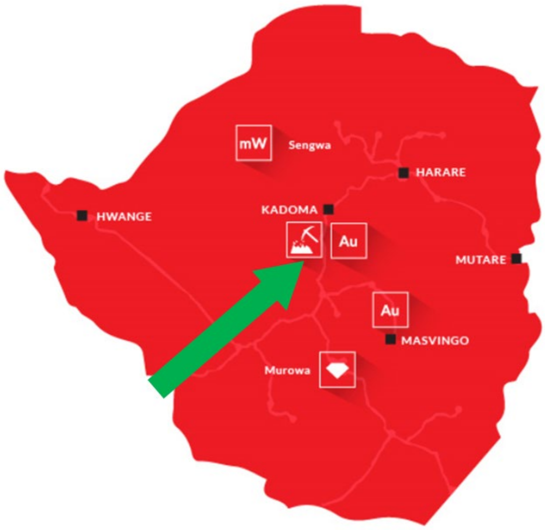


Figure 1: Location of the Cam&Motor Mine in Zimbabwe (Source: RioZim Web-site)

Riozim evaluated a number of process options for the treatment of the refractory sulphide concentrate. BIOX was finally selected as the preferred technology for this site due to the lower capital and operating cost, ability to implement the project in phases, ease of future expansion and environmental friendliness of the process.

Phase 1 BIOX Plant

BIOX batch amenability test work on a number of concentrate samples from the Cam&Motor mine were performed at SGS South Africa, confirming the design criteria for the design of the BIOX plant. The test work confirmed that high bacterial activity can be maintained during the oxidation stage, achieving near complete sulphide oxidation.

The Cam&Motor BIOX project will be implemented in two phases to limit the initial capital spend while ensuring access to an oxidation step to commence treatment of the refractory portion of the deposit. The Phase 1 design capacity is 100 tpd concentrate at a sulphide sulphur grade of 21.2%, expanding to the full capacity of 200 tpd concentrate in Phase 2.

Although the plant will be implemented in two phases, the design was completed for the full plant capacity, with only certain equipment installed during Phase 1. The phase 1 design of the BIOX plant is shown in Figure 2.

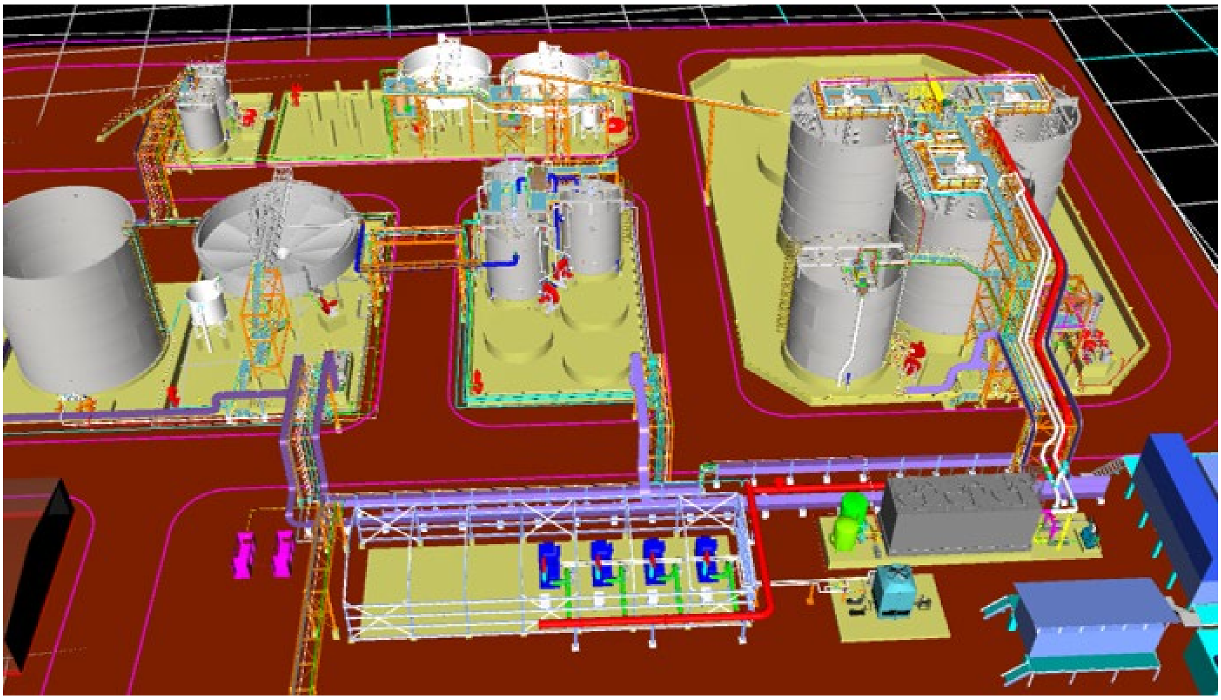


Figure 2: Phase 1 Cam&Motor BIOX Plant Lay-out

The Phase 1 plant will consist of the BIOX stock tank and 3 BIOX reactors configured as two primary reactors and one secondary reactor to achieve the desired extent of oxidation. The BIOX reactors will have a retention time of 6.8 days at the design concentrate feed rate. The design does, however, cater for a high concentrate feed rate, low sulphide grade scenario where the retention time will decrease to 5.5 days. A high sulphide grade, low concentrate feed rate scenario was also developed. This is part of the BIOX Gen 3 design principles and is to ensure flexibility for the plant to handle variations in the feed flow rate or sulphide grade while maintaining the required sulphide oxidation rate and extent.

The bio-oxidation reactor train creates the core of the BIOX process performance. The BIOX process requires high amount of oxygen for oxidation of sulphidic compounds and thus the main criteria for agitation is to provide sufficient oxygen mass transfer from air to solution. Air to the plant will be supplied by standard low-pressure air blowers feeding through a sparge ring in the BIOX reactors. Evaporative cooling towers will be used to remove heat from the cooling water circulated through the cooling coil baffles in the BIOX tanks.

The OKTOP BIOX reactors for the first phase of the plant was designed as 3 primary reactors and will be the three primary reactors for the second phase of the plant. However, for the phase 1 the tanks will be configured as 2 primary and one secondary reactors. The reactors will have an operating volume of 1 200 m^3 each and will be constructed from SAF 2304 duplex stainless steel. The OKTOP BIOX tanks were designed by Metso Outotec and will be supplied from South Africa and manufactured and assembled by Betterect.

The Generation 4 BIOX design is focussed on achieving a step change lowering of the power requirement for agitation and aeration of the BIOX reactors while maintaining the oxygen mass transfer duty. For this purpose, dual OKTOP 3105 impellers were selected for the primary reactors to supply the required oxygen mass transfer and mixing duty at Cam&Motor as shown in Figure 3. This configuration was the most efficient agitator configuration for the application, achieving a significant reduction in the agitator size and power requirement when compared to the conventional configuration. The dual impeller systems have also been successfully implemented at the Runruno BIOX plant in the Philippines.

Figure 3: Cam&Motor OKTOP® Primary BIOX Reactor Configuration

The Counter Current Wash (CCD) circuit will initially consist of two CCD thickeners at a higher wash water flow rate to achieve the required wash efficiency. The acid solution from the first CCD thickener will be pumped to the neutralisation circuit consisting of three neutralisation tanks. The neutralisation circuit is designed to achieve a neutralised product with the arsenic precipitated as a stable ferric arsenate and adhering to the USA EPA standards for long term stability. The oxidised BIOX product solids will be neutralized prior to pumping to an existing CIL circuit, reconfigured for the new process flow sheet.

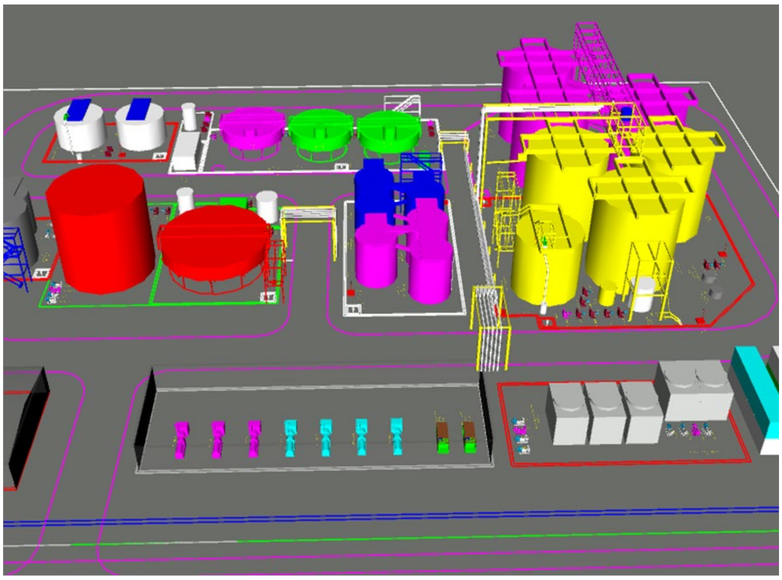
RioZim took the decision early on to complete the earthworks and civil construction for the BIOX, CCD and neutralisation sections of the plant for both Phases 1 and 2 during the Phase 1 construction. Although it increased the upfront capital cost of Phase 1, it was felt that it would reduce the potential impact of the Phase 2 construction on operations, as well as reduce the need for separate bund areas for Phase 1 and Phase 2.

All services and reagent make up systems will be included as per the standard BIOX design. Phase 1 will see the installation of only sufficient blower and cooling tower capacity for Phase 1 although provision in the design is made for the full plant. All reagent make-up and storage was designed for the Phase 2 capacity.

The Cam&Motor facility will include an ASTER plant to treat tailings dam return water and allow for recycling of the water to the process water circuit. This will enable for efficient water management especially during the dry season. Some redundant CIL reactors will be converted to ASTER reactors for this purpose, reducing the initial capital spend required. Construction of the BIOX plant commenced in 2019 but had to be suspended due to the COVID-19 lock-down in the country in 2020. A significant portion of the equipment is sourced from South Africa, also subjected to an extended lock-down. However, site work is in progress again with most major equipment already ordered and a significant portion of the stainless steel already on-site for construction of the BIOX tanks.

Phase 2 BIOX Plant

Phase 2 will see the expansion of the plant to the full design capacity of 200 tpd concentrate as shown in Figure 4. This will be achieved by adding three new BIOX secondary reactors to result in the standard BIOX configuration of three primary reactors in parallel and three secondary reactors in series.



- Phase 1: 100 tpd
- Phase 2: 200 tpd

Figure 4: Phase 2 Cam&Motor BIOX Plant Expansion

The CCD circuit will be expanded with the addition of a third CCD thickener and three additional neutralisation reactors will be added to the neutralisation circuit. Additional blower and cooling tower capacity will also be installed to cater for the higher sulphide sulphur loading on the BIOX at the higher feed rate.

ESTABLISHING THE ASTER PROCESS AS A MATURE DETOXIFICATION TECHNOLOGY

During the cyanide leaching of biooxidation product solids, cyanide reacts with reduced sulphur species to form thiocyanate (SCN), with concentrations of up to 4,000 mg/l recorded in cyanidation tailings effluent. Due to their toxicity, the presence of residual cyanide, metal cyanide complexes and thiocyanate in the effluent streams has necessitated the development of specific treatment technologies for the remediation of these effluents.

Some of the familiar and established chemical cyanide and thiocyanate destruction processes are summarised in Table 3.

Table 3: Summary of published cyanide destruction processes

Process	Description
Inco sulphur dioxide	High reagent consumption (SO_2, lime and Cu). pH Control required. Moderate SCN degradation efficiency.
Hydrogen peroxide	Relatively high reagent costs. Low SCN removal.
Caro's acid	Reactive and decomposes quickly and requires production onsite. SCN removal possible.
Alkaline chlorination	Very effective for CN removal. Oxidation of SCN is possible when excess chlorine present.
Ozonation	Ozone use is becoming more frequent as ozone generators become simpler. Ozone is a stronger oxidant than oxygen and removes CN effectively. The removal of SCN is also possible.

Another class of treatment options are biological processes. These rely on the metabolic capability of certain microorganisms, which have enzymatic pathways capable of catalysing the metabolism of cyanide and thiocyanate. The primary reaction products are ammonia, sulphate and carbon dioxide/bicarbonate. Ammonia may be assimilated as the nitrogen source for the organism. Biological systems are advantageous from the perspective that the microorganisms are able to adapt, within limits, to changes in flow rates and substrate concentrations in the short term, providing robustness to the process.

Metso Outotec's ASTER process was developed specifically to treat tailings effluent produced during the biological processing of refractory gold ores using the BIOX process where thiocyanate is the primary contaminant. The process configuration is modular, with a number of primary oxidation reactors in parallel, feeding a set of secondary reactors in series. Depending on the project specifics, the overflow from the final secondary can pass to a settler/clarifier which yields clarified effluent and settled sludge, a portion of which may then be recycled to the primaries to maintain high biomass concentrations. The reaction pathways as well as the overall reaction that is believed to occur are summarised as:

$$SCN + H_2O + \rightarrow HCNO + HS \quad (1)$$

$$HCNO + 2H_2O \rightarrow NH_4 + HCO_3^- \quad (2)$$

$$HS + 2O_2 \rightarrow SO_4^2 + H+ \quad (3)$$

$$SCN + 3H_2O + 2O_2 \rightarrow HCO_3 + NH_4 + SO_4^2 + H+ \quad (4)$$

Scanning electron microscopy images of the ASTER community is shown in Figure 5 below.

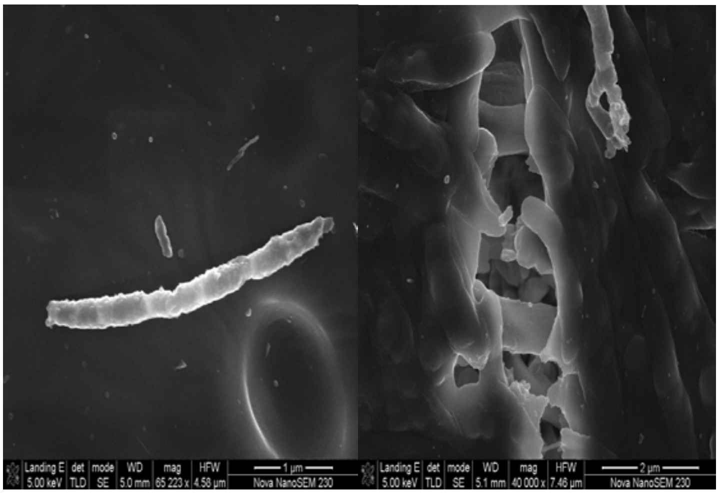


Figure 5: Schematic cycle for pyrite degradation (van Hille, 2013)[1]

Today, 3 commercial ASTER plants have been installed across the globe and some process design information is shown in Table 5. A fourth ASTER installation, the Fosterville plant in Australia is currently being commissioned while two further ASTER plants are in the final design stages, viz.: the CAM and Motor and Selinsing ASTER installations in Zimbabwe and Malaysia respectively. Views of the Suzdal and Runruno ASTER installations follow in Figure 6.

Table 5: ASTER Technology Commercialisation

Mine	Year Commissioned	Capacity (m^3/d)	Reactor Size (m^3)	SCN Level (mg/L)	Status
Consort, South Africa	2010	320	20	150	Operating
Suzdal, Kazakhstan	2013	528	200	1 200	Operating
Runruno, Philippines	2016	5 000	600	350	Operating
Fosterville, Australia	2020	792	200	5 000	Commissioning
Cam & Motor, Zimbabwe	2021	3 000	400	300	Design
Selinsing, Malaysia	2021	5 520	550	400	Design


Figure 6: Views of the Suzdal (Kazakhstan) and Runruno (Philippines) ASTER plants

Fosterville (Kirkland Lake) ASTER Plant

The Fosterville Gold Mine is located near the town of Bendigo, in the state of Victoria, Australia. The Fosterville BIOX plant was commissioned in 2005 and has been in operation since. The Fosterville ASTER plant currently under commissioning will be the fourth commercialised landing of the technology. This plant has been designed to treat a 792 m^3/d, 5 000 mg/L SCN^- feed and has the additional features noted as follows:

- It will be the first ASTER installation in Australia;
- The plant will treat the highest feed SCN level to date, i.e. 5 000 mg/L;
- The processing will be solution based and thus the reactors have no installed agitators with solution homogenisation brought about by aeration only.

The Fosterville metallurgical team identified the ASTER process as a potential solution to treat tailings dam return water to reduce the thiocyanate concentrations to levels where the water can be circulated to the process plant and used upstream of the BIOX process. The team at Fosterville set up a pilot plant facility and commenced a detailed ASTER test work program in cooperation with the Metso Outotec BIOX team. The test work campaign focussed on adapting locally sourced microbes to the Fosterville tailings solution, followed by optimising the performance of the culture through further adaptation to progressively higher duties and optimising the process parameters.

The test work was successful and confirmed the suitability of the ASTER process for the required application. The test work also generated the required destruction rates and other process design criteria required for the Metso Outotec BIOX team to develop an ASTER process design for the Fosterville ASTER plant. The process design was reviewed and optimised a number of times between the Fosterville and BIOX teams to select the optimum reactor configuration and materials of construction for the application shown in Table 6.

The plant will consist of six tanks with an operating volume of 180 m^3 each followed by a static settler. The static settler will enable recycling of thickened biomass to the ASTER primary tanks, thereby increasing the biomass concentration in the primary ASTER reactors and increasing the thiocyanate degradation rate. The reactors will also be fitted with heating elements to maintain the optimum temperature for the ASTER culture.

Table 6: Summary of the Fosterville ASTER Design Specification

Parameter	Unit	Design
Plant design	m^3/d	792
Primary reactor volume	m^3	200
No of primaries		4
Secondary reactor volume	m^3	200
No of secondaries		1
Tertiary reactor volume	m^3	200
No of tertiaries		1
Feed SCN^-	mg/L	5 000
Feed CN^-	mg/L	<5
Retention	hours	26
Effluent SCN^-	mg/L	≤ 0.1
Effluent CN^-	mg/L	≤ 0.1
Dissolved O_2	mg/L	≥ 4
Temperature	°C	24
Nutrients: Molasses	kg/m^3	0.15
Nutrients: Phosphorous	kg/m^3	0.15
Sludge recycle	% v/V_{Feed}	Variable

Figures 7 that follows shows a 3-D rendering as well as a view of the Fosterville ASTER plant.

Figure 7: Views of the Fosterville ASTER plant, Australia

Construction of the plant commenced in 2019 at the Fosterville site. Commissioning of the Fosterville ASTER circuit is currently underway.

BASIS FOR MESOTHERM BIOOXIDATION

While biooxidation may be described as a simple process, the actual oxidation of sulphide is complex. Refractory gold and base metal bearing minerals typically present sulphur as sulphide (-2) in sulphide minerals. It is improbable that the oxidation path of sulphide (-2) to sulphate (+6) is simple and direct during biooxidation as the microbial facilitated kinetics is slow and biooxidation likely occurs via single electron transfer steps with rate limiting steps favoring the existence of metastable species of intermediate oxidation states, as indicated in Figure 8.

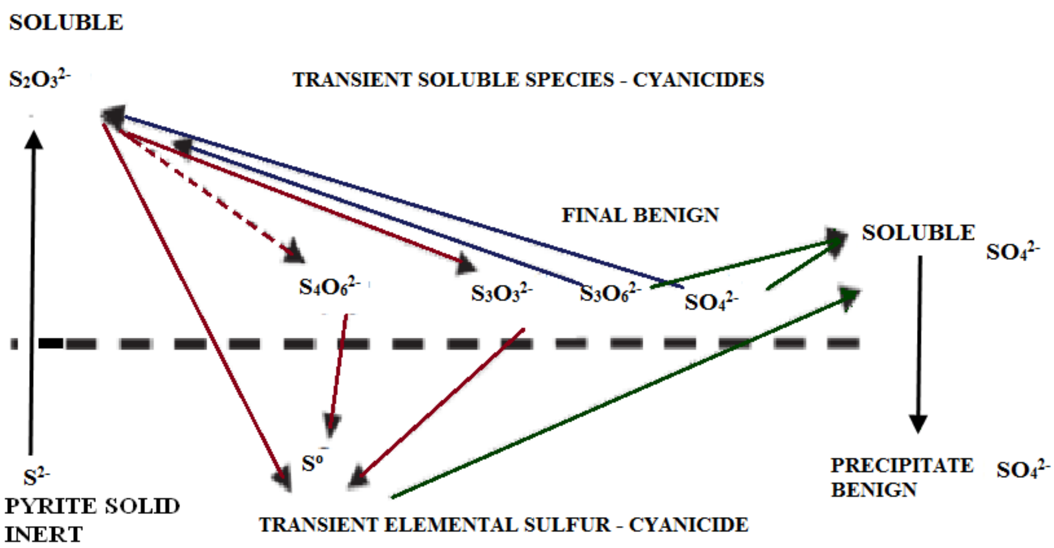


Figure 8: Schematic cycle for pyrite degradation (Sand et al, 1995)[2]

This pathway focuses specifically on the oxidation of pyrite by *Acidithiobacillus ferrooxidans* and some key components of this pathway suggest that the initial oxidation of pyrite at the mineral surface can occur by direct oxidation of the sulphide catalysed by glutathione leading to sulfite and thiosulfate, or can occur by an indirect mechanism involving the ferrous iron hexahydrate, again with an intermediate of thiosulfate. The acid-unstable thiosulfate is converted to polythionates and sulfites and it is well accepted that soluble sulfates are expected to be the final stable species of biooxidation which are removed by washing except from the small fraction retained as jarosite. As may be inferred by the above reaction scheme, the total reaction pathway associated with biooxidation is complex, resulting in the conversion of sulphides into potential cyanicides and finally to benign sulfates. These labile sulfur species, although unstable, may form to a significant extent and be part of the final product of the biooxidation stage and the accumulation of the labile sulfur species as globules either inside or outside the cells and / or on residual solids react with cyanide to increase cyanide consumption through the general reaction schemes shown in the accompanying equations with thiocyanate as the principal remaining species:

$$S_xS^{2-} + CN^- \rightarrow [S_{(x-1)}]^{2-} + SCN^- \qquad (5)$$

$$S_2O_3^{2-} + CN^- \rightarrow SO_3^{2-} + SCN^- \qquad (6)$$

$$SO + CN^- \rightarrow SCN^- \qquad (7)$$

The early batch biooxidation test work using the mesophile – thermophile combination showed that much lower cyanide consumptions was obtained when compared to the traditional mesophile cultures and with effluent leach liquors containing lower thiocyanate levels. This therefore pointed to a cleaner biooxidised residue being produced post the higher temperature thermophile biooxidation stage resulting in less reactive sulphide species. This early work showed that not only was the cyanide speciation different, but also the cyanide consumption was reduced by almost 50%. Figure 9 shows a leach liquor speciation comparison from a conventional mesophile and a MesoTherm cyanide test.

The figure shows that the cyanide consumption was reduced on leaching the MesoTherm product by as much as 50% and importantly, the thiocyanate was significantly lower in the leach liquor. These results perhaps supported the thinking that the higher thiocyanate formation and hence an increase in the cyanide consumption on the mesophile product was being promoted by higher labile sulphides carrying over to the leach with a lower level presenting from the MesoTherm product.

The mesoplile BIOX product consumed a total of 19 kg/t of cyanide during the leach with 92 % of the cyanide converted to thiocyanate by reacting with intermediate or partially oxidised sulphur species present in the BIOX product. Only a very small fraction of the cyanide was still available as free cyanide at the end of the leach. In comparison to this, when leaching the MesoTHERM product, the cyanide consumption was only 8 kg/t to achieve the same gold dissolution. The reason for this is apparent when we look at the cyanide speciation in the leach residue. Only 22 % of the cyanide added was converted to thiocyanate with 58 % still available as free cyanide.

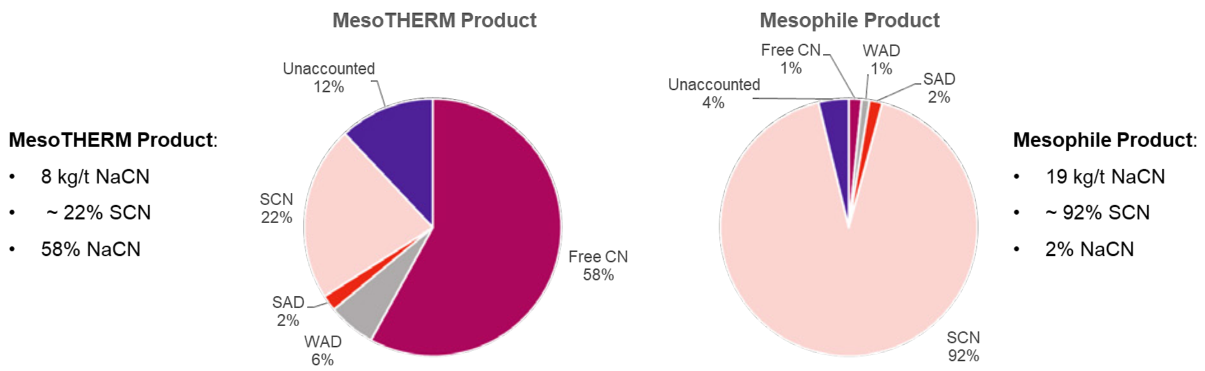


Figure 9: Comparison of batch cyanide consumption achieved on Mesophile and MesoTherm biooxidation product

Development Trajectory of the MesoTherm Technology

Scanning electron microscopy images of the mesophile and thermophile community cultures are shown in Figure 10.

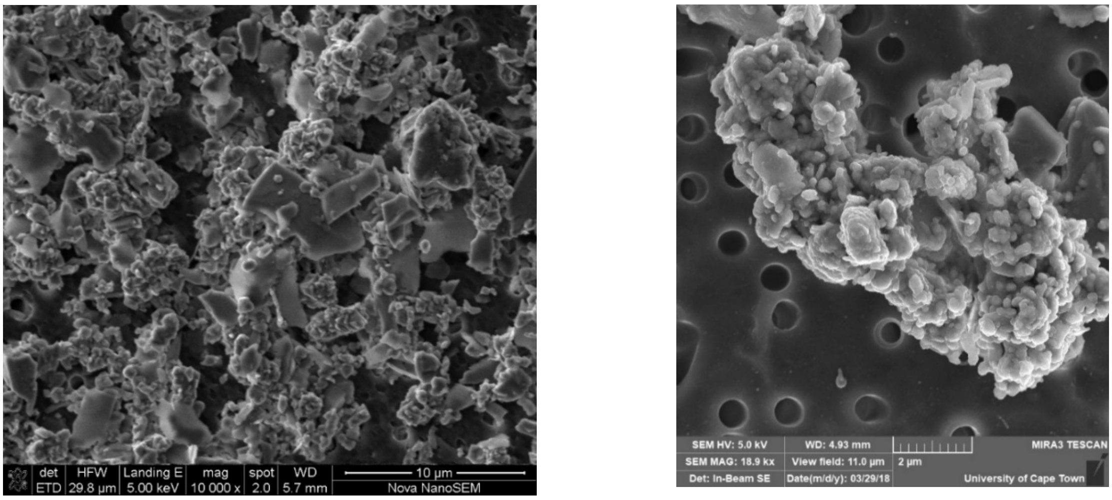


Figure 10 Metso Outotec resident mesophile and thermophile cultures (Smart et al, 2017)[(3)]

The dominant species determined by qPCR analysis are listed in Table 7. The mesophile culture includes both iron and sulphur oxidising bacterial and archaeal species. The thermophilic culture currently present in the MesoTherm process has indicated the presence of *Ap. cupricumulans*, mostly dominant at moderate thermophilic temperatures, and species belonging to the *Metallosphaera* genus becoming more dominant at higher operating temperature.

Table 7: Typical dominant species present in the MesoTherm process consortia

Mesophile Species	Thermophile Species
Leptospirillum ferriphilum	*Metallosphera sp(p)*
Acidithiobacillus. caldus	*Ap. cupricumulans*
Thermoplasma sp	
Ferroplasma acidiphilum	
Acidiplasma cupricumulans	
38°C to 42°C	60°C to 70°C
pH : 1.2 to 1.4	1.2 to 1.4

Metso Outotec undertook a rigorous technology development process which saw the MesoTherm technology being screened through various tollgates where the performance was interrogated in different developmental stages. Table 8 summarises this tollgate development trajectory.

Table 8: Developmental tollgate trajectory

Capture and Develop Ideas	**Opportunity Checking**	**Concept Development**	**Product Development**
Batch scale test work	Small scale continuous piloting	Larger scale continuous piloting	Scale-up and Demonstration testing
5 Litre reactors	135 Litre reactors	1,000 Litre reactors	21 – 80 m^3 piloting
7 – 10% Solids	7 to 10% Solids	15 – 17 % Solids	15 – 17% Solids
Low sulphates	Low sulphates and iron	Sulphates 90 – 100 g/L	Sulphates 90 – 100 g/L
High thermophile temperature	High thermophile temperature Validate batch results	Moderate thermophile temperature Validate 135 L piloting results Inter-stage thickening	Moderate thermophile temperature Validate 1 000 L piloting results Inter-stage thickening Mass Transfer and Engineering Scale-up Culture Robustness

Figures 11 and 12 show some views of the continuous piloting and engineering scale-up reactors.

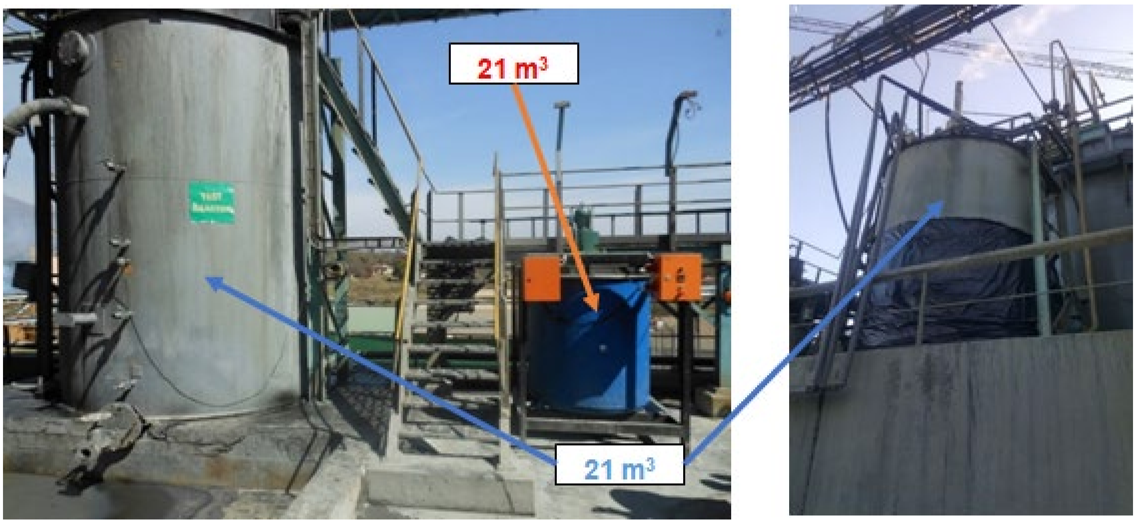


Figure 11: Views of the 1 000 Litre pilot and 21 m^3 engineering scale-up thermophile reactors

A summary of the MesoTherm engineering scale performance results is shown in Figures 13 and 14. Throughout the test campaigns daily overflow samples were collected and subjected to standard bottle roll leaches to determine the god recovery achievable and the corresponding cyanide consumption. Figure 13 shows the cyanide consumptions achieved in these discreet batch leach tests – from the pilot plant stages through to demonstration scale. It must be noted that, although the graphs for the different stages are shown on one timescale from day 1, the different test campaigns did not follow directly on one another and often up to a few months passed between the different sampling periods.

The red line indicates the average cyanide consumption achieved on the Fairview BIOX plant. The use of the thermophile stage resulted in a significant reduction in the cyanide consumption. Throughout the test work the cyanide consumption remained in the range of 2.5 to 12.5 kg/t. The best period, in terms of cyanide consumption was achieved on the 21 m^3 reactor product with maximum consumptions in the range of 7.5 kg/t.

It is important to confirm that the cyanide reduction was achieved without sacrificing gold recovery – as seen in Figure 14 showing the corresponding gold recoveries for the different test work stages. The red line again indicate the average gold recovery for the Fairview BIOX plant. Although there are periods where the gold recovery were lower, these were in fact mirrored on the commercial plant, maintaining a steady correlation between the mesoTHERM and BIOX product gold recovery.

Figure 12: Views of the engineering (21 m^3) and demonstration (80 m^3) scale thermophile reactors

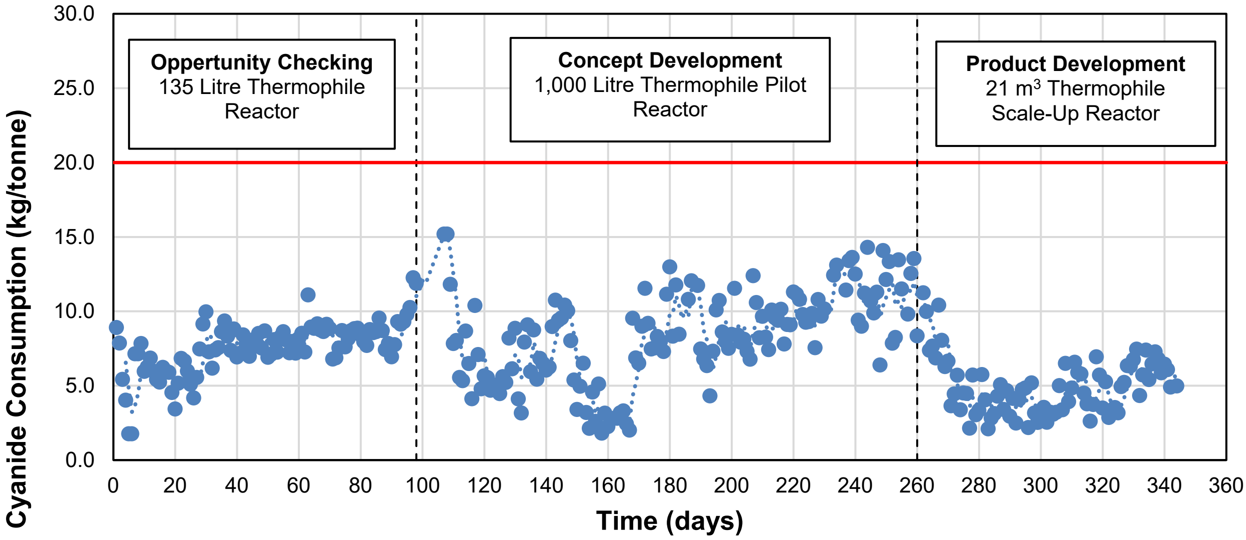


Figure 13: Comparative MesoTherm cyanide consumptions

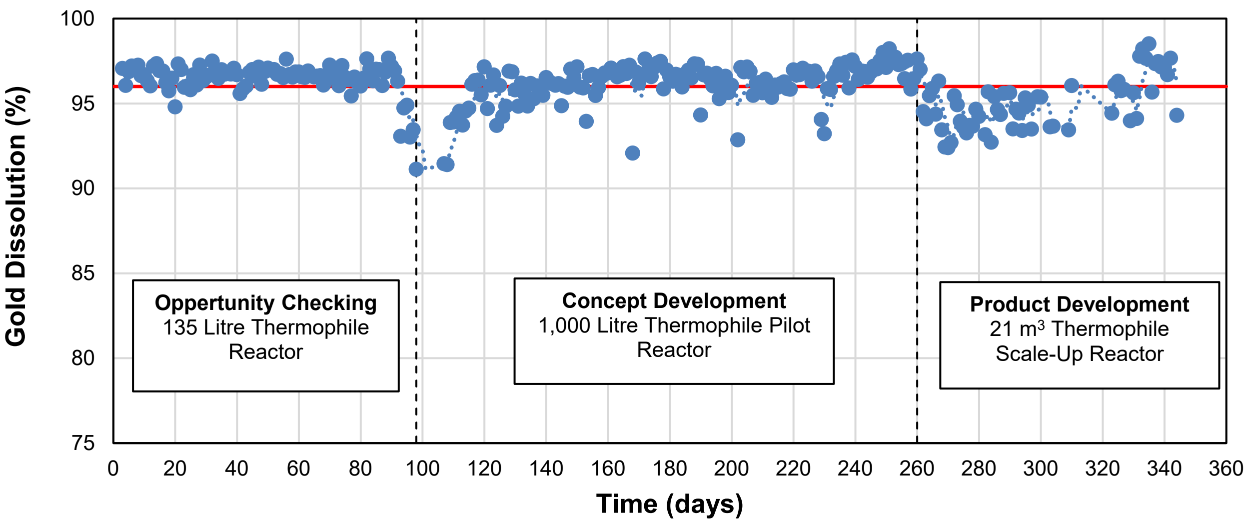


Figure 14: Comparative MesoTherm gold dissolutions

The successful piloting, engineering scale up assessments and demonstration trialling of the MesoTherm technology presents a new generation BIOX process to specifically target ores which traditionally have realized high cyanide consumptions. Figure 15 that follows shows a schematic of the Metso Outotec MesoTherm circuit.

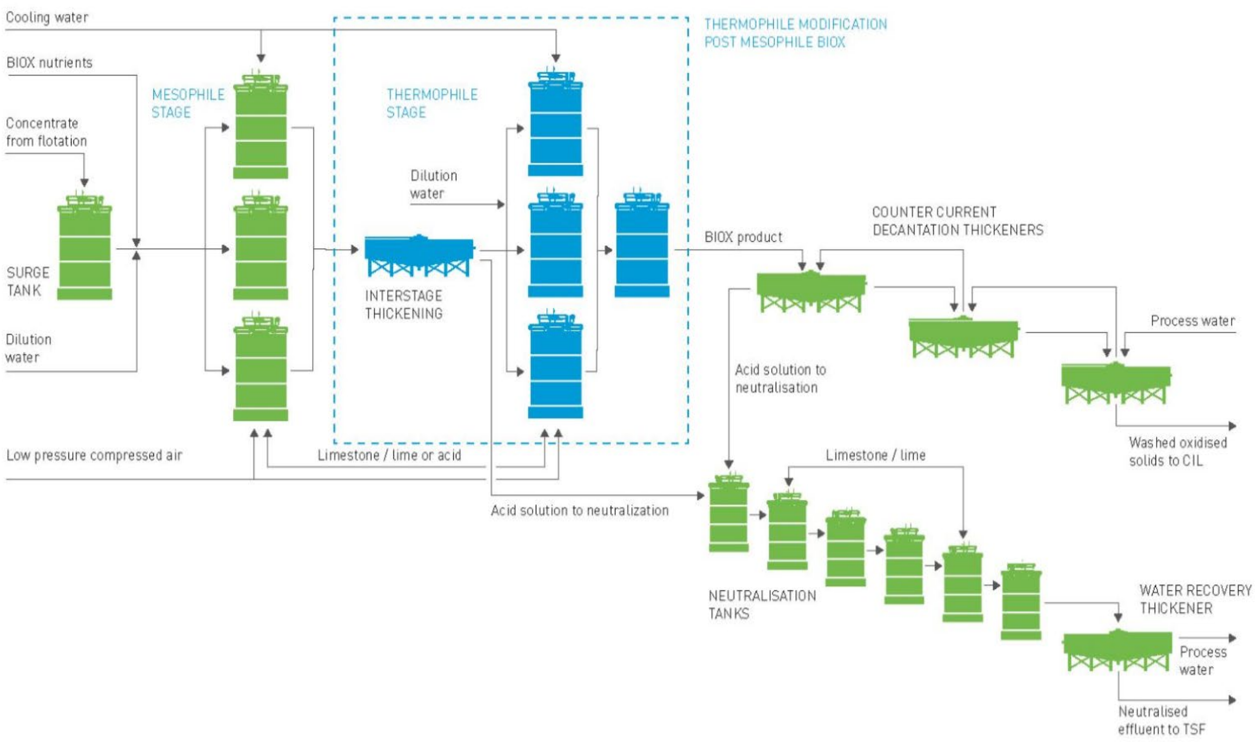


Figure 15: MesoTHERM BIOX flowsheet for refractory gold

The MesoTherm biooxidation technology leverages off the well-established and commercialized BIOX process, operating at 40 °C as the primary oxidation stage, targeting in the range of 70% oxidation. The BIOX process is a well-known technology with defined design and operating parameters. The organisms used in BIOX have also shown their robustness over the years.

With the MesoTHERM process we use high temperature, or thermophile bacteria, operating at ~ 65 °C as the final oxidation stage. The utility requirements are lower in the secondary reactors, offsetting the more complex design at the higher temperatures. The materials of construction are also important when operating at the higher temperatures.

The design also includes an interstage solution removal step, for the management of the dissolved iron and sulphate levels in the thermophile stage. Testwork has shown that it is important to maintain the dissolved ion levels to below certain set-points to reduce precipitation on the thermophile stage and optimise the performance of the thermophile bacteria.

CONCLUSIONS

The BIOX technology has been in commercial operation for 25 years with thirteen BIOX plants successfully designed and implemented in that time. The Cam and Motor BIOX plant, currently under construction in Zimbabwe will be the 14th successful landing of the BIOX technology.

Metso Outotec's biological thiocyanate and cyanide degradation process has been in commercial operation since 2010 and the three commercial installations are constantly validating the laboratory results and design specifications.

The Fosterville ASTER plant is currently under commissioning and will treat feed SCN levels as high as 5 g/L. This will be the fourth commercialisation of the technology and will be the highest SCN loading to ASTER to date.

Metso Outotec has recently launched its combination mesophile-thermophile biooxidation technology targeting those ores which upon mesophilic biooxidation typically result in high cyanide consumption. This hybrid biooxidation process uses a mesophile culture to bring about the primary stage oxidation and thermophiles thereafter to realise near complete sulphide oxidation.

This MesoTherm technology has been tollgated through various developmental stages and has shown that cyanide consumption can be reduced by 50% to around 8 kg NaCN/tonne to 10 kg NaCN/tonne from 20 kg NaCN/tonne when compared to the conventional leach consumptions from only mesophile BIOX processing.

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