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THE HPAL PLANTS THAT SNC-LAVALIN BUILT: WHERE ARE THEY NOW?

By

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ABSTRACT

The high-pressure acid leaching (HPAL) process is one of the most effective solutions for extraction of nickel and cobalt in laterite ores due to its leach selectivity for these metals over iron. Historical applications of this technology have been marred by a number of start-up / ramp-up difficulties, challenges, and failures due to the extreme and aggressive operating conditions intrinsic to the process. However, over the years, the technology has evolved to maturity owing to lessons learned, relentless R&D, and the cooperation of equipment vendors, engineering companies, and owners. This has paved the way to overcoming some of the biggest issues in HPAL, and has resulted in progressively more successful HPAL operations.

SNC-Lavalin, a global engineering and construction company with over 100 years of history, is a world leader in the engineering, design, and construction of HPAL plants. The company has been heavily involved in the design, construction, commissioning, and operational support of almost 50% of the global greenfield HPAL plants (including Ambatovy, Coral Bay Nickel Corporation (CBNC) Line 1, Goro Nickel, Gördes, and Bulong) and also actively assisting in process optimisation, troubleshooting, and expansion of other brownfield facilities.

This paper revisits some of the HPAL plants engineered and built by SNC-Lavalin, re-examining some of the pivotal lessons learned, achievements, and improvements, which together are helping to readjust the reputation of the HPAL process in terms of its success potential on future projects.

Keywords: Nickel, Laterite, High Pressure Acid Leach (HPAL), Lessons Learned, Gördes, Ambatovy, Coral Bay Nickel, CBNC L1, SNC-Lavalin

INTRODUCTION

The high-pressure acid leaching (HPAL) process is one of the most effective solutions for extraction of nickel and cobalt in laterite ores due to its leach selectivity for these metals over iron. Historical applications of this technology have been marred by a number of start-up / ramp-up difficulties, challenges, and failures due to the extreme and aggressive operating conditions intrinsic to the process. However, over the years, the technology has evolved to maturity owing to lessons learned, relentless R&D, and the cooperation of equipment vendors, engineering companies, and owners. This has paved the way to overcoming some of the biggest issues in HPAL, and has resulted in progressively more successful HPAL operations.

SNC-Lavalin is global engineering and construction company with over 100 years of experience in end-to-end project delivery (studies to decommissioning) across more than 100 countries worldwide. The company is a world leader in high pressure acid leach (HPAL) technology, having played a major role in its application since its early development for gold pressure oxidation (POX) leaching at Goldstrike, Lonetree, and Twin Creek from the late 1980s until the present(18).

The late 1950s saw the first application of HPAL technology for low-grade nickel laterites at Moa Bay, which used vertical pressure tanks called “Pachucas”. Since then, interest in HPAL technology started to increase due to the steady decline of global sulphide deposits and due to the growing perception that the lower-grade laterite ore was the next major source for global nickel supply. HPAL is the preferred technology for processing lower-grade laterites due to its selectivity to impurities like iron and aluminium that dominate the ore feed and its ability to minimise acid consumption by hydrolysis of these impurities at high temperatures and pressures.

In the late 1990s, the second generation of HPAL plants was built. Three Western Australian plants (Bulong, Cawse, and Murrin-Murrin) revolutionised the application of HPAL technology using a horizontal multi-compartment titanium-clad autoclave vessel based on the concept of brick-lined autoclaves of gold POX application. SNC-Lavalin was on the front line during the engineering and delivery of one of these projects (Bulong), drawing on its broad knowledge and extensive experience in gold POX development.

The second generation HPAL plants proved to be the biggest learning ground due to numerous technical difficulties in start-up and ramp-up, and equipment and material failures typically not encountered in gold POX technology, which involves much lower acidity and lower temperatures. Owners, engineers, and vendors have since pulled together in a relentless pursuit of design and materials improvements, operational practice improvements, and R&D. All combined, these efforts have contributed to significant developments and improved maturity of the HPAL technology.

As an engineering company actively participating in developing optimum engineering solutions for the HPAL technology, SNC-Lavalin has become a world leader in the design and construction of nickel laterite HPAL plants and, to date, has been heavily involved in the design, construction, and support of almost 50% of the global greenfield HPAL plants. The company has the most diverse experience in delivering HPAL plants, which have ranged in size from the smallest to the world’s largest facilities, featured with various downstream processing routes, and been located in some of the most remote and geographically challenging sites in the world.

This paper revisits some of these HPAL plants that SNC-Lavalin has built over the years, updating their current status and recapturing some of the important project developments, technical and operational issues, lessons learned, and operational and design improvements that have all contributed to the maturity of HPAL technology observed today.

THE HPAL PLANTS THAT SNC-LAVALIN BUILT

Since the extensive development of HPAL technology for nickel laterite application in the 1990s, SNC-Lavalin has continued to be actively involved in numerous studies, executions, optimisations, and expansions of laterite projects around the world. SNC-Lavalin's experience in the design and construction of the world's greenfield HPAL plants is presented in Table 1.

Table 1 – HPAL Plants Built by SNC-Lavalin

Operation	Location	Flowsheet*	Capacity Ni tpa	Start-up	Generation
Bulong Nickel Operation	Australia	Mine-HPAL-DSX-EW	9 600	1998	2nd
Coral Bay Nickel L1	Philippines	Ore Stockpile-HPAL-MS	10 000	2004	3rd
Goro Nickel	New Caledonia	Mine-HPAL-DSX-Pyrohydrolysis	60 000	2011	3rd
Ambatovy	Madagascar	Mine-HPAL-MS-Reduction	60 000	2012	3rd
Gördes Nickel	Turkey	Mine-HPAL-MHP	10 000	2014	3rd

* MS = mixed sulphide; DSX = direct solvent extraction; MHP = mixed hydroxide precipitate

Although all the above plants used HPAL technology for leaching, they adopted various ore-processing circuits, which were tailored to the specific characteristics of their ore feed, and selected different downstream processing routes, which were significantly influenced by the technical experience and market requirement of the owner.

The different approaches taken can be summarised as follows:

- Bulong prepared their ore by oversize rejection and fines recovery through scrubbing (log washer). Bulong pioneered the recovery of nickel and cobalt by direct solvent extraction (DSX), which proved to be one of the biggest bottlenecks of their operation due to gypsum saturation within the solvent extraction circuit. The final product was a nickel cathode and a mixed cobalt sulphide. While Bulong did finally manage their process bottlenecks and mechanical problems, the plant was eventually closed in 2003 after it lost its acid supply from WMC and could not source an alternative cheaper source(27).

- Coral Bay Line 1 uses the same ore preparation flowsheet as Bulong but scrubbing is performed in drum washers. The plant uses the Sumitomo's MS (mixed sulphide) technology and produces intermediate MS product for shipment to their overseas refinery.

- Vale New Caledonia (Goro Nickel) has two ore types, namely limonite and saprolite, each handled by a separate crushing stream. Barren oversize is rejected by screening, fines are recovered by scrubbing, and middlings are recovered by a comminution circuit. Vale has adopted several of their patented novel technologies for nickel and cobalt recovery in the HPAL and downstream refining process. The facility produces three main product streams: NiO spheres, nickel hydroxide cake (NHC), and a $CoCO_3$ precipitate by-product.

- Ambatovy crushes their coarse ore in the feed, recovers the fines by scrubbing, and rejects the barren oversize by screening. The metal recovery and refinery is designed after Sherritt's established refining technology at Fort Saskatchewan (Canada) and from their experience as technology provider for Murrin Murrin (Western Australia). Ambatovy produces LME Class I nickel and cobalt briquettes and an ammonium sulphate fertiliser by-product.

The majority of HPAL laterite plants worldwide have experienced various levels of technical difficulties during commissioning and start-up, leading to slow ramp-up, poor operational reliability, and financial difficulties. This in turn has led to financial write-downs, changes of ownership, and ultimately closures. Combined with the high capital costs associated with HPAL, this assortment of problems has contributed to a negative perception of the technology, earning it a reputation as the "bad boy poster child" of nickel hydrometallurgy processing.

While this negative reputation stuck with the second generation plants, the mining industry is now recognising the various relative levels of success being achieved in the succeeding generation (represented by Coral Bay, Taganito HPAL, and Ambatovy). Progress has largely been due to design improvements, successful application of lessons learned from the second generation, and owners' operational excellence. SNC-Lavalin has played a major role in the evolution of the technology and has been instrumental in slowly changing the image of HPAL within the industry. Successful HPAL technology application has been demonstrated in the fast ramp-up of Coral Bay Nickel L1 and the major progress observed in Ambatovy several years after start-up. SNC-Lavalin was involved in the engineering and design for both of these plants.

Figure 1 presents the ramp-up performance of the HPAL plants built by SNC-Lavalin along with the rest of worldwide operating HPAL plants. The current status of some of these plants is presented and discussed in the following sections.

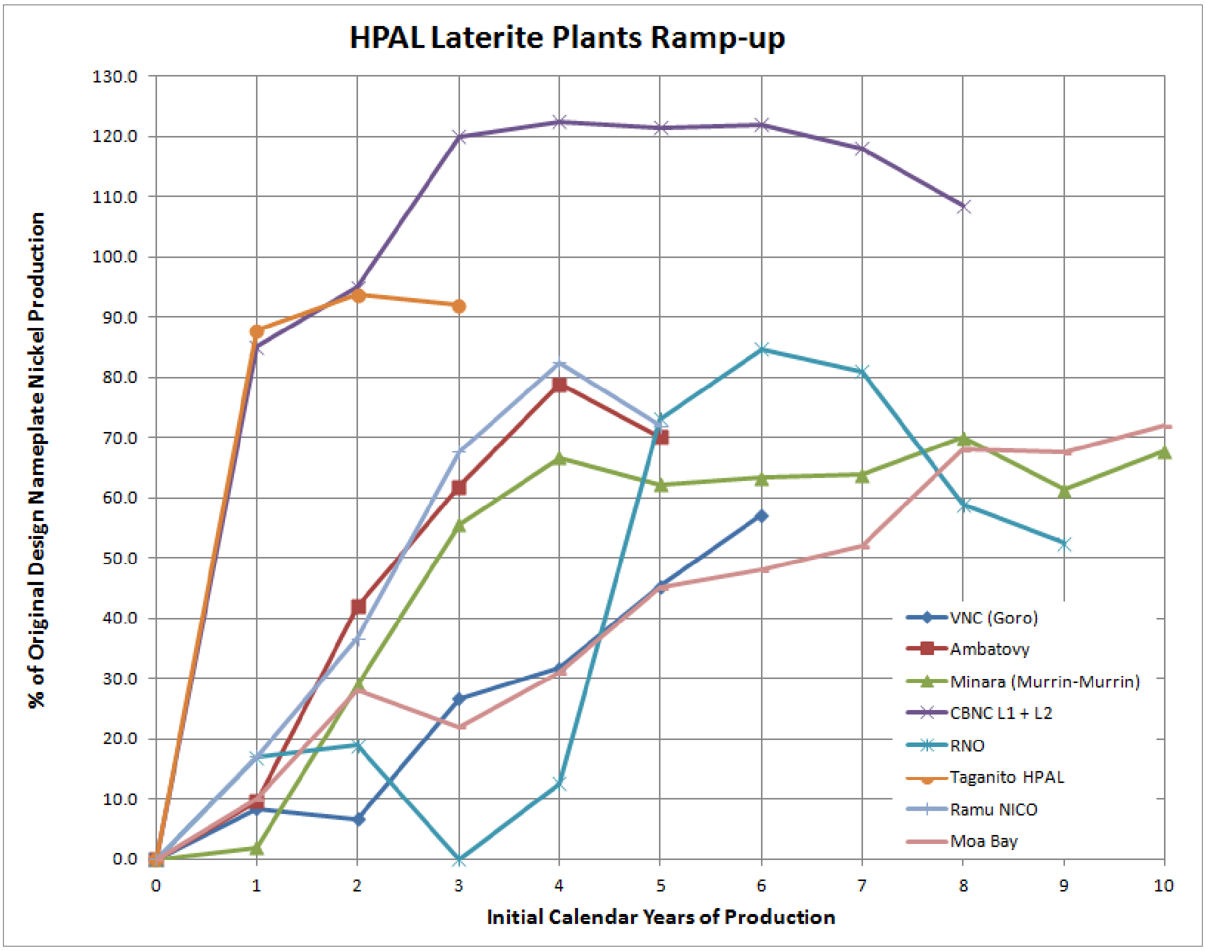

Figure 1 – HPAL Plants Ramp-up [2-10]

GÖRDES NICKEL COBALT HPAL PROJECT

The Gördes Nickel Cobalt HPAL Project, located in Gördes, Manisa (Figure 2), is the only HPAL operation in Turkey. The project is owned and operated by Meta Nikel Kobalt A.Ş. (Zorlu Group) with an initial capital investment of around US$360 million(33). Meta Nikel Kobalt A.Ş. owns a total of 15 mining leases, with a total Measured and Indicated Resource of about 15 Mt (~ 1% Ni at 0.4% Ni Cut-off Grade) that supplies ore to the Gördes HPAL plant.

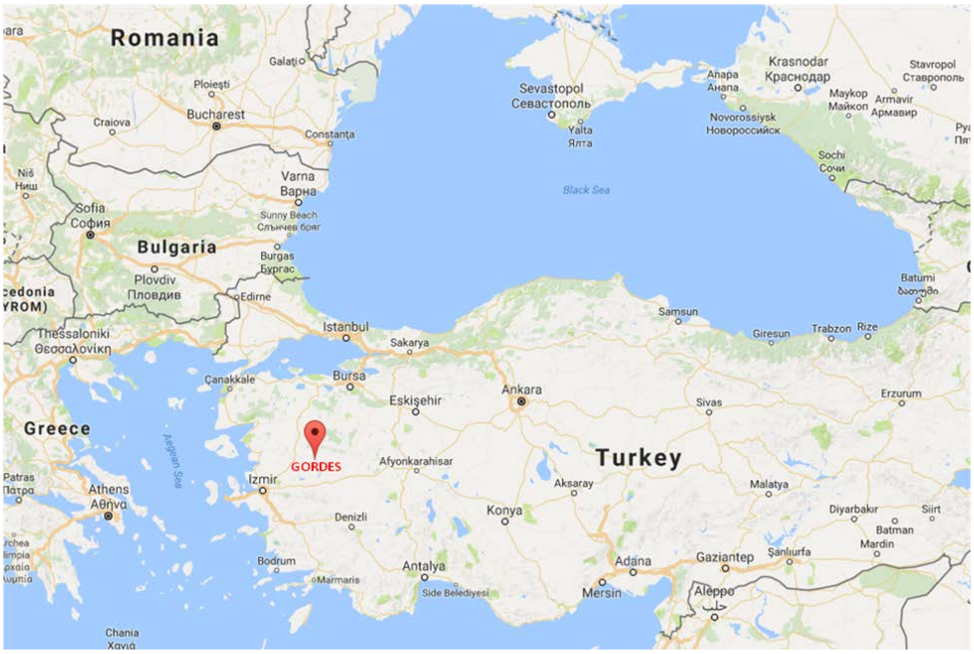

Figure 2 – Gördes Nickel Cobalt HPAL Project Location

The process plant (Figure 3) was designed to process a run-of-mine (ROM) laterite blend of 1% Ni and 0.06% Co to produce around 10 000 tpa Ni and 750 tpa Co in mixed hydroxide product (MHP) intermediate (38-40% Ni, 2-3% Co, 45-55% moisture) via the proven HPAL-MHP processing route (Figure 4). This is the Phase 1 of the total project(1).

Figure 3 – Gördes Nickel Cobalt Process Plant *(Photo courtesy of Meta Nikel Kobalt A.Ş.)*

The process flowsheet for Gördes includes an ore preparation circuit consisting of fines scrubbing and barren oversize rejection by screening. The slurry is then thickened to around 38 %w/w solids for HPAL feed. Nickel and cobalt are selectively leached from other impurities by the HPAL process at 255°C and 5 MPag in a 6-compartment autoclave measuring 5.2 m diameter x 27 m length tan/tan. The free acid in the leached slurry is neutralised by the addition of limestone in the subsequent primary neutralisation prior to solid-liquid separation in a 6-stage counter-current decantation (CCD). The impurities in the pregnant liquor overflow (O/F), particularly iron and aluminium, are mostly removed in the secondary neutralisation by hydroxide precipitation with limestone. The precipitate slurry is recycled to primary neutralisation for recovery of the co-precipitated and entrained nickel and cobalt.

The impurity-free pregnant leach solution (PLS) is sent to the MHP Precipitation Stage 1 for recovery of nickel and cobalt as MHP product by precipitation with magnesia. Residual nickel and cobalt in the solution are further recovered in the succeeding MHP Precipitation Stage 2 by precipitation with lime. The recovered slurry is recycled to the primary neutralisation for re-leaching while the barren solution is treated with lime to remove the manganese prior to tailings disposal. The final tailings from the CCD underflow (U/F) are treated with lime to precipitate the heavy metals as per environmental regulations prior to tailings disposal with the treated barren solution.

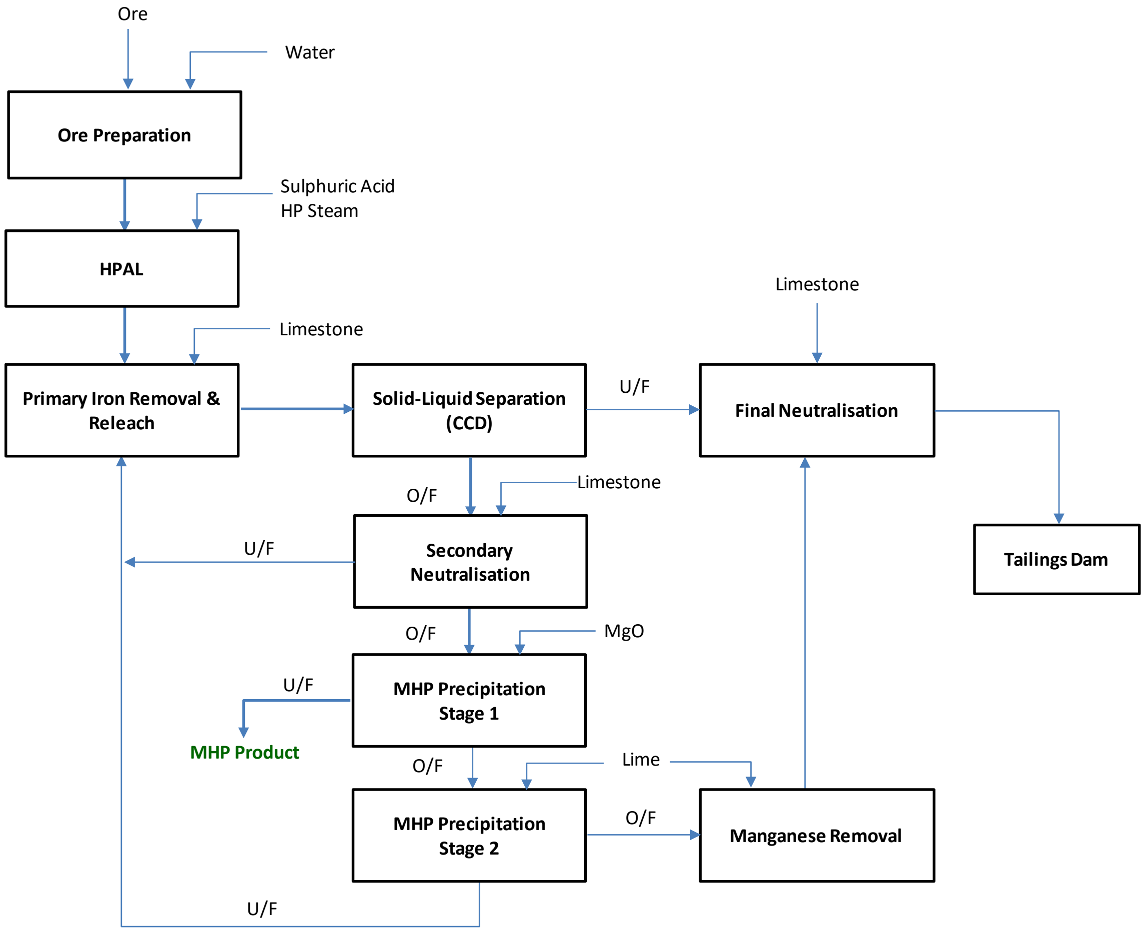

Figure 4 – Gördes Process Flowsheet

The MHP intermediates produced at Gördes have an average composition shown in Table 2. The product is packaged in a 1m^3 bulk bag for shipment to the market.

Table 2 – Gördes MHP Average Product Composition (%w/w)

Moist.	Ni	Mn	S	Co	Mg	Fe	Zn	Si	Al	Ca	Cu	Cr
45-55	37-40	4.5-6	4.5-5	2-2.5	1.5-2.5	1.5-2.3	0.5-0.7	0.4-0.5	0.3-0.5	0.2-0.3	0.1-0.2	0.06-0.01

Engineering and Start-up

Meta Nikel Kobalt A.Ş. awarded SNC-Lavalin the mandate for front end engineering design (FEED), detail engineering, procurement of long-lead and critical equipment, and technical support services (for commissioning and start-up) for the Gördes Project in 2011. SNC-Lavalin has also been involved in providing technical support for the process plant debottlenecking and modifications.

The Gördes Phase 1 construction began in 2012 and its mechanical completion was achieved in the beginning of Q3 2014, followed by commissioning completion in the late Q4 2014. Plant ramp-up began in Q1 2015. First production of MHP was achieved on March 15, 2015 and Gördes subsequently shipped its first product to the market in May 2015.

Like all HPAL start-ups, Gördes encountered their share of challenges and issues during commissioning and ramp-up. Some of the major problems were:

- Poor mass and nickel recovery in ore preparation – caused by the short-circuiting of the ore in the drum scrubber due to lack of retention time. This resulted in poor de-agglomeration, with the majority of nickel-bearing fines being reported to the rejects stream. The poor mass recovery in the ore preparation circuit effectively created a bottleneck in the downstream HPAL operation, frequently starving the circuit of slurry feed even during turndown operations. In July 2015, a first major shutdown was conducted, and through a series of analysis and vendor collaborations, intensive equipment modifications were carried out including the replacement of a larger-sized drum scrubber.

- Problems with heater feed pumps (both duals and triples) – attributed to the ore characteristics (particle size and composition), pump type, and material selection (not the hardest and thus not suited for the erosive characteristics of the slurry). Many shutdowns were required to rectify this issue. Replacement of selected pumps by more appropriate design, made of abrasion-resistant material, as well as diligent equipment monitoring significantly improved the performance of the feed pumps.

- Poor pH control system – unsuitable probes for high-temperature application, wrong locations, and process problems such as scaling, caused erroneous reading and resulted in poor pH control in various operation processes. Poor control directly affects overall production efficiency.

Gördes Now

At present, Gördes is ramping up steadily, with the aim to demonstrate a long-term operation of 100% capacity by the end of 2017. Process optimisation is being done in parallel, particularly in reducing the moisture contained in the MHP product to increase the payable metals per tonne and minimise the shipping and transport cost. Gördes also plans to install an additional MHP pressure filter to improve the operability of the circuit. It was apparent during the early periods of ramp-up that achievable moisture content of the MHP is around 45-55 w/w% (versus 25 w/w% target as per design). This has created a bottleneck for the area as the current capacities of the filter presses are not sufficient to continuously service the filter feed tank.

Gördes is also actively developing a value-adding stream to recover scandium in the leached slurry as a by-product. A number of studies and benchscale testworks are being investigated to assess the viability of the process.

Meta Nikel Kobalt A.Ş. plan to double the capacity of Gördes process plant to 20 000 tpa Ni and 1 500 tpa Co and to extend the refining to LME Class I finished products after the ramp-up and sufficient skills/operational learning from the Phase 1 plant. The Phase 2 expansion will be a twin line of HPAL-MHP plant with an addition of an on-site refinery (either SX-EW or SX-nickel/cobalt chemical plant). The Phase 2 construction is aimed to be implemented in the future.

AMBATOVY

The Ambatovy Joint Venture (JV) is a world-class integrated nickel and cobalt mining and processing enterprise located in Madagascar, on the southeast coast of Africa (Figure 5). The operation has an annual design capacity of 60 000 tonnes of nickel (in nickel briquettes) and 5 600 tonnes of cobalt (in cobalt briquettes) and 210 000 tonnes of ammonium sulphate fertiliser, which makes it the largest LME Class I nickel and cobalt operation from laterite ore in the world. The estimated life of the operation is approximately 29 years(12).

Figure 5 – Ambatovy JV Project Location(15)

Ambatovy represents one of the biggest and most successful undertakings of SNC-Lavalin Mining & Metallurgy. SNC-Lavalin had a long involvement with Ambatovy starting from the feasibility stage in 2007 until the project achieved its financial completion in 2015, a significant milestone for the project. In terms of complexity and cost, the project is comparable to large-scale international infrastructure megaprojects such as the upgrade of Panama Canal (a US$5+ billion undertaking).

The design and construction of a self-sustaining, integrated mine and process plant complex on the remote island of Madagascar provided a number of unique project management, engineering, and procurement challenges that were successfully managed through SNC-Lavalin's competence, expertise, and integrated database systems. The successful management of this complex project was recognised by the Association of Canadian Engineering Companies in 2014 when SNC-Lavalin was granted an "Award of Excellence in Project Management" for its work on the Ambatovy Project(15).

Project Development

The Ambatovy Project has a long history of development dating back to 1960 when the Malagasy Service Géologique carried out an exploration of the Ambatovy mining area. Mining rights were granted in 1995, and significant environmental and engineering studies were conducted from 1995 to 2001. In 2003, Dynatec Corporation signed a JV agreement with subsidiaries of Phelps Dodge to evaluate the Ambatovy Project. Dynatec then became extensively involved in the development of the project, including process selection and pilot plant testing in Fort Saskatchewan.

Dynatec acquired 100% of the project in 2005 and a JV between Dynatec, Sumitomo Corporation, Korea Resources Corporation (KORES), and SNC-Lavalin was formed shortly thereafter to provide funding for further development. SNC-Lavalin was responsible for engineering, procurement, and construction management of the commercial facilities. Sherritt International Corporation reacquired Dynatec Corporation, including 40% ownership in the Ambatovy Project, in 2007. In September 2015, SNC-Lavalin sold its interest to Sumitomo Corp(11). In May 2017, the entire Ambatovy JV was restructured, with the current partnership consists of Sherritt (12% owner and mine and plant operator), Sumitomo Corporation (47.7% owner) and KORES (40.3% owner)(34).

In 2006, Ambatovy received a 40-year mining permit from the Government of Madagascar. Construction subsequently began in 2007 and was completed in 2011 within its budget of US$5.5 million(14,29).

Commissioning and start-up of the Ambatovy mine and plant facilities began in 2010 and were completed in 2012, with acid from the on-site acid plant first introduced to the ore leach in March 2012 and test nickel briquettes first produced in the refinery on June 26, 2012.

Commercial production (defined as 70% of design capacity) was achieved in January 2014 and the production level required to achieve financial completion (90% of design capacity for 90 days) was achieved in March 2015(11,12). Ramp-up of the facilities to nameplate capacity is on-going (Figure 1).

The Ambatovy Project is composed of the following major integrated facilities(12)

- **Mine** – consists of two large, weathered lateritic nickel deposits (the "Ambatovy Deposit" and the "Analamay Deposit") located approximately 3 km apart. Combined, the two deposits constitute one of the world's biggest lateritic nickel reserves, covering an area of about 1 600 ha, with depths ranging between 20 and 100 m.

- **Ore Preparation Plant** – rejects the barren oversize and slurries the laterite ore for HPAL feed. The slurried ore is pumped to the process plant via a 220-km pipeline that links the mine site and the process plant.

- **Process Plant** – consists of 2 major areas: PAL (pressure acid leach), which includes 5 trains of HPAL, to extract the nickel and cobalt from the ore, and a refinery to recover the metal values as Ni and Co briquettes and an ammonium sulphate by-product. The process plant is shown in Figure 6.

- **Sulphuric Acid Plant** – includes 2 trains of 2 750 tpd sulphur-burning acid plant with a heat recovery system and acid tank storage equivalent to 10 days of 100% operation.

- **Power Plant** – includes 3 trains of coal-burning power plant which generates steam and electricity for the operations.

- **Other Reagents and Utilities** – includes three H_2S plants, an H_2 plant, an air separation plant, lime and ground limestone plants, and a water treatment plant.

- **Port** – consists of an upgraded Port of Toamasina, which is now capable of handling 275 000 tpa nickel, cobalt, and ammonium sulphate products for export and 3.5 Mtpa of imported commodities required by the plant.

- **Tailings Storage Facility (TSF)** – facility where treated and stable residue is permanently impounded, and subsequent decant water is recycled back or sent for marine disposal.

Figure 6 – Ambatovy Process Plant *(Photo from Ambatovy website)*

Process Flowsheet[11]

The leaching process at Ambatovy (Figure 7) is very similar to that in Moa Bay, Cuba. Both the leaching and nickel-refining processes are very similar to those used at Murrin Murrin, Australia. In the HPAL plant, ore slurry received from the pipeline is thickened and then fed along with sulphuric acid to the HPAL autoclaves. After HPAL, the leached slurry is partially neutralised with limestone (slurry neutralisation) followed by a CCD wash, which separates the nickel- and cobalt-bearing solution from the residue. Sulphuric acid in the CCD product solution is further neutralised with limestone in the raw liquor neutralisation circuit. The neutralised raw liquor is then contacted with hydrogen sulphide in the sulphide precipitation circuit, and the solids washed to produce a clean mixed sulphide intermediate, containing the nickel and cobalt that was leached from the ore. The barren liquor from sulphide precipitation is partially neutralised with limestone before being used to wash the leached ore slurry in the CCD circuit. Excess, partially-neutralised barren liquor is combined with the washed leach residue, further neutralised with limestone and lime, and directed to the tailings management facility.

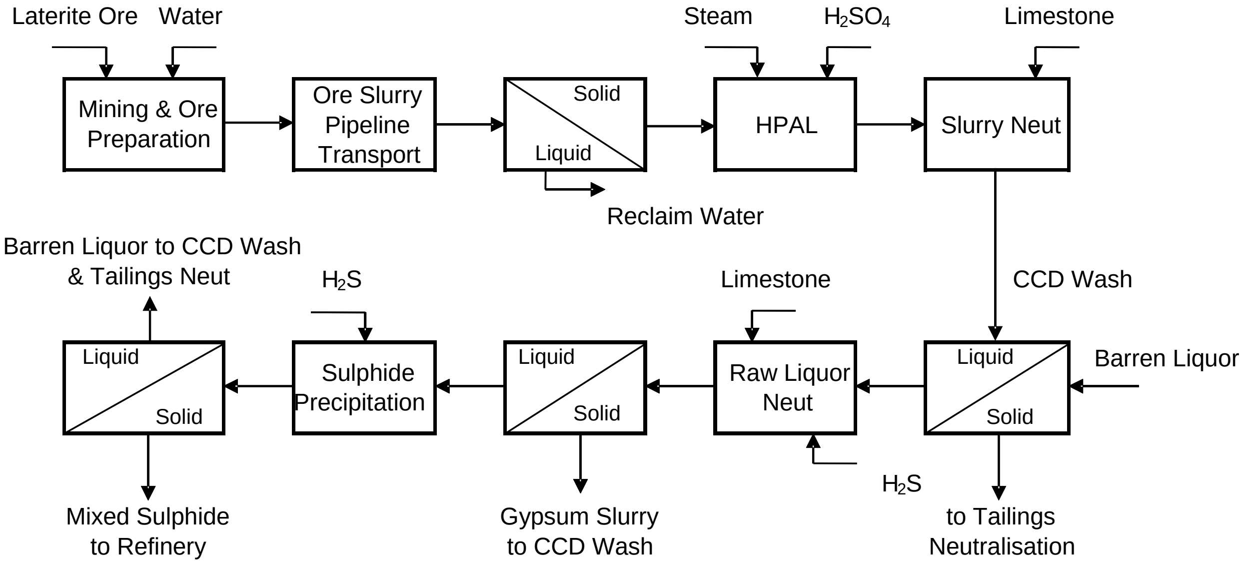

Figure 7 – Process Flowsheet for the Ambatovy Pressure Acid Leach Plant

In the adjacent refinery process (Figure 8), nickel and cobalt in the mixed-sulphide intermediate produced in the PAL plant are re-leached into solution, iron and copper are separately precipitated from solution, zinc is removed by solvent extraction (SX), and nickel and cobalt are separated by solvent extraction before being separately precipitated as metal powders by hydrogen reduction, and formed into briquettes for sale. Ammonium sulphate fertiliser is also recovered in the refinery, as a by-product of the process.

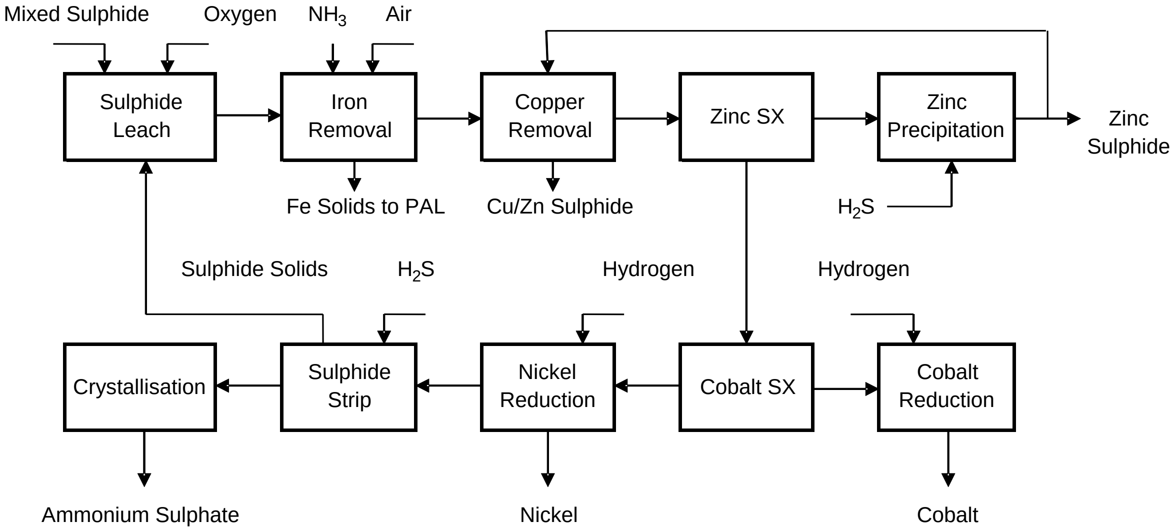

Figure 8 – Process Flowsheet for the Ambatovy Refinery

Project Ramp-up

Of the three large and integrated mine-to-metal greenfield operations (Ambatovy, Murrin Murrin, and Goro Nickel), Ambatovy had the fastest ramp-up so far within 4 years from start-up (See Figure 1). However, as with most HPAL operations, the start-up experienced a number of design, materials, and operational issues resulting in below-expected production results in Year 1-2. Some of these issues are discussed in the following subsections.

In Year 3, Ambatovy approved the inception of the PEI (Performance Enhancement Initiative) team to solve process and equipment bottlenecks, particularly in critical areas of HPAL operations. The PEI team was composed of individuals from Sherritt Technologies, SNC-Lavalin and independent consultants with deep technical and operational know-how from similar pressure hydrometallurgical operations. The collective effort of the PEI and HPAL operations team resulted in a significant 20% production increase in Year 4.

In the same year, the project achieved a long-term demonstration of designed-capacity operation (more than 90% average capacity over 90 days of continuous run) and LME product specification for nickel. The contribution of the PEI team to the successful ramp-up of Ambatovy was documented in a technical paper presented to ALTA 2016(11).

Start-up Challenges

The first three years of Ambatovy operations faced challenges similar to those encountered by most HPAL operations. A number of design and operational challenges were encountered during operations ramp-up. However, many of these design challenges were effectively corrected in the first two years of operations and problem areas were debottlenecked during the PEI involvement in the 4th year, paving the way to successful ramp-up and Financial Completion in 2015.

The initial operational ramp-up issues in Ambatovy is listed here by area:

Ore Thickening

- Repeated failure of the ore thickener rake (design inherent) such as rake misalignment.
- Lack of feed-slurry dilution in the thickener, resulting in poor compaction, high bed levels, and low underflow densities.

- Improper thickener operation, lack of bed-control instruments (bed pressure and bed-level measurements), and sensitivity of torque-control logic often led to frequent bogging of the 80-m diameter thickener.
- Isolated autoclave feed tank for each train limited the overall buffer capacity.

HPAL

- Cavitation in the GEHO® pumps caused by insufficient net-positive suction head available (NPHSa) due to a combination of low solids density, pressure loss in the pipes, and lower feed-heater elevation. Low solids density also caused shorter expected mean-life-before-failure of cone valves.
- Repeated failure of the autoclave agitator seal systems leading to the loss of barrier fluid and flush water. This impacted two trains at a time as two trains share one common seal system (Train 1 and 2, Train 3 and 4).
- Leaking of flashed-steam lines due to high carryover of acid and particulates and high pipeline velocities brought by high amounts of flashed steam (especially at low solids density feed at high rates). Lengthy line repairs impacted two trains at a time due to shared scrubber system (Train 1 and 2, Train 3 and 4).
- Repeated premature failure of the autoclave isolation valves and HP letdown valves due to insufficient overpressure from the autoclave and inadequate supply and control of choke solution, particularly during turndown operations.
- Materials failure such as frequent leaks in the rubber-lined flash-seal-tank discharge lines (to pre-neutralisation tanks).
- Repeated failure of triple heater-feed pumps during change-over or start-up due to backflow and thermal shock.

Pre-Neutralisation and CCD

- Multiple leaks on rubber-lined pre-neutralisation tanks.
- Frequent slurry overflow of all CCDs due to poor process control and poor thickener operation. This resulted in massive excursions of iron, silicon and calcium all the way through to the refinery in 2013, slowing down the entire production for about 3 months.
- Clogging of flocculant lines due to the use of dirty overflow for secondary flocculant dilution.
- Frequent bogging of CCD thickeners due to low torque capacity, poor thickener operation, and lack of process control instrumentation such as bed pressure, rake pressure, and bed-level measurement.
- Materials failure – multiple leaks and peeling of fibreglass liners of the thickeners.
- Multiple failures of mixing tank agitators due to insufficient support.

Raw Liquor Neutralisation

- Material failure – leaks due to rubber-lining damage during de-scaling.
- Bogging of the thickeners due to problems with discharging solids to the underflow.
- Clogging of flocculant lines due to the use of dirty overflow for secondary flocculant dilution.
- High solids carry-over in the O/F due to poor thickener operation and process control.
- Frequent thickener overloading due to poor process control of limestone and seed addition.

Mixed Sulphide Precipitation

- Material failure – frequent leaks on rubber lined pipelines.
- Sulphur buildup on H_2S lines limiting the gas flow.
- High rate of pipe erosion in the recovered steam line from HPAL and constantly fluctuating pre-heater pressure subject to stability of HPAL operation.

Design and Operational Improvements

During the first few years of Ambatovy operations, a number of design and operational improvements were implemented, significantly increasing the efficiency and performance of the overall plant over the following years. The majority of these improvements were discussed in more details in the previous technical paper presented by SNC-Lavalin and Sherritt Technologies in ALTA 2016(11). The improvements, listed here by area, can be summarised as follows:

Ore Thickening

- The ore thickener rake was modified with improved and stable torque cage and stabiliser. Rake torque logic was also modified to improve the control of the bed pressure and bed level.
- A forced dilution system was installed to improve the dilution of the incoming feed. This resulted in better flocculation and in the achievement of target underflow density.
- Dedicated HPAL slurry-feed tank for each train was fitted with interconnecting lines providing flexibility and improving the overall buffer capacity of autoclave slurry feed.

HPAL

- Proper control of inert gas in the vent of heaters provided the necessary overpressure required by the GEHO® pumps. Coupled with improved solids, cavitation was significantly reduced.
- Proper control of inert gas in the heaters and autoclave (especially on reducing ore feed) and the relocation of the autoclave isolation valve several meters away from the autoclave discharge eliminated incidents of premature flashing and significantly improved the life of the autoclave isolation valves and the Caldera letdown valves. Caldera also trialled a flat plug which has an improved life (compare to parabolic) due to reduction of surface area exposed to sonic velocities.
- Modification of the agitator seal system with an additional water-filtration system, instrumentation, and control loop improved the performance of the seal system. Tie-ins between 3 seal systems were also added to provide flexibility.
- Rubber-lined autoclave discharge pipes were replaced with a cross-linked polymer (PexGol™) and continuous pipe (minimum flanging) which is more reliable and appropriate for hot, acidic slurries.
- The combination of design and operational improvements increased the mechanical availability of the HPAL area while the overall area utilisation also increased.

Pre-Neutralisation & CCD

- Alloy relining of all rubber-lined pre-neutralisation tanks eliminated the occurrence of leaks.
- Establishment of process control parameters, critical instrumentations, and improvement in operating practice, all contributed to the stability of the CCD circuit. Overflow total suspended solids (TSS) was dramatically reduced (from >1 200 ppm to <200 ppm) and U/F solids were increased (from ~35 %w/w to >40 %w/w) across all CCD thickeners. These improvements positively impacted the subsequent downstream processing and overall metal recovery.
- Rubber lining was installed in the lead thickeners and epoxy coating in the others.
- Provision of clean reclaimed water as backup for secondary flocculant dilution and addition of forced dilution system on the lead CCDs contributed to improvement in flocculation.
- The mixing tank agitator was removed.

Raw Liquor Neutralisation

- The dual trains at Ambatovy were valuable in implementing process debottlenecking and optimisation in a timely and effective manner. Adjustments were made in one train while the other was kept as a baseline. The overall internal and external impact to the system was kept at a minimum while results were achieved in a timely and reliable manner.
- Establishment of process control parameters, critical instrumentations, and improvement in

operating practice, all contributed to the stability and achievement of design conditions in the raw liquor thickeners. This was a monumental improvement since reduction of carryover impurities to the downstream MS circuit meant achievement of the product specifications through to the final product in the refinery.

- Addition of dedicated thickener U/F lines and tie-ins to each train provided operational flexibility and eliminated the incident of rake bogging.
- Alloy re-lining of all rubber-lined raw liquor neutralisation tanks eliminated the occurrence of leaks.
- Provision of clean process water as backup for secondary flocculant dilution eliminated clogging of the flocculant lines.

Mixed Sulphide Precipitation

- Establishment of process control parameters, critical instrumentations, and improvement in operating practice, together contributed to the stability of the MS thickener operation and minimised the nickel loss to the TSS.
- Retrofitting of smaller U/F pumps in the MS wash thickeners enabled continuous operation (instead of batch), thereby eliminating the occurrence of frequent overflow and H_2S alarms. Solids densities were also increased with the improved operations, minimising the required wash water and overall MS area water balance.

General Design Improvements (since 2nd generation)

- A twin sulphur-burning acid plant provided Ambatovy a greater flexibility and protection of the overall sulphuric plant considering the frequent stoppages and low availability of the HPAL circuit during the first 3 years of ramp-up.
- The production of a stable intermediate MS product decoupled the link between PAL and the refinery, providing flexibility for one section to operate continuously while the other is unavailable and vice versa.
- Ambatovy's SX circuit in the refinery is probably the most robust and reliable of all unit areas (and in comparison to other SX operations). Organic cross-contamination was never an issue since only one organic type was used for various extractions (Zn SX and Ni-Co SX).

Ambatovy Now

The Ambatovy ramp-up took a slight step back last year due to multiple pipe and equipment replacements necessitated by expected wear. Annual production decreased by 9%(13). The raw liquor neutralisation area flocculant trial recommended by the PEI team in 2015 was proven to be a success in terms of thickener performance improvement and flocculant demand optimisation. The plant is still continuing to optimise process control parameters particularly in the acid, H_2S, and lime consumption, which will contribute to a significant reduction of the overall operating cost.

Important milestones achieved in year 2015, namely the financial completion, LME grade registration for Ni, and 93% monthly Ni nameplate capacity (August 2015), demonstrated the importance of a strong dedicated technical support team to the successful ramp-up and operation of a large, complex hydrometallurgical plant such as at Ambatovy(11).

Ambatovy is currently continuing its steady ramp-up, a reflection that it had already overcome its major bottlenecks. It is poised to achieve a target of 48 000 to 52 000 of finished nickel (or 80-87% of nameplate capacity) this year(13).

CORAL BAY NICKEL PROJECT

The Coral Bay Nickel Project is the first HPAL laterite operation and a world-class hydrometallurgical facility in Asia. It is located in Palawan, Philippines (Figure 9). The plant (Figure10), along with its sister company Taganito HPAL (THPAL) are one of the few "economically and technically successful" laterite HPAL plants in the world to date. Both are owned and operated by Sumitomo Metal Mining (SMM). Coral Bay Nickel Corporation (CBNC) is a JV of Sumitomo Metal Mining (54%), Rio Tuba Nickel Mining Corporation (RTNMC) (10%), Mitsui (18%), and Sojitz (18%)(16).

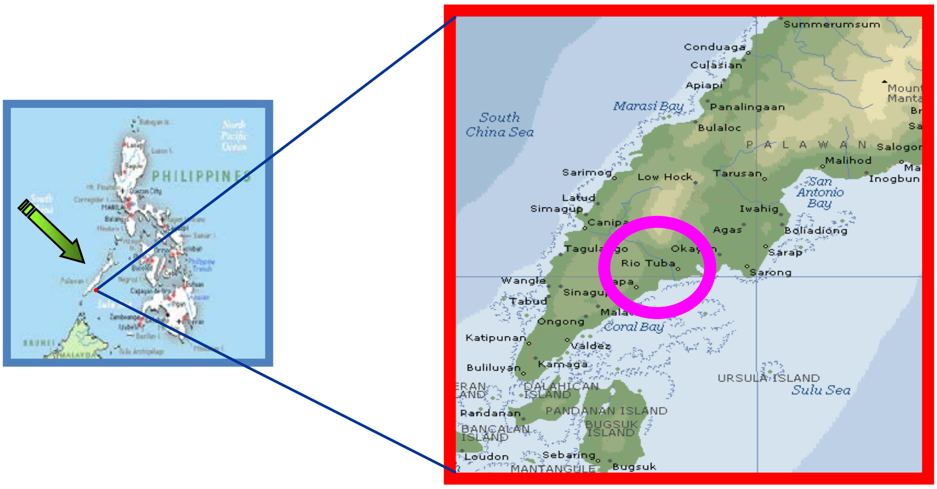

Figure 9 – Location of Coral Bay Nickel Project(16)

Figure10 – HPAL Section of the Coral Bay Nickel L1 Project *(Photo Courtesy of CBNC)*

The total Coral Bay Nickel Project is a strategic execution of two independent (but interconnected) HPAL processing plants, with each line designed to produce 10 000 tpa Ni and 750 tpa Co in mixed sulphide product via the HPAL – MSP route from low-grade laterite stockpiles. The overall Coral Bay Nickel operation produces 20 000 tpa Ni and 1 500 tpa Co in mixed sulphide (MS) products, which are shipped to SMM's Niihama Nickel Refinery (NNR) in Japan for further processing into nickel and cobalt cathodes and nickel and cobalt chemical products(17).

Process Flowsheet(17)

The CBNC process flowsheet includes eight major proven process steps, from ore processing to MS production, as shown in Figure 11.

In ore preparation, certain proportions of three types of ore feed are fed into the two trains of the ore preparation circuit, where barren oversize are rejected by stages of screening and agglomerated nickel-bearing fines are recovered from the coarse by scrubbing. The -1.4 mm size is recovered as slurry by wet screening and sent to a thickener, where blending occurs and solids content is increased to ~45 %w/w.

The ore slurry is sent to the HPAL circuit through three stages of preheating to 200ºC prior to pressure leaching. Nickel and cobalt are selectively extracted in the autoclave, with sulphuric acid addition under high temperature (245ºC) and high pressure (4 MPag) operating conditions. The leached slurry from the autoclave is cooled down and depressurised to 100ºC and atmospheric conditions through three stages of flashing.

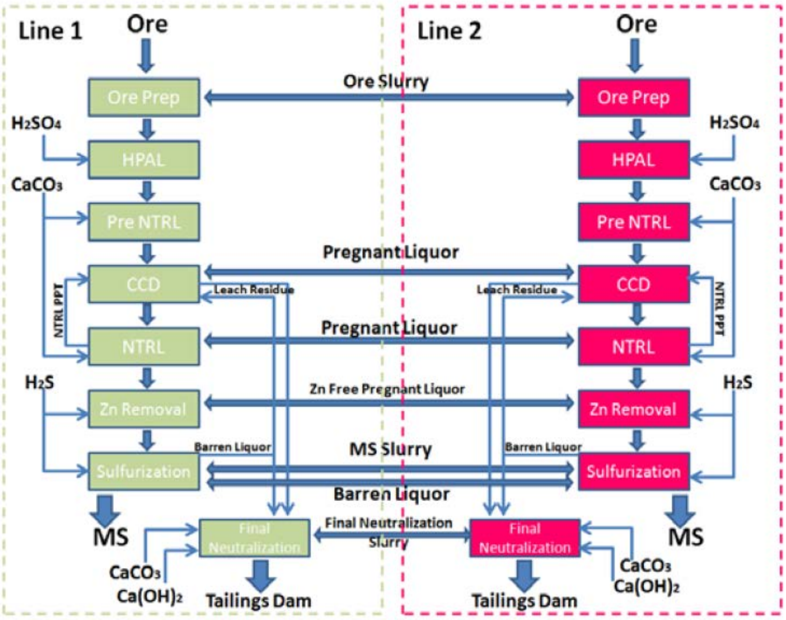

Figure 11 – CBNC L1 + L2 Flowsheet(17)

The free acid in the leached slurry is neutralised by limestone addition in the pre-neutralisation tanks prior to solid-liquid separation in the CCD circuit. The leach residue is washed with MS barren liquor in a counter-current fashion in the seven stages of CCD.

The pregnant liquor solution from CCD 1 overflow is forwarded to the neutralisation area, where limestone is added to precipitate impurities like iron (Fe^{3+}), chromium (Cr^{3+}), and aluminium in the PLS. The precipitate is sent back to the CCD to recover the entrained and co-precipitated nickel and cobalt.

Prior to MS precipitation, the pregnant solution is further removed of impurities such as zinc by H_2S injection in the de-Zinc circuit. Zinc is preferentially precipitated by controlling the pH (3.0 - 3.5) and temperature (<60ºC) at atmospheric conditions.

The impurity-free PLS is then sent to a mixed sulphide (MS) circuit, where nickel and cobalt are selectively precipitated and recovered from the solution by H_2S under low temperature (80ºC) and low pressure conditions (100 to 200 kPag). The MS precipitate is then dewatered to 85% solids and packaged in bulk bags for shipment to NNR. The barren liquor is recycled to the CCD circuit as wash water and a portion is bled to the final neutralisation for tailings treatment along with the CCD 7 underflow.

In the final neutralisation, limestone and lime slurry are added to neutralise any remaining free acid and to precipitate heavy metals into a stable form at pH 8 prior to disposal to the tailings dam. One of CBNC's critical environmental discharge criteria is the reduction of Mn in the solution to <10 ppm (undiluted) in the final neutralisation, as part of the tailings decant that is being discharged to the sea.

Project Development and Ramp-up(16-20)

The CBNC Line 1 Project development was relatively short but well defined and carefully thought out. It only took five years for SMM to develop the project from conception in year 2000 to first production in year 2005(16). SNC-Lavalin was engaged by SMM early on in the project until its full implementation in 2002. SNC-Lavalin was selected by SMM and JGC (the main contractor on the project) for its wide experience with pressure leaching in gold (POX) and execution of Bulong Nickel Project. Below are the key project milestones:

- July 2000 – SMM and Rio Tuba Nickel Mining Corporation (RTNMC) undertook joint investigation of the Rio Tuba stockpiled laterite ore through a PFS.

- July 2001 – SNC-Lavalin and JGC undertook the delivery of a feasibility study, where SNC was a subcontractor to JGC. The scope of work included interpretation of the testwork results conducted at Dynatec (2001), development of the process flowsheet and equipment, along with the capital and operating cost estimates for HPAL and utility facilities.

- June 2002 – SNC-Lavalin and JGC undertook a Bankable Feasibility Study (BFS), where SNC delivered the basic engineering for key areas such as HPAL, De-Zn, and MS as sub-contractor to JGC. SNC-Lavalin also interpreted pilot test results conducted in SGS Lakefield and NNR, which was integral to the finalisation of the design criteria for the project.

- August 2002 to August 2004 – JGC was appointed the EPC contractor with SNC-Lavalin as a subcontractor responsible for the delivery of detailed design and bid review/selection of critical equipment for the key areas mentioned. Construction commenced in January 2003 and mechanical completion was achieved in August 2004, one and a half months ahead of schedule.

- September 2004 to April 2005 – Pre-commissioning and commissioning, where SNC-Lavalin provided the development of operation and commissioning procedures and site support during these periods. First MS production as achieved on Dec 2004 and the process plant was formally inaugurated for commercial production in April 2005.

- November 2005 to March 2006 – Achievement of a demonstration of long-term operation at >95% capacity and 110% production (Figure 12).

- Year 2007 – Nameplate capacity of 100% annual production or 10 000 tpa Ni was achieved (Figure 13).

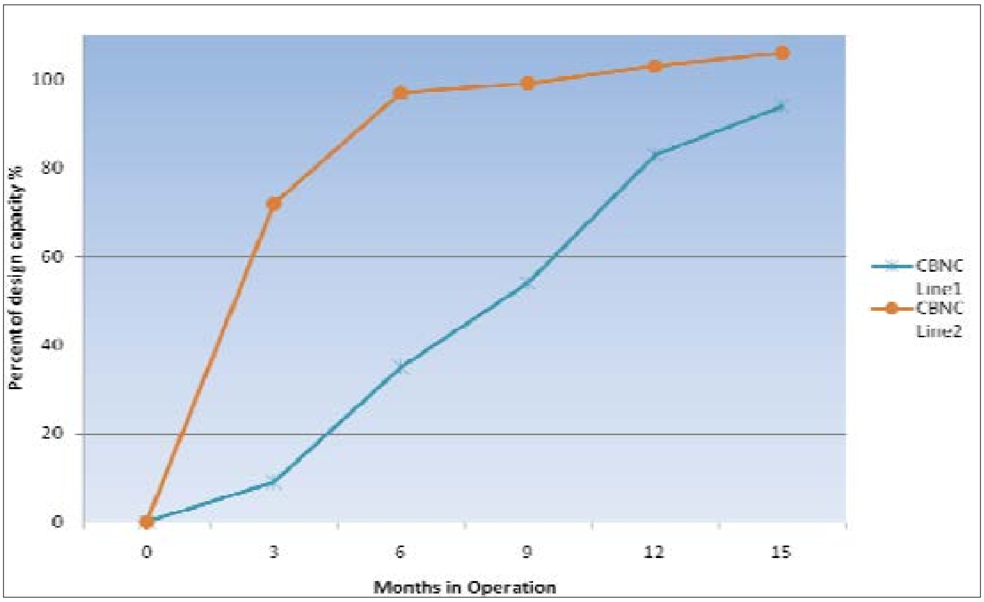

Figure 12 – CBNC L1 + L2 Ramp-up Comparison(17)

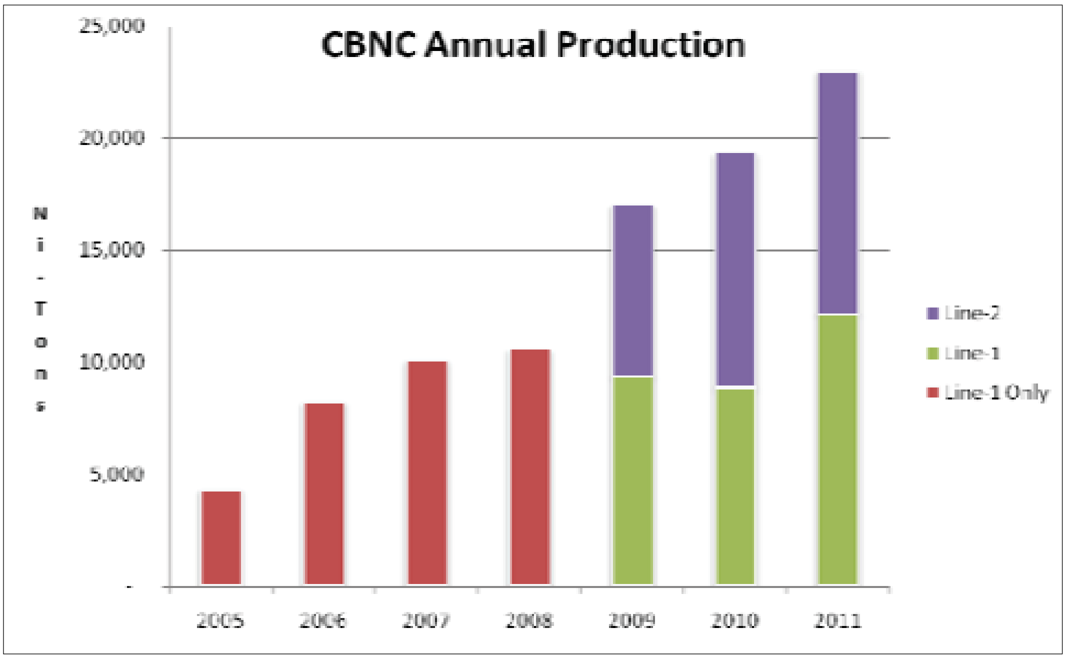

Figure 13 – CBNC Annual Production(17)

Sufficiently equipped with historical knowledge and skills from CBNC Line 1, SMM then embarked on the implementation of CBNC Line 2 in 2006. Line 2 was an exact copy of Line 1 with incorporation of design improvements learned from Line 1. The two lines run independently but are provided with strategic interconnections to allow for more operational flexibility (see Figure 11).

Construction of Line 2 began in April 2006 and mechanical completion was achieved on February 2009. This relatively longer construction time compared to Line 1 was due to brownfield expansion challenges and the low availability of skilled manpower during the global mining boom in 2006-2009. However, prior technical and operational knowledge from Line 1 and strategic tie-ins between the two lines provided huge advantages for the fast commissioning and ramp-up of Line 2.

Pre-commissioning and commissioning of Line 2 were completed within 5 months, while 75% of the annual nameplate capacity was achieved within 6 months after commissioning. In the succeeding 3 months, Line 2 demonstrated a long-term operation of 100% design capacity; 120% of the nameplate capacity was achieved within 15 months of ramp-up (Figure 13). From 2011 to 2015, CBNC Line 1 and Line 2 achieved ~24 000 tpa Ni (in combined production or 120% of both nameplate capacities(17).

Success of the Coral Bay Project

To appreciate the success of the Coral Bay Project, one has to understand the SMM corporate philosophy, which embodies integrity and sound management, foresight, and flexibility. These values trace back to the 17th century in SMM's "Founder's Precept" which states that *"under no circumstances should the house of Sumitomo pursue easy gains or act imprudently"*(21).

The development of the CBNC Project was guided by these principles, as illustrated by:

- The prudent approach to the selection of technology and strategies to defer the implementation of Line 2 expansion;
- An application of sufficient design allowances to allow for greater plant flexibility and operability;
- A well-structured and integrated competent team of owner (SMM), contractor (JGC), subcontractors (SNC-Lavalin, etc.) and vendors.

The overall success factors of CBNC can be broadly classified into two categories discussed in the following subsections.

One Half of the Success Story – Well Managed and Engineered Project

The CBNC Line 1 Project is one of few HPAL projects that have accomplished fast development, on-time delivery, and delivery within budget (US$180 million)(26). These achievements can all be attributed to sound project management and execution and to competent project stakeholders (owner - SMM, engineering team - JGC, SNC-Lavalin, vendors, etc.). These attributes were discussed in detail by CBNC, JGC, and SNC-Lavalin in their respective ALTA 2006 papers, where the key points captured were as follows(16-20):

- SNC-Lavalin was instrumental in providing valuable contribution to the design of CBNC Line 1 Project leveraging from its in-house design, engineering, and construction experience of HPAL and POX plants as well as having highly competent engineers dedicated to the project.

- The selection of the HPAL-MS flowsheet was made based upon extensive HPAL testwork conducted in certified laboratories (SGS, Dynatec) and NNR laboratory, upon proven demonstration of technology in actual application, and using in-house technical and operational knowledge of SMM in mixed sulphide precipitation process.

- The solid basis of engineering design was drawn from extensive and targeted testworks (both bench scale and pilot-plant test runs).

- Timely and early freezing of engineering-design basis and design criteria allowed for a clear definition and direction of the project

- Two committees, whose formation was initiated by SNC-Lavalin, were created to analyse and investigate risks in key areas. The committees were:

    - *Science committee (SMM, SNC-Lavalin, and key scientist and metallurgist)* – responsible for the process design criteria (PDC) and process flow diagram (PFD), the issue of scale formation in the HPAL circuit, solids weight loss in leaching, and selection of construction materials for HPAL.

    - *Engineering committee (SMM, JGC, SNC-Lavalin, and consultants in design and operation of HPAL plants)* – responsible for lessons learned analysis and critical review of operability and maintainability of the overall flowsheet, including plant availability, shutdowns, key equipment and valve designs, and critical maintenance items.

- Strong in-house technical and operational knowledge of the SMM owner's team in mixed sulphide operation, allowing for innovative ideas to be de-risked and incorporated early on in the feasibility study.

- Practical operations training of key SMM Owner's team in Bulong Nickel Operation, facilitated by SNC-Lavalin, provided the Owner's team an appreciation of the challenges of critical areas such as ore preparation and HPAL, leading to a prudent design that allows for greater operability and flexibility. This led to the design of:
  - Two trains in the ore preparation area (2 x 84% = 168% total capacity);
  - 120% design capacities for all areas outside ore preparation for catch-up and flexibility to adjust for changing feed chemistry;
  - 70% turndown capacities; and
  - Realistic basis of overall plant availability of 83%.
- Value engineering and cost-optimisation workshops.
- Maximisation of local fabrication and tight control and supervision of all subcontractors.
- Well defined project structure that allowed good relationship between SMM and the engineering contractors/subcontractors (JGC, SNC-Lavalin, vendors).

Other Half of the Success Story – Operational Excellence

A well managed and engineered project is only good as it is until the hand-over of the plant from the engineering contractor to the Owner's team. The long-term success of a project depends on the skills and work culture of the operations personnel, as they ultimately drive and influence the plant's safe and efficient operating practice. The continued success of CBNC is largely credited to the competent Owner's team (composed of a small portion of Japanese expatriates and a majority of Filipino workers) and the implementation of SMM culture. The technical skills of the Filipino workforce are highly acknowledged by SMM as world-class and as the other half of the success story of CBNC(22). The operational excellence in CBNC has been described in several ALTA papers presented in 2006 and 2011. These are summarised into the following important points(16,17):

- Early engagement of the operational team (both maintenance and production personnel) on the project – Filipino operations workforce were brought as early as the detailed engineering phase to provide better understanding of the process flow and key operational and maintenance challenges.
- Technical training and cultural immersion in Japan – Notably, CBNC was the first complex and automated hydrometallurgical operation in the Philippines. SMM initiated a program to train the pioneering Filipino workforce in NNR, which has the same level of process technicalities and automation. The Filipinos and Japanese were also engaged in a cultural exchange and immersion to foster a good working relationship, which led to an effective transfer of knowledge between the Japanese mentors to their Filipino counterparts.
- Engagement of operational workforce into the pre-commissioning and commissioning activities, including the preparation of standard operating procedures and operations manual and working side by side with JGC, SNC-Lavalin, and various vendors.
- Good understanding of historical maintenance and operations of critical equipment.
- Exposure of the operations personnel to various process areas, providing appreciation of cross-area impacts and increasing the worker skill base.
- Ownership by the operations personnel of their respective areas and good communications and integration across all plant areas. All operations personnel have intrinsic knowledge of both equipment function and chemistry, a component that is integral to the personnel's wide understanding of the overall operations.
- Effective implementation of SMM corporate philosophy, which is embraced by every worker across the board. This includes the highest commitment to safety and environment and a prudent approach to all areas of operations, no matter how complex or simple the operation

may be. Some of these are illustrated in their application of reasoned decisions, practical risk assessments, gradual step changes, and operating only within the design envelope.

Commissioning Challenges – CBNC Line 1

Well executed as it was, CBNC Line 1 also experienced commissioning and ramp-up challenges during its early years of start-up. However, they were relatively minimal compared to the technical difficulties experienced by the 2nd generation HPAL plants. The details of these challenges were discussed in a technical paper presented by CBNC during ALTA 2006. The challenges highlighted were as follows(16):

- Intensive maintenance was required in the ore-preparation circuit due the challenges of materials handling during the rainy season and a high rate of wear in the screens and oversize-material conveyor belts due to escape of coarse material.

- Extensive scaling in the heaters and autoclave caused frequent downtimes to the autoclave feed pump, where scale particles accumulated in the strainer. This issue was primarily caused by the use of recycled tailings decant, which was high in calcium and magnesium, and which CBNC was forced to use due to a drought.

- The brick lining in the lead flash tanks collapsed during water commissioning due to excessive release of energy brought by massive differential pressure between the autoclave and the first flash tank.

Design and Operational Improvements – CBNC Line 1

A number of design improvements implemented in CBNC Line 1 were attributed to:

- The application of lessons learned from the technical and operational challenges of three Western Australian operations (Bulong, Cawse, and Murrin Murrin);

- SMM's prudent approach and high consideration to operational flexibility; and

- Modifications as a result of commissioning challenges(16-19).

Engineering and design improvements on the CBNC Line 1 were as follows:

- Evolution in autoclave feed-pump design – GEHO® single-acting triplex with CS-Ti lined wet end parts and metal seated cone valves and sliding frame with Teflon-to-metal contact were implemented to compensate for dropleg expansion.

- Elevated HT Heater to provide sufficient NPSHa and flexibility to the autoclave feed pumps.

- Improvements in the materials of construction, design of batten strips, wear plates, baffles and welding techniques were applied to the CBNC autoclave.

- The application of a letdown valve-blast tube assembly (instead of the typical fixed choke assembly) for depressurisation on the lead flash vessels enabled more operational flexibility during turndown operations.

- Design improvement in flash-vessel aspect ratio and the use of tracers during commissioning, to establish the extent of acid carry-over and therefore the operating philosophy of the flash vessels, resulted in significant reduction of acid carry-over.

- Slurry check valves were applied in the discharge of heater feed pumps and anti-reverse rotation system to prevent backflow and damage to the pumps during start-up. This approach was adapted from the early Goldstrike POX and Bulong operations.

- The innovative slow kinetics (low temperature and pressure) and fine-seed recirculation concept applied to the MS circuit resulted in a relatively thinner scale build-up in pipes and on the reactor surface (~1 mm) and in an optimum recovery (~98.5%) of Ni and Co in the MS circuit.

- HP Air addition to the autoclave provided the necessary overpressure for discharge on reducing ore feed periods.
- Provision of adequate redundancy and buffer capacities in between critical areas resulted in improved operational flexibility (in terms of turndown and catch-up scenarios).
  - The availability of two trains in the ore-preparation stage, with individual capacity of 84%, and a total combined capacity of 168%, allows for catch-up, blending of ore feed, and high availability. This concept of flexibility has paid a huge dividend for CBNC as the ore preparation turned out to be the most maintenance-intensive area of the whole process plant. Frequent maintenance in ore preparation has had little impact on the operation of the downstream HPAL circuit. When possible, catch-up was achieved in a fast manner due to the significant applied design allowance (168%).
  - Provision of 20% design allowance on all process plant equipment including HPAL (except ore preparation) or 120% design capacity provided CBNC a means for catch-up but more importantly, provided a greater flexibility for process adjustments during feed composition fluctuations. The designed 70% turndown also allowed for flexible operations in case of process troubles in certain areas to increase the overall availability.

Modifications and later improvements on CBNC Line 1 included the following:

- Installation of pre-screening grizzlies in the ore preparation to maximise the scalping of coarse oversize during the dry season.
- Reconfiguration of the oversize conveyor belts to minimise the rate of wear in the impact rollers.
- Control of process water quality to prevent scaling in the heaters.

The following improvements were made in operations:

- Process control of the ore feed composition was improved by blending to minimise process chemistry fluctuation and adverse impact on downstream processing. This allowed CBNC to establish a fast and stable operation during ramp-up and to conduct process optimisation in parallel. As a result, product specification was achieved in the early part of the ramp-up period.
- Operation of GEHO® pumps in parallel increased the valve life, improved the overall dynamics of the pump system, reduced pump maintenance interruptions, and paved way for the successful achievement of 120% plant-wide operations.
- The seed recycle of leach residue (from CCD) developed by SMM significantly minimised the scale formation in the neutralisation tanks (compared to other operations which use neutralisation thickener underflow). This approach also improved the settling characteristics of the slurry precipitate due to the presence of heavier hematite in the residue. Moreover, the nickel and cobalt loss from co-precipitation were almost negligible.
- Controls and operating philosophy of the differential pressure between the autoclave and the first flash vessel were implemented to prevent massive energy releases in the flash vessel.
- CBNC also conducted several flocculant trials that help optimise the overall plant operating conditions and solids throughput to the autoclaves.

CBNC Now

CBNC is currently operating steadily at 100-120%, achieving or exceeding expected annual targets in a sustainable manner. The strategic tie-in lines between L1 and L2 provide the overall plant with greater flexibility and operability. In 2009, deep cone paste thickener was added to Line 1 to improve the total solids density (in combination with the existing high-rate thickener U/F). CBNC is currently readjusting the operating conditions of their HPAL circuit to minimise the levels of iron impurity extracted in the autoclave and caused by changing characteristics of their current ore feed. These improvements will be presented by CBNC at this year's ALTA presentation.

Previously, many experts attributed the failures of large HPAL projects to their significant project size, which they said magnified their inherent complexity and technical difficulties. Nevertheless, this view has been completely invalidated with the repeated success of CBNC in the implementation of Taganito HPAL (THPAL) in Surigao, Philippines in 2013.

THPAL was designed to produce 30 000 tpa Ni and 2 600 tpa Co in MS product; it is three times the size of CBNC Line 1, with feed coming from run-of-mine (ROM) ore. The plant has achieved a fast commissioning and ramp-up similar to CBNC L1, and consistently achieved over 90% of its nameplate capacity within the first 3 years of operation following commissioning (see Figure 1)(10). These achievements demonstrate that although HPAL application can be challenging, it can also be successful if executed with the two key ingredients of CBNC's success story: a well-managed and well-engineered project, and operational excellence.

DESIGN IMPROVEMENTS OF CRITICAL EQUIPMENT AND INSTRUMENTS

Technical difficulties and various material failures experienced during the 2nd generation HPAL in Western Australia brought about the biggest advances in the design and technology of HPAL equipment, which became adapted to the more aggressive process conditions. Major advancements in the manufacturing, material selection, and engineering and design of critical equipment and instruments since the 1990s were presented in detail by SNC-Lavalin in ALTA 2005. The presentation by Rod Clary et al. discussed improvements in the materials and design of autoclaves and pressure vessels, agitator seal systems, severe-service valves, pressure letdown and angle valves, and acid injection systems, all of which are critical to the mechanical availability of the entire HPAL circuit(29). These improvements were applied in the engineering and design of Coral Bay Line 1, Ambatovy, Goro Nickel, and Gördes projects, contributing to the relatively higher circuit availabilities observed in these operations.

Over the years, two of the most critical equipment/instrument components in HPAL have improved significantly in adapting to the challenges of the process: the autoclave feed pump and the pressure letdown system. These improvements resulted from vendors' incessant endeavours to further improve and optimise the performance of their equipment through R&D and collaboration with owner-operators and engineers.

Autoclave Feed Pump(30,31)

Autoclave feed pumps are considered to be critical equipment, whose failure can bring down the whole HPAL circuit. In second-generation installations, it became apparent that premature failures of cone valves and diaphragms were due to their design being unsuitable for the much more aggressive laterite process. Since then, several design improvements have been implemented; a new breed of "third-generation heat barrier pumps" has been developed by GEHO®. This technology was first used in Coral Bay Nickel Line 1 with the following features:

- Triplex Single Acting – Using three droplegs and three diaphragms. The triplex pumps generate a more constant slurry displacement during the pump-shaft rotation and require a smaller dampening air vessel compared to the second-generation duplex pump used in Bulong and Murrin Murrin.
- Heat barrier design – horizontal droplegs and a floating mechanical separator (elastomer disc), which limits the mixing of the cool semi-stagnant slurry in the dropleg and hot incoming slurry in the valve housing, effectively protecting the diaphragm from thermal degradation. The droplegs are also fitted with a cooling jacket to dissipate the heat of the reciprocating slurry in the most efficient way. GEHO® moved away from the use of static mixer for their heat barrier due its inability to protect the diaphragm from high thermal exposure and increased internal stress due to the stiffness of the mixer.
- Thermal expansion compensation – expansion of the droplegs at high temperatures (>200ºC) brings substantial stress that can cause cracking if not compensated. GEHO's prior experience with expansion bellows led to the development of a sliding frame due to the inherent fatigue failure of the bellows when exposed under prolonged pulsation. The CBNC Line 1 pumps were the first GEHO® pumps to have the sliding frame technology,

where the entire power- end and diaphragms were mounted on a sliding steel skid (Teflon on stainless steel), while the air dampener vessels and valve housings are anchored to the ground. This allows the pump to slide as a result of the thermal expansion of the droplegs without imposing unacceptable stresses to the pump structure (Figure 14).

- Design of diaphragm housing and diaphragm material – GEHO's extensive R&D using finite element analysis allowed for the visualisation of the diaphragm flexing therefore high stress areas were accurately predicted. This led to the improvement of the shape of the diaphragm housing to compensate and minimise the stress. The material of the diaphragm has also been changed to a modified EPDM elastomer, which is tougher and more heat-resistant than the previous material.
- Cone valve material – the most wearable part of the pump as it is in direct contact with the hot and abrasive slurry. The low mean life before failure of the elastomer seat and cone valves in the second generation HPAL plants prompted GEHO® to test a range of materials and design. So far, the most effective is their patented Outlast® valve, a tapered ultra-high chrome design (metal to metal), which is self-hardening and has high resistance to abrasion.
-

Figure 14 – GEHO® Triplex Pump Sliding Frame Configuration$^{(31)}$ *(Photo Courtesy of GEHO)*

- Wet-end material of construction – the CBNC Line 1 autoclave feed pumps were the first pump made from CS and titanium lined wet-end, which is more acid resistant. The low thermal conductivity of the titanium also improves the overall dynamics of the pump and increases the diaphragm protection against thermal degradation.

The overall improvement in the mechanical availability of the autoclave feed pumps is owed to the advancements in design as mention. However, it is also significantly driven by the way the equipment is being operated. Improvement to the overall performance and internal dynamics of the pumps were seen with the following operational changes:

- Parallel operation (dual operation).
- Minimising the acid carryover to the heaters by improvement of control philosophy at the flash vessels.
- Control of particle size in the slurry feed.
- Sufficient net positive suction head available (NPSHa) from the heater to prevent cavitation.

Pressure Letdown System(32)

The flash system (or the pressure letdown system) is the area where single biggest energy releases / dissipation occur in an HPAL system, making it the most violent and one of the most critical areas in the circuit. The top entry flash vessel designed by SNC-Lavalin for Bulong proved to be the optimal solution to-date and is implemented in the majority of the succeeding HPAL plants.

The other significant improvement is the design optimisation of the slurry letdown system. Notable vendors, such as Caldera Engineering, have made numerous important developments and innovations over the years; they have drawn on their extensive in-house R&D and experience / cooperation with various sites to understand contributing factors of failure and how these could be rectified and improved. Details of such many developments were presented in SNC-Lavalin's ALTA 2005 technical paper (Rod Clary, et.al)(24). Some of the latest developments since then are:

- Optimisation of slurry letdown systems – it has been observed that the optimum letdown-system configuration features a letdown valve and blast tube assembly in the lead flash vessels and a fixed choke in the atmospheric flash. This was deduced by Caldera from experience in various sites with different slurry letdown configurations. The level valve-blast tube offers more flexibility and operability (in high-pressure letdown system such as in the lead flash vessels) particularly during turndowns and where limited autoclave overpressure is available. The fixed-choke system's operating range is limited to the available overpressure and choke solution adjustment to prevent premature flashing of the slurry in the discharge line or in the valve entry.
- Improvement in plug head geometry – innovation of plug head profile from parabolic to truncated plug. The new design is less susceptible to thermally-induced tensile stresses due to less mass and surface area exposed to the flashing flow stream. Better flow controllability is also achieved in combination with properly sized actuators, which is important in maintaining a stable autoclave level. The new plug had been implemented by Caldera in some of the SNC-Lavalin-built plants such as Ambatovy and Gördes, where improvements are observed.
- Improvement in impingement block designs – improved strength and life of impingement blocks as a result of development in design and materials of construction used (ceramic materials as nitride-bonded SiC, reaction-bonded SiC, and sintered SiC).
- Extensive use of mathematical flow modelling which accounts for the thermodynamic and compressible properties of flashing slurries in conjunction with computational fluid dynamics (CFD) enables Caldera to visualise and simulate various scenarios and flash-vessel failure modes along with process behaviours such as acid and particulate carry-over. This allows them to provide better solutions and enable to continuously improve the design of the pressure letdown technology to meet the requirements of the aggressive operating conditions of the system.

CONCLUSION

Over the years HPAL technology has been negatively associated with technical difficulties, cost blow-outs, and closures. However, as presented above, successful operations have been demonstrated by recent generations of HPAL plants such as at Coral Bay Nickel, Taganito HPAL and Ambatovy. These examples are a testament to the improvement and evolution of HPAL technology since its inception in the late 1950s.

SNC-Lavalin's long-term involvement on projects such as Coral Bay, Ambatovy, Gördes, and Goro Nickel, from study stages through to execution and commissioning, has represented repeated opportunities to deepen our knowledge of the success factors of HPAL design and operation, as well as understand each client's fundamental requirements, and the unique geographical and local challenges of each HPAL project. The company's extensive experience with HPAL engineering and its practical application has led to a solid understanding of design requirements and operational challenges inherent to nickel laterite HPAL plants.

As SNC-Lavalin's extensive experience indicates, two aspects are essential to a successful HPAL plant implementation: well managed and engineered project on the one hand, and operational excellence on the other. Combined, these two aspects are key ingredients to the success of HPAL projects and to the maturity of HPAL technology.

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