KEYS TO A SUCCESSFUL NICKEL LATERITE HPAL DESIGN AND OPERATIONS: A FIRST HAND EXPERIENCE

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ABSTRACT

It has been over 60 years since the HPAL application for nickel laterites was first commercialised in Moa Bay in the late 1950s. The following decades saw the technology in an open patent, which subsequently paved way to the modernisation and adaptation of HPAL technology to global nickel laterite deposits. To-date, these operations have varied levels of technical and economic successes and failures, several of which have eroded a considerable portion of their net value early-on in the project lifecycle.

Whilst there has been more than 60 years of exhaustive technical knowledge, improvements and skills that were shared across the greater nickel laterite community including lessons learned, several greenfield HPAL installations were still marred with difficulties. This consequently gave the HPAL technology a negative reputation. However, there are a few operations that got it right and have demonstrated the success of HPAL technology both technically and economically.

This paper provides personal insights into “why it happened” and what differentiates a successful HPAL operation from the perceived failures. These insights are leveraged from the author’s first hand comprehensive experience in the end-to-end-project lifecycle of HPAL plants (project development, engineering and design, execution, commissioning, operations, debottlenecking and optimisation) and involvement in various roles from field operation, DCS (control room) operation, production crew supervision, R & D, process engineering, consultancy and corporate roles.

Keywords: Nickel, Laterite, High Pressure Acid Leach (HPAL), Lessons Learned, Successes, Failures, Adaptive Leadership, Operational Discipline, Work Culture, Integrated View, Process Integration, Holistic Skills,

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INTRODUCTION

Global Nickel Demand

In the past decades, the industrial application of nickel has been primarily driven by the demand for stainless steel. While the stainless-steel sector is still the anchor market for nickel (representing 69% of the demand), growing calls for world decarbonisation is dramatically increasing the demand for nickel in battery applications. By 2040, it is projected that batteries will represent >40% of the global nickel consumption due to burgeoning demand for electric vehicles[12].

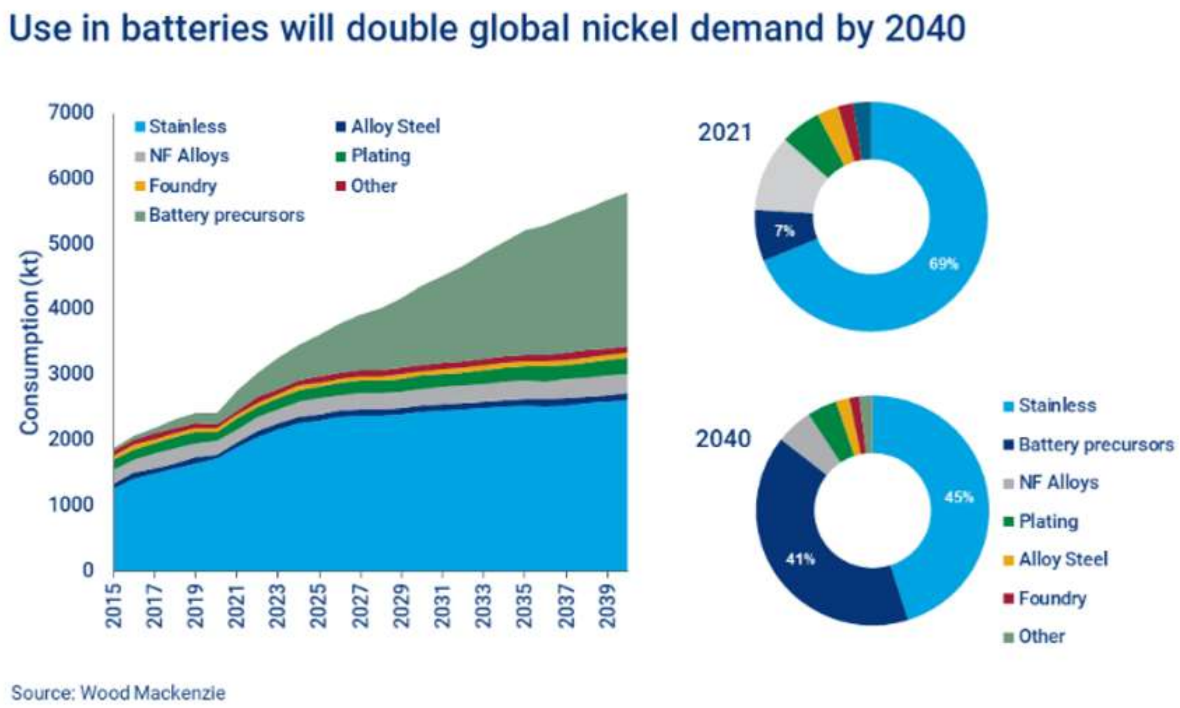

Figure 1 – Nickel Demand by End User[12]

Battery technology is fast evolving, and the size of EV battery packs is increasing. The nickel-based cathode, NMC 811 (80% Ni, 10% Mn, 10% Co) is predicted to be the most dominant type with around 69% market share by Year 2030. An EV car with about 77kWh NMC 811 battery pack requires around 52 kg of nickel sulphate, 6.6 kg of manganese sulphate and 6.6 kg of cobalt sulphate for its cathode composition[9]. With the EV car sales predicted to grow by 19-36% in the coming decade, this will push global demand to outstrip the current supply by ~50% in Year 2040[12] (see Figure 1).

It is predicted that around 1 600 ktpa (equivalent to 27 Ambatovy Nickel HPAL facilities) of new production is required by 2026 to 2038 in order to meet the projected demand. Majority of the new capacity is expected to come from Indonesia (either from ferronickel smelting or hydrometallurgical processing such as HPAL)[12]. At least four HPAL projects are now either under development (Indonesia Morowali Industrial Park, Eramet's Weda Bay, PT Vale/Houyaou) or operating (Lygend)[13].

Nickel Production

The world nickel production comes from two primary sources: nickel sulphide and nickel oxide. Table 1 presents the recent global nickel production and reserves update from USGS. Nickel laterites account for 60-70% of the world reserves.

Table 1 – Global Nickel Production and Reserves[16]

Country	Mine Production, kt Nickel		Reserves, Kt Nickel
	2020	2021	
Australia	169	160	21 000
Brazil	77.7	100	16 000
Canada	167	130	2 000
China	120	120	2 800
Indonesia	771	1 000	21 000
New Caledonia	200	190	7 100
Philippines	334	370	4 800
Russia	283	250	7 500[1]
United States	16.7	18	340
Other countries	373	410	20 000
World Total	**2 510**	**2 700**	**>95 000**

Production from nickel sulphide remained flat for a decade due to the declining head grades of some major mines. Since the discovery of Voisey's Bay in early 1990s, no other nickel sulphide deposit of that grade and size has ever been discovered and brought to production.

In 2020, about 69% of world nickel production came from nickel laterites[21]. About 88% of this is produced from pyrometallurgical flow sheets (FeNi, pig iron) with the rest from hydrometallurgical processes such as High-Pressure Acid Leaching (HPAL).

High Pressure Acid Leaching (HPAL)

The increasing demand for battery grade nickel products, which require high purity, drew more attention to HPAL due to its rejection of impurities, particularly iron and aluminium. Acid leaching at high temperature and pressure precipitates the iron and aluminium from the leach solution and regenerates the majority of the acid consumed (to leach the iron and aluminium) through hydrolysis. This results in a lower net acid consumption (compared to atmospheric leaching), rendering the process economically viable. While HPAL is an elegant solution, it is also tarnished with a chequered reputation.

HPAL was first commercialised at Moa Bay Nickel in Cuba in the late 1950s. Since then, about 11 HPAL projects have been built and operated around the world with varying success (refer to Table 2). These plants employed ore preparation suited to their ore feed characteristics and adopted varying downstream recovery processes which were influenced by the owner's technical experience / expertise and market off-take. The most common approach is to recover the nickel as saleable intermediate product in the form of MSP (Mixed Sulphide Precipitate) or MHP (Mixed Hydroxide Product) and refined products such as Class 1 Nickel Briquettes or NiO pellets.

Table 2 – HPAL Operations Summary[15,18]

Operation	Location	Flowsheet*	Capacity Ni tpa	Start-up	Gen	Status	Capital Intensity, US$/tpa Ni*
Moa Bay Nickel Operation	Cuba	Mine-HPAL-MSP	35 000	1958	1st	Operating	N/A
Bulong Nickel Operation	Australia	Mine-HPAL-DSX-EW	9 600	1998	2nd	Mothballed	$24 000
Cawse Nickel Operation	Australia	Mine-HPAL-MHP	10 000	1998	2nd	Mothballed	$ 27 500
Murrin-Murrin (now Minara)	Australia	Mine-HPAL-MS-Reduction	45 000	1998	2nd	Operating	$29 000
Coral Bay Nickel Line 1 + Line 2	Philippines	Ore Stockpile-HPAL-MSP	10 000 (L1) 10 000 (L2)	2004 2007	3rd	Operating	$19 600 L1 $31 000 L2 **$25 300 tot**
Ravensthorpe Nickel Operation	Australia	Mine-HPAL-MHP	45 000	2007	3rd	Operating	$47 000 >$54 4000**
Goro Nickel (now Prony Resources)	New Caledonia	Mine-HPAL-MHP/DSX****-Pyrohydrolysis	60 000	2011	3rd	Operating	>$75 000 >$133 300**
Ramu NICO	Papua New Guinea	Mine-HPAL-MHP	31 000	2012	3rd	Operating	$67 400 $71 000**
Ambatovy	Madagascar	Mine-HPAL-MS-Reduction	60 000	2012	3rd	Operating	$91 700 >$133 300***
Taganito HPAL (THPAL)	Philippines	Mine-HPAL-MSP	30 000	2013	3rd	Operating	$53 000
Gördes Nickel	Turkey	Mine-HPAL-MHP	10 000	2014	3rd	Operating	N/A
Lygend HPAL	Indonesia	Mine-HPAL-MHP	37 000	2021	4th	Operating	N/A

*At mechanical completion only. **Including remediation capital and/or debottlenecking capital. *** About 25% were capitalised ramp-up costs capitalised after mechanical completion. ****DSX – Direct SX

HPAL Project Challenges

Any greenfield HPAL project, regardless of its size, is a challenging undertaking in that these projects are mostly located in remote areas, where major off-site infrastructure is required (port, workforce accommodation, roads or rails, airstrip, tailings dam, etc.). Process infrastructure such as power plants, gas plants or acid plants, reagents preparation and tailings neutralisation facilities, integrated into the whole process plant, is also required. Not surprisingly, the associated complexity of the operations demands high technical operating skills and maintenance capabilities[2].

As such, HPAL projects are known for their high upfront cost, with capital intensity ranging from US$24 000 to US$ 67 400 per annual Ni nameplate contained tonne for projects producing intermediate products (MSP, MHP). and >US$ 91 700 for facilities with integrated refinery producing Class 1 or 2 refined products (Ni briquettes, NiO pellets). In addition, HPAL projects are also notorious for capital cost overruns (with as high as 100% by mechanical completion). Additional capex (as high as 100% from the original budget) is spent to rectify shortcomings during commissioning and remediation works to get the facility to achieve ramp-up.

The majority of installed HPAL projects do not have a good record for economic success due to various levels of difficulties experienced during commissioning and start-up (slow ramp-up), poor plant utilisation (low availability), intensive maintenance (high operating cost) and difficulties to consistently produce on-spec products in the early years of the project. These led to financial write-downs, changes of ownership and ultimately closures. These challenges, along with the high capital cost associated with the project, have earned HPAL a negative reputation in hydrometallurgical processing. While a problematic project is inevitable, this should not be considered as typical.

Although HPAL projects are notorious for high capital cost and operational challenges, there are projects that had poor initial performance but are now providing considerable revenues and positive cashflows to their current owners. More importantly, there are some greenfield HPAL projects that are recognised to have achieved both technical and economic success, from project execution through to initial operations. These demonstrate continuous improvement in the HPAL industry in engineering and design improvements, successful applications of lessons learned, and best practices and owner's work culture and operational excellence.

HPAL Plants Ramp-up Profile

Figure 2 presents the ramp-up performance of some HPAL plants around the world. The original version of this graph appeared in the ALTA 2017 paper[18]. This current version is updated to include the annual production of these HPAL plants from to 2020.

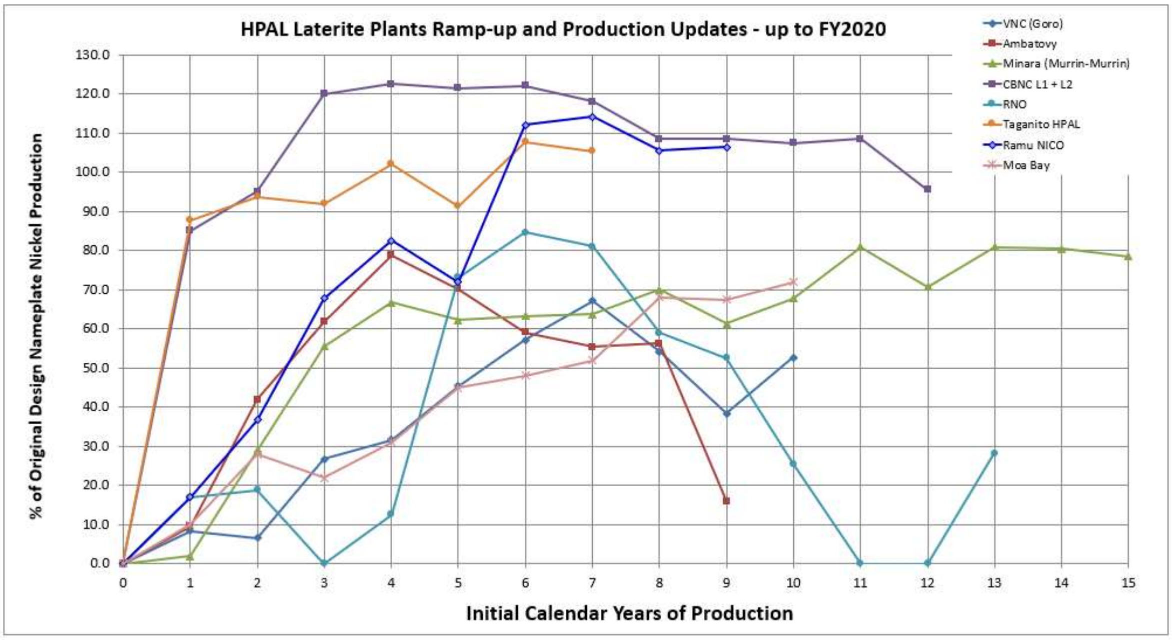

Figure 2 – HPAL Plants Ramp-up[18]

As can be seen in the historical ramp-up profile, the majority of these installations did not achieve their designed nameplate capacity within 3 years of projected ramp-up. Large and integrated mine-to-metal facilities like Murrin-Murrin, Goro Nickel (now Prony Resources) and Ambatovy, all suffered from a very long ramp-up and difficulties of integration. The same can be said for mid-size HPAL plants like RNO (Ravensthorpe Nickel Operation) and Ramu NICO, where lower availability of the process plant in the early years significantly impacted the performance and reliability of the integrated sulphuric acid plant. Murrin-Murrin, RNO and Goro Nickel all fell within Series 4 of the McNulty curve while Ramu and Ambatovy sit in between Series 3 and 4.

Murrin-Murrin had virtually no production in its first year of operation and slowly ramped-up to <70%, four years after start-up. In 2013, it had achieved its highest annual production on record at 89% buoyed by additional sulphide concentrate feed. Murrin-Murrin is the last surviving second generation HPAL plant and had been consistently operating at >80% of its designed nameplate capacity, 14 years since start-up.

RNO had suffered from the failure of deviation in ore preparation design. The original design employed a steep angled conveyor for oversize rejects of the vibrating screen and screw classifier, which are typically used in dry materials handling. It proved to be problematic for wet application resulting to constant downtimes in the beneficiation plant. This in effect, negatively impacted the rest of the downstream processing including the HPAL and sulphuric acid plant. As a result, RNO only produced less than 20% of its nameplate capacity on its early years of start-up, leading the original owners to sell the facility. The new owners had to spend significant capital to remediate the front-end beneficiation plant and back-end product handling and packaging[5]. RNO then ramped-up to 83% in its first two years of re-start under the new ownership before closing the facility again in late 2017 due to low nickel prices. The facility has since restarted in 2020 driven by the development of a new mine and increasing demand for nickel in batteries.

Of the three large scale and integrated mine-to-metal projects, Ambatovy had the most improved performance, achieving more than 80% of its design capacity in Year 4 after start-up. This achievement had been largely credited to the inception of PEI (Performance Enhancement Initiative) team, a specialised taskforce consisting of SMEs (Subject Matter Experts) and seasoned operators, which helped with the process and mechanical debottlenecking of the process plant. PEI's contribution to the achievement of Ambatovy's Financial Completion has been documented in the ALTA 2017 presentation paper[18].

In its early years Ambatovy suffered numerous difficulties integrating major project areas into one cohesive process flowsheet including the mine and ore preparation facility (which feeds the processing plant by a 220 km long slurry pipeline) and auxiliary process infrastructure such the sulphuric acid plant, gas plants and lime production system. Moreover, there were numerous technical issues relating to materials / equipment failure and operational issues associated with large thickeners. These had resulted to low plant availabilities and products not meeting the LME specification. The contribution of PEI from mid-2014 to mid-2015 significantly improved the performance of the plant leading to its Financial Completion (defined as 90% of nameplate production over 90 days) and LME product registration.

Goro Nickel is by far the most challenged of all currently operating HPAL projects. The process flowsheet had incorporated a number of step-outs. The project was able to overcome and prove a few of them after repairs, modification and/or rebuild such as the fleater design (combining the flash vessel and feed slurry heating into one structure), relatively high operating pressure and temperature (resulting to a lower retention time and smaller autoclaves), pulsating columns for Ni/Co-SX, and use of Cyanex 301, a novel SX reagent (which is regarded as liquid organic sulphide in terms of selectivity and corrosion aggressiveness). However, the most notable step-out was the application of LPG-fired fluid-bed roasting to pyrohydrolysis, a thermal decomposition process in presence of water to convert the nickel chloride solution to nickel oxide. Whilst the technology is widely used in iron pickling industries it was rarely used in nickel application with a liquid fuel. The former owners of Goro Nickel had tested the process using the proven spray roaster in an integrated pilot plant but had encountered issues in agglomerating the resulting NiO product. They then conducted a short-run, stand-alone fluidised bed unit and achieved some successes, which became the basis for the commercial plant[17]. However, in a large-scale application, it proved to be difficult to operate and has a number of technical issues, hence failed in scale-up. The Goro Nickel operations were severely limited by this bottleneck, until the owners decided to produce mostly the intermediate product (NHP or MHP). Unfortunately for Goro, not only that the project was saddled with technical issues from early in its start-up, it was also plagued with social and environmental issues owing to the location of the project with stringent environmental regulations and complicated community relationships.

Despite known failures there are some success stories.

Following the addition of hydraulic mining , process improvements in ore feed density and remediation capital employed to the process plant and sulphuric acid plant, Ramu NICO made a significant turn-around of its operation by Year 6. Since then, Ramu consistently achieves above nameplate capacity until to-date[20].

Coral Bay Nickel (CBNC) Line 1 + Line 2 and Taganito HPAL (THPAL), which are all owned and operated by Sumitomo Metal Mining (SMM) in the Philippines are one of the few HPAL plants that achieved or exceeded nameplate (along with Ramu NICO) to-date. Coral Bay Line 1, which was the first installation achieved a McNulty Series 1-2 ramp-up, while Line 2 which was an expansion 4 years later demonstrated a McNulty Series 1 ramp-up. The combined production of Coral Bay's Line 1 and 2 consistently exceeded nameplate capacity by exploiting the design allowance into additional capacity.

The story of Coral Bay Nickel is a demonstration that it is indeed possible to achieve both technical and commercial successes using the HPAL technology.

McNulty CURVE IN REVIEW

Over the years, there has been a number of publications analysing ramp-up performance of various chemical and metallurgical plants installed worldwide. Most notable is the insightful study of Dr. Terry McNulty (originally published in 1998), introducing the McNulty ramp-up curves, which have been extensively referenced by many projects, including HPAL, in benchmarking designed ramp-up profiles. The McNulty curves have been expanded and further developed by several other authors (Mackey & Nesset 2003 and Nice 2003) to include updates on several developments particularly in complex integrated processing plant. The work of Dr. Terry McNulty and other authors offered insightful analysis grouping processing plants into similar ramp-up series, which are still relevant today.

The following discussion summarises McNulty's analysis, followed by further observations.

The compilation and study of Dr. Terry McNulty in 1998 on the histories of metallurgical and chemical plants found some common features of projects in each ramp-up category as follows (Table 3):

Table 3 – McNulty's Ramp-up Categories[2]

Factors	Series 1	Series 2	Series 3	Series 4
	Achieved >95% of annual nameplate in Year 1	Achieved >75% of annual name plate in Year 1	Achieved >50% of annual nameplate in Year 1 and 80% in Year 3	Has not achieved >60% of annual nameplate in 3 years since ramp-up
Technology	Mature			Unusually complex flowsheets
Condition		Unusually severe and/or corrosive		Process chemistry not understood
Licensing	Several predecessors	One of the first licensees		
Equipment	Similar in size and duty to existing prototypes	Utilised prototypes for major unit operations	Serious design flaws	Prototypes used for two or more critical unit operations
Piloting	Thorough for potentially risky unit operations	Incomplete or non-representative samples tested	Limited or excluded key process steps	Did not sufficiently address process parameters
Feed Materials			Feed properties poorly understood	
Engineering		Poorly executed for ancillary operations	Engineering and construction fast-tracked	
Management				Design compromise to avoid cost overruns

Additional reasons cited for projects falling behind expectations are observed as[10]:

- Initiation of design and construction before the process was understood;
- Ill-conceived driving forces underlying a project;
- Inadequate training or manuals;
- Inexperienced supervisory staff and;
- Inadequate technical support during commissioning and start-up

Nice (2003) had added some additional factors based on his analysis with some recent projects in Australia and Australia, including Cawse, Bulong and Murrin-Murrin as[4]:

- Very limited input from owner's to day-to-day engineering;
- Inattention to ore receipt and ore preparation circuits;
- Translation of the testwork to design was compromised;
- Materials of construction were addressed but new ground was being broken;
- Serious engineering problems and;
- Insufficient safety margins

Over the last two decades, seven (7) other HPAL plant had been built, incorporating much of the technical lessons learnt from the second generation. Albeit the exhaustive information publicly shared, poor ramp-up and operating performance is still prevalent. Below are some additional observations from the author on her extensive experience with HPAL project development and operations:

- Project schedule and capital cost were driven by cognitive bias from executive decision with inadequate technical input or consideration;
- Lack of operational experience from owner's and engineering teams;
- Lack of ownership from the owner's team – majority of the work is externalised to the engineering services provider and/or vendors;
- False sense of economy - low-cost materials, substitute materials, unproven vendors, seduction to economies of scale etc.;
- Poor planning and lack of experience in commissioning a complex and integrated facility;
- Siloed operational approach. Lack of appreciation for integration of unit operations
- Reactive approach as opposed to proactive approach;
- Limited integration of mine development and planning to production planning and decision making;
- KPIs (Key Performance Indicators) across different departments are not aligned, often driving opposing and sub-optimal behaviours and;
- Lack of strong work culture.

KEYS TO A SUCCESSFUL HPAL DESIGN AND OPERATIONS

Targeted industry-centric annual conferences such as ALTA, COM, TMS' International Nickel Laterite Symposium have been focal points for various HPAL project developments including lessons learned, project updates, equipment and design improvements. It can be deduced that the community at large has largely been generous in knowledge-sharing with the collective intent to continuously improve the application of HPAL and break its negative reputation.

One of many good examples are those papers published by HPAL owners themselves (SMM, Sherritt, Murrin-Murrin, Ramu, Gordes, Cawse, Bulong among others) and engineering services providers who had been involved in these projects (SNC-Lavalin, JGC etc). The paper Start-up and Reliability of Nickel Laterite Plants by Campbell, McConaghy & Vardill (2004) is another great one, which discusses difficulties encountered in complex nickel laterite project development, start-up and operations based on their experience with Sherritt-Dynatec projects. It also provides insightful information on how to overcome these difficulties for future projects.

A recently published book entitled "The Art of HPAL" by Tsuchida, Iwamoto & Yokoyama (2020) extensively articulates a collection of key considerations for a successful HPAL project in flowsheet technology selection, implementation and operations. The authors base their observations on their involvement in various roles with SMM's HPAL projects and operation as well as observations from other projects. Below is a paraphrased summary of their observations for a success HPAL Project based on weighing of risks and benefits, which was presented as a conference paper in ALTA 2020[15]:

- Where possible, start the project with a minimum scope i.e., without mining operation, brownfield expansion to existing saprolite mining;
- For greenfield projects, start from saprolite mining to generate early cashflow and stockpile unsaleable limonite for future HPAL processing;
- Sustainable size that supports the economies of scale is ideally between 30-40 ktpa Ni, preferably with intermediate product (MSP, MHP) to start with and expand as necessary in the future (additional lines and/or downstream refinery to final product);
- Consider incremental innovation / improvements / modification to existing and proven technologies. Avoid integrating a completely novel technology with insufficient pilot demonstration;
- Operating experience and capability of the owner's team to operate the plant is paramount;
- Guaranteed market-offtake for the product and ability of the owner to fund the project (sound financial health);
- Project execution based on EPC lump sum contract to share accountability and risk & rewards. Key to this model is the early integration of the EPC contractor into the project

development and involvement through to post-delivery i.e. commissioning, contract maintenance and;
- Teamwork of integrated owner's team, contractor and investor, who are bound together by transparency and alignment in SDGs (Social Development Goals) and CSR (Corporate Social Responsibility) goals.

In succeeding sub-sections, the author offers some insights based on her personal experience, complementing some of the key factors for a successful HPAL design and operations already shared within the industry, including those mentioned in this paper.

Project Development

The early stages of project development begin with the understanding of geological formation, variability, and extent of the deposit. A competent owner's team with a sound and holistic understanding of the resource characteristics (particularly the mineralogical association of various deposits) and various processing routes is paramount. This is because the development of subsequent metallurgical testwork program anchors on thorough understanding of the resource and its characteristics. Ideally, the metallurgical testwork program should be owned and developed by the owner's team rather than externalising it to engineering or laboratory services providers. An owner-led program could result to a targeted and cost-effective testwork. Project owners can benefit from foundational knowledge and information in their direct involvement with the testwork. A thorough understanding of the testwork could also lead to the development of the right flowsheet for the project.

The interpretation of testwork results to process design criteria is a critical step in the conversion of information from a small scale to an industrial scale application. This is developed collaboratively by both owner's team and the engineering services provider. As such, it requires considerable competence and operating experience from both stakeholders. A mistake in the interpretation of testwork results could negatively impact the design of an equipment or parts of the flowsheet.

Such is the case of poor mass and nickel recovery at Gordes, which was a result of interpreting the ore scrubbing testwork results at face value into process design criteria. When benchmarked to a similar application at CBNC (at the same throughput), the Gordes ore scrubber retention time was about 80% less. As a result, the installed ore scrubber was severely undersized resulting to short-circuiting of feed and low mass recovery. It became one of the major process bottlenecks during the facility start-up causing the downstream HPAL circuit to run in periodic campaigns[19].

There are other process design considerations that are difficult to determine from the testwork (even with a continuous pilot testing) such as equipment reliability, rate of scaling and wear. These parameters are largely dependent on various operational conditions and the way a facility is operated (stability and frequency of thermal cycling). Such information can come from years of operational experience. Although, it can also be derived from benchmarking against other HPAL plants with similar feed and process conditions.

The capability of the owner's team to use and develop an HPAL flowsheet using a metallurgical simulation software (such as METSIM®, SysCAD or Ideas Simulator) is also one of the necessary competencies to have (see example in Figure 2). Metallurgical software is a powerful tool used to investigate various processing flowsheets and develop mass and energy balances. In combination with testwork this software can help determine the high-level technical viability and economic feasibility of flowsheet options early on, before committing to subsequent studies and considerable expenditures. An in-house development of a simulated flowsheet model provides many advantages to the owners including a holistic perspective of the end-to-end flowsheet and an appreciation of how testwork results would be scaled to industrial scale parameters. A simple well-developed mass balance serves as a foundational tool for engineering basis during project development and can be used as an advanced diagnostic tool in operations.

A comprehensive understanding of the process from project conception through to the project development stages, detailed design, construction, and operation of the plant and finally closure is a requisite to a sustainable hydrometallurgical processing[3].

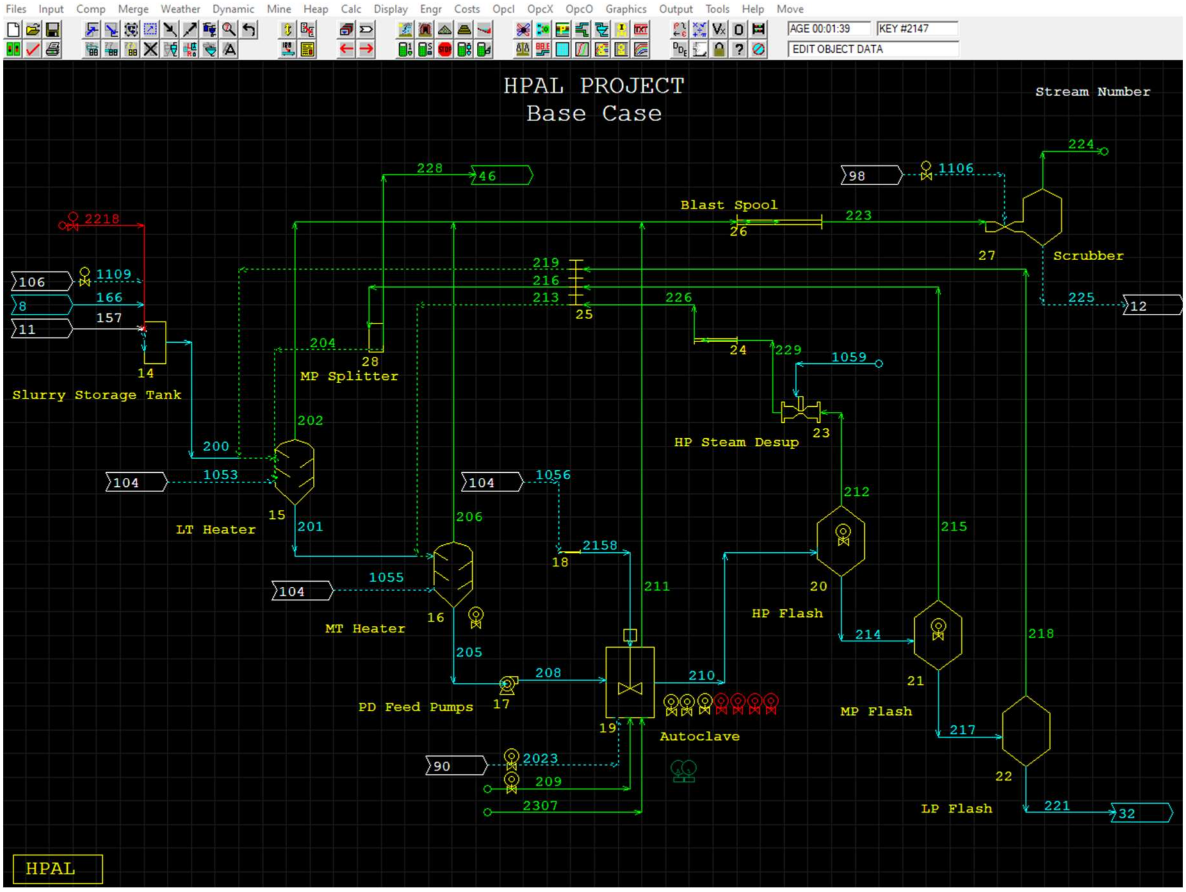

Figure 3 – Sample HPAL METSIM® Model

Tailings Disposal Consideration

Following catastrophic tailings dam failures at Samarco and Brumaldinho, a call for action was initiated to enhance the safety and governance of tailings facilities across the globe. The GISTM (Global Industry Standard on Tailings Management) was published in 2020, is aimed at the owners of existing and future tailings facilities to use specified measures to prevent the catastrophic failure of tailings facilities[6]. While it is not explicitly stated in the GISTM, the consideration for an upstream tailings dam construction (cheaper but the method prone is to failure) has become unpopular. Countries like Brazil had banned this method in 2019[11]. The standard also encourages new projects to consider new technologies, particularly dewatering technologies to reduce the risk of failure.

Furthermore, a growing call from Western markets and investors to uphold environmentally sustainable mining operations (green standards) led to the criticisms of Deep Sea Tailings Placement (DSTP). The Indonesian government had recently stopped issuing permits for DSTP for future projects in the country[13].

As most nickel laterites are located in a tropical locations (with positive water balance), a consideration to a safe, sustainable and reliable tailings management is the most important issue in a currently ESG (Environment Social Governance) – constrained business environment. Failure to address this issue early in the project development could lead to delays and/or cancellation of project permits.

Engineering and Design Considerations

<u>Ore Preparation Design</u>

Ore preparation is an area, which often receives less engineering attention compared to the rest of the flowsheet. Contrary to many public opinions, the reliability of an HPAL plant is not entirely due to the poor availability of the HPAL circuit itself BUT the reliability of an HPAL circuit and the entire flowsheet is strongly dependent on the supply of a predictable, stable, and on-spec feed from the ore preparation. Most upsets encountered downstream are likely from the poor quality of ore slurry produced from the ore preparation and/or poor integration of mine planning to the rest of the operations. Therefore, design and flexibility of the ore preparation circuit is as equally as important as the design of the HPAL itself.

The low availability of ore preparation had significantly contributed to slow ramp-ups of the second generation HPAL projects[14]. Recent generations like RNO and Gordes also suffered the same fate.

A one-week on-the-job exposure to Bulong had provided the CBNC engineering team the magnitude of challenges in materials handling of wet “clayey” laterites and the intensity of maintenance required in the area. This led to a prudent design of two individual trains with 35% design allowance (a total of 168% design capacity) for CBNC Line 1. It was recognised that operational flexibility in multiple trains was a cost-effective trade-off to shifting the capital to a larger storage tank. The dual ore preparation train not only secured a continuous feed, but it also provided the flexibility to blend proportions of various feedstocks to meet the desired requirements of the HPAL circuit.

<u>Autoclave Feed Pump and Pressure Let Down System</u>

In an HPAL circuit, there are two critical equipment systems, whose function and availability are crucial to the reliability of the overall system: the autoclave feed pump and the high pressure let-down system (see highlighted areas in Figure 4).

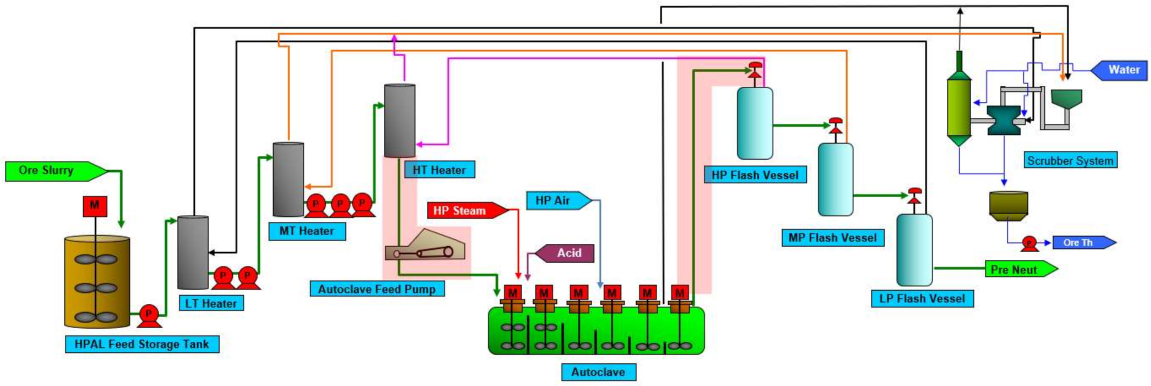

Figure 4 – HPAL Circuit Schematic Diagram

The autoclave feed pump cone valves are the highest wearing parts of the pump as they are in direct contact with the hot and abrasive slurry. Also, these are prone to failure from cavitation due to the insufficient NPSHa (Net Positive Suction Head available) which causes flashing. Often, the source of low NPSHa is the variability in solids density feeding the pump (specially at low wt% solids) and pressure loss from complex pipe runs. The design of the heater feeding the autoclave feed pump is therefore crucial in minimising the NPSHa fluctuation caused by the variability in feed.

CBNC had installed their high temperature heater, which feeds the autoclave pump more than 21m from the grade. It was placed on top of the medium temperature heater, using it as the base support structure (see Figure 5). Whereas, Ambatovy had installed their heater at about half of this height, rendering the autoclave feed pump with a very narrow safety margin. During episodes of low solids feed (under spec feed) frequent cavitation issues are often encountered.

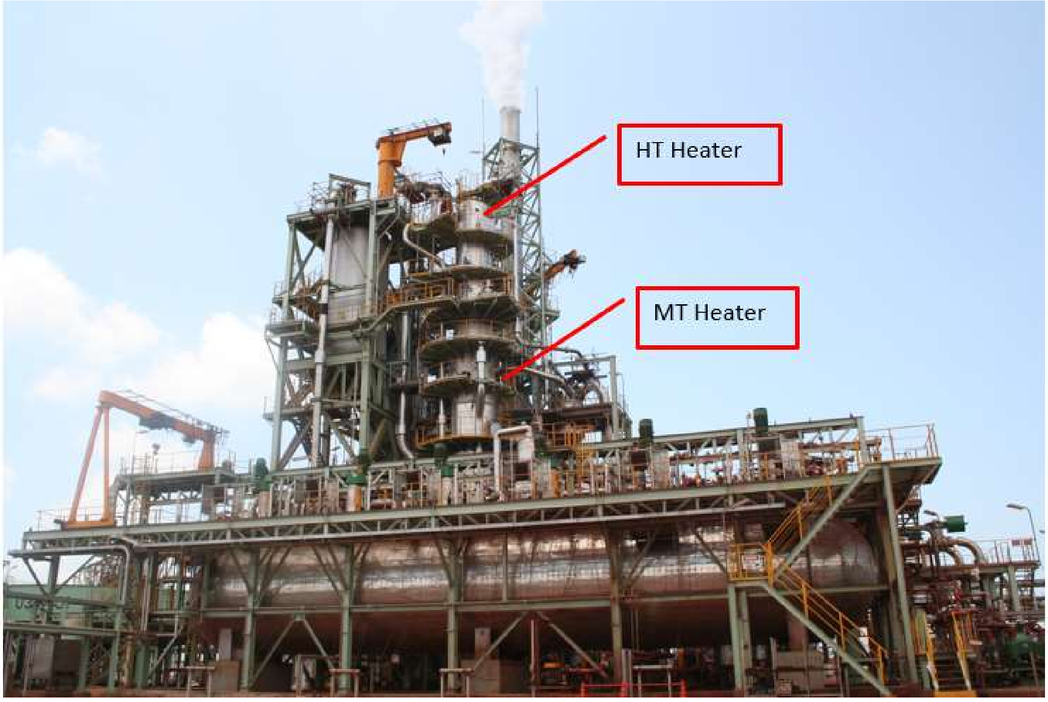

Figure 5 – Coral Bay Heater Train Arrangement

The flash system (or the pressure let-down system) is the area where the biggest energy releases / dissipation occurs in an HPAL system, making it the most violent and one of the most critical areas in the circuit. The selection of the let-down system (between a level valve - blast tube or fixed choke arrangement) is an important consideration that could impact the operating flexibility of the HPAL circuit. Coral Bay had adopted the level valve – blast tube arrangement which offers more flexibility in turndowns, where limited autoclave overpressure is available. Other HPAL installations such as RNO and Ambatovy adopted the fixed choke arrangement. The fixed choke operating range is limited to the available overpressure. Additionally, the choke solution adjustment during turndown is difficult to match to the autoclave discharge flowrate. This could result to a supersonic concentrated flow (without or with little energy dissipation), which could penetrate past the wear plate and drill into bottom of the flash tank (experienced at RNO and Ambatovy). The fixed choke arrangement also delivers a higher volume displacement in the flash tank resulting to a higher acid carry-over to the heater train (Figure 6). This subsequently causes the faster wear of the vent lines and pre-leaching of the heater slurry. The scales formed in the heater from pre-leaching are thin and brittle, which when knocked off from the walls, cause a number of issues in the autoclave feed pump system.

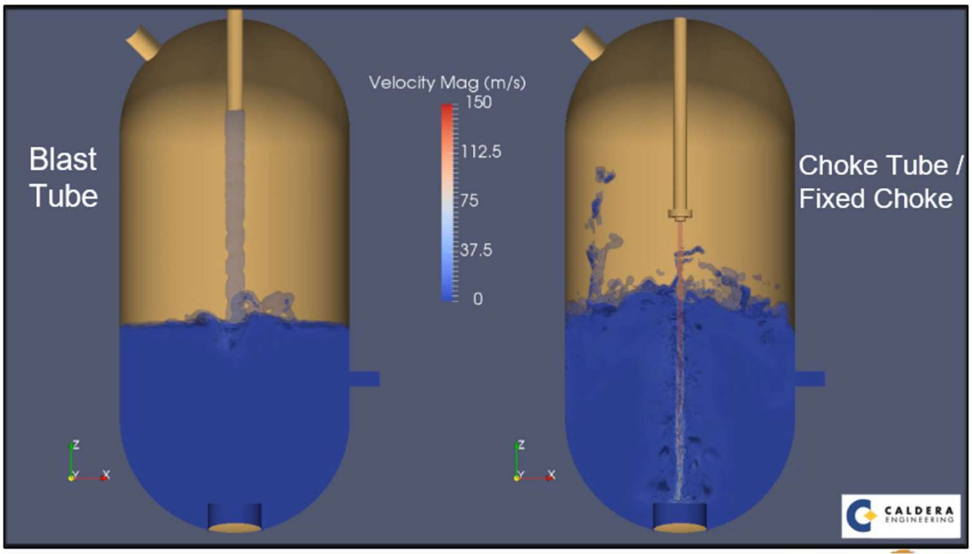

Figure 6 – Pressure Let Down System Comparison (Blast Tube vs Fixed Choke, Caldera Engineering)

Operational Flexibility

One of the important design features of CBNC is the prime consideration to maintain operational flexibility and operability. The entire project was engineered with operations in mind, starting from the early stages of project design. This was driven by an owner's team with a strong operational and engineering background. This is evident in multiple trains of preparation and redundancy in batch equipment (filters), bypass capabilities, recirculating lines for every tank/area and buffer storage such as the (Ore Slurry Storage Tank, PLS Storage Tank, H_2S Buffer Tank) which allows the box – in and de-coupling of critical areas. These features have proven to be beneficial for the project, especially during commissioning and in the early stages of ramp-up.

Of notable mention is the H_2S buffer tank (or H_2S holder) which absorbs the downtimes of the downstream Mixed Sulphide area. This tank also comes with a very high risk due to the large inventory of concentrated H_2S gas in one location. Murrin-Murrin and Ambatovy did not install it in their flowsheet for this reason. The H_2S buffer tank at CBNC represents the maturity of experience and confidence of SMM in managing the safety of an H_2S system. CBNC had significantly minimised the H_2 and H_2S gas plants from cycling during commissioning and ramp-up because of this buffer tank. When the H_2 plant shuts down, its subsequent start-up would require a very slow and controlled heat-up. Therefore, frequent cycling of H_2/H_2S plants would mean long downtimes for the entire process plant without the H_2S buffer tank.

Multiple Trains vs Single Train

The cost of multiple trains vs single trains is often a subject of debate during the engineering design. Projects team, which are focused on cost and schedule tend to argue that multiple trains cost more upfront and requires more maintenance.

There is a trade-off between the cost of multiple trains versus the benefit of operational flexibility and minimising single points of failure. However, the cost of maintenance is not quite proportional. Take for example the case of CBNC. The dual ore preparation trains secured a continuous feed to the downstream HPAL circuit even during rainy seasons, minimising downtimes (>90% availability). A single train design would have been detrimental to the HPAL circuit, considering its low availability (50-75% for a single train). Unavailability of feed would require boxing the HPAL the circuit, which subjects the whole system to a thermal cycle. Frequent thermal cycling is a major cause of mechanical failures in HPAL (gasket failure, faster wear of autoclave discharge lines, block valves and high-pressure vessel let down valve). Cycling also exacerbates scale formation. Aside from production losses, these consequences would require intensive maintenance far exceeding the maintenance requirement for a multiple train ore preparation.

Another consideration is the operational flexibility, as in the case of Ambatovy, where having a single train ore thickening created numerous problems in managing ore to ore variabilities. Even the subsequent installation of a second ore thickener only partially mitigated the ore thickening challenges. While on the other hand, a dual train of solution neutralisation circuit allowed for timely process troubleshooting and continuous feed to the downstream Mixed Sulphide circuit.

These are important trade-offs in design considerations that are often overlooked due to a short-sighted focus on capital reduction compromising long-term operability beginning at ramp-up. In a highly integrated system like an HPAL flowsheet, the owner's team must have a holistic view of the integration.

Project Execution and Operations

Commissioning and Ramp-up

Commissioning and ramp-up are probably the most critical phase of the project execution as the project transitions to operations. During this period an enormous amount of knowledge and information must be transferred by the projects team to the commissioning and operational readiness teams[2]. A study conducted by Deloitte on start-up of new capital projects had established that more than 30% of project value destruction happened during commissioning and ramp-up (refer to Figure 7)[4]. This has been the experience of many HPAL plants. Unlike a simple mineral processing plant, commissioning of an HPAL facility requires niche procedures (brick curing, thermal cycling, steam blowing, chemical passivation, pressure / tightness testing, etc) which demand a niche set of skills and experience to prepare the equipment and the process for operations.

A number of subsequent operational issues in HPAL start-ups are direct results of fast tracking the required stages of pre-commissioning and commissioning. Many of the equipment issues are left to chance, resulting in operations bearing numerous repairs and rectifications instead of focusing their efforts in integrating and ramping up the facility. Optimism and hope are not substitutes for good planning and data[8].

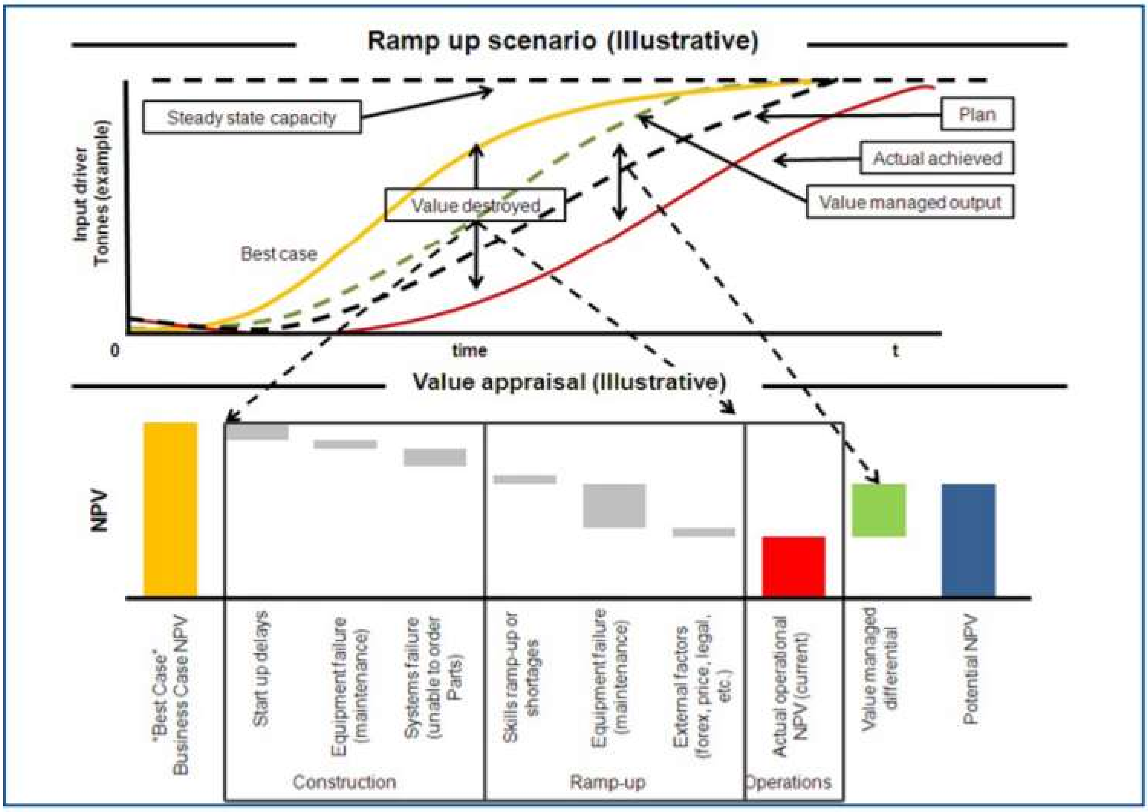

Figure 7 – New Capital Project Value Destruction (Deloitte 2012)[4]

The successful start-up of CBNC is owed to the methodical and meticulous planning of pre-commissioning and commissioning in the early stages of the project. The competence of the project EPC contractor (JGC) also played a vital role with their extensive experience in oil and gas industries, with many close analogues to HPAL. The owner's team are embedded within the commissioning team of the EPC contractor, working alongside throughout the stages of pre-commissioning and commissioning. By the time the facilities are handed over, the owner's team had already gained sufficient operational and troubleshooting knowledge / training to operate and ramp-up the plant on their own.

Operational Excellence

A well-engineered and managed project only delivers a facility that still needs to be run and generate returns to its investors. The owner's team who will take-over the project from the EPC contractor has the ultimate responsibility to start-up the plant successfully. 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.

Any future projects and operating plants should reference the best practices that constitute the operational excellence at Coral Bay as follows[19]:

- Key Filipino (national) workforce (maintenance and production) are embedded early in the project execution to gain better understanding of the process chemistry and flowsheet including key operational and maintenance challenges.

- Technical training and cultural immersion in Japan early in the project – the pioneer workforce was sent to Niihama Nickel Refinery in Japan to acquire technical skills and perspective in operating a complex hydrometallurgical facility. Both Filipinos and Japanese were also engaged in a cultural exchange and immersion to foster a good working relationship. This led to an effective transfer of knowledge between the Japanese mentors to their Filipino counterparts. Filipinos trained overseas became mentors to subsequent workforce brought on-board.

- Operations personnel were embedded in the pre-commissioning and commissioning, which enriched their understanding and appreciation of individual equipment and instruments. It also provided an opportunity to learn and practice problem solving skills.

- Balanced priority on nickel and cobalt recovery over throughput – workforce had a good understanding on the volumetric / hydraulic limitations of the pipe and the equipment. The priority is stability of the integrated process and delivering constant, desirable ore slurry feed to the autoclave with the following precedence of control: U/F density>Mg>Ni.

- Advance ore feed knowledge – informs the blending strategy and enables the predictability of downstream process performance so countermeasures are planned and implemented ahead of the feed.

- 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.

- Good operational and maintenance discipline (proactive approach) – equipment is operated within the design envelope establishing predictability in performance and maintenance. Operators are well-rounded and armed with holistic view of the process. They function as operator-maintainer and minor issues are immediately abated before they escalate into a bigger problem.

- Effective implementation of SMM corporate philosophy, which embodies prudency and foresight. This guiding principle 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.

Importance of Work Psychology and Strong Work Culture in HPAL Operations

Despite the advances in project delivery practices and technology, improvements in design and people skills, the question remains *Why do failure of HPAL plants persist?*
In the author's observation, it is not entirely because the industry has not learned. In fact, the industry at large gets most of the technical aspects right, but a large part of the recurring issue has something to do with the workforce psychology and work culture.

In a complex and integrated operation like HPAL, quick and rationalised decision-making is very important. This is because when upsets happen, they happen very quickly, and consequences are far reaching due to the nature of integration. Ideally, the workforce should have a level of decision-making regardless of where they sit in the organisation. They should be enabled to solve their own problems without relying to authority for help. These are important elements of what is termed Adaptive Leadership. This form of leadership lends itself from a strong foundation of work culture and principles which aligns people to the same core values and goals[7]. There is a significant advantage in businesses practicing Adaptive Leadership as demonstrated by the success of CBNC and Ambatovy.

A workforce that has good understanding of both process and equipment functionality is enabled to make informed and timely decision-making. When operators are given the latitude to make decisions and solve their own problems, they develop confidence and a sense of ownership. A workforce that feels included and has a sense of accomplishment, will go above and beyond their job description and deliver more. Middle managers can then dedicate their time managing the workplace and their people, improving the efficiency of day-to-day operations.

The practice of Adaptive Leadership at CBNC is a significant factor of its successful operations. Likewise, the inception of PEI for a year had a made a tremendous difference in a mega facility like Ambatovy. The PEI team practiced Adaptive Leadership, helping the Ambatovy workforce help themselves. While the mandate was purely technical, the team went on to re-create and promulgate the Sherritt culture (data-driven decision-making and workplace camaraderie), which provided a common ground for people especially the operators. Even though, the PEI team was only small in numbers (a dozen members at any given time), it was able to deploy resources efficiently and helped the entire facility achieved its best operating year and financial completion.

CONCLUSION

HPAL has made a major leaps of progress on technical aspects since the second generation plants. This is evident in improvements in: safety, critical equipment design, materials of construction, constructability, and levels of automation.

As mining continues to evolve, a new challenge has emerged. The demand for a sustainable and safe tailings disposal in mining operations is increasing. This is an important issue which needs to be addressed by future HPAL projects.

The need for a competent engineering services provider and owner's team, in particular, right from the project development cannot be overstated. Stakeholders come and go throughout the project phases but what remains constant in the lifecycle is the owner's team.

The success story of CBNC and subsequent SMM installations (CBNC L2 and THPAL) is a product of technical improvements combined with excellence in human capital throughout its project lifecycle. The Sumitomo work culture embedded in project delivery and operations is a key factor in success of these facilities. The positive impact of work culture and adaptive leadership is likewise observed in the successful ramp-up and financial completion of Ambatovy in 2015.

Technology is constantly improving and is highly imitable. Technical knowledge is widely shared and can be acquired. Technical skills can be learned. But the work culture is unique to each owner. An organisation with a strong work culture fosters efficient and empowered workforce, which ultimately drives the project to success. This is one of the important keys to a successful HPAL design and operations.

ACKNOWLEDGEMENTS

The author is grateful for the peer review and inputs of esteemed colleagues within the nickel and HPAL community - Mark Benz (MRB Consulting) and Mark Steemson.

Further appreciation is due to Coral Bay Nickel Corporation for their review and permission to publish the data and information mentioned on this paper.

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