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ALTA Metallurgical Services PO Box 1211, Blackburn North, Vic, 3130, Australia
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Nickel-Cobalt-Copper Keynote

PROCESS EXPERTISE:
THE KEY TO MANAGING HYDROMETALLURGICAL PROJECT RISK

By

Mark Benz
President
MRB Business Services (Canada)

mrb-business-services@shaw.ca

ABSTRACT

The feedstocks for ore beneficiation and subsequent extraction and recovery of metals have always had at least some unique and variable characteristics. Therefore the development and selection of a given project's extractive metallurgy, and its implementation, operation and optimisation are often critical to the project's success. Today, new ore bodies are declining in grade demanding increased scale to maintain economics. These same resources are increasing in complexity and are often remote from developed industrial infrastructure and workforces. Worker and process safety, sustainability, environmental and local stakeholders' demands are rising. Yet the prices of process inputs and recovered metals continue to be volatile. Hence, the required sophistication and robustness of all aspects of project execution and operation have substantially increased and the deployed extractive metallurgical technology is no exception.

Successful development, selection, implementation and operation of extractive metallurgical technologies requires skillful and experienced scientists, engineers, practitioners and management throughout the life of the project. Unfortunately this key element, process expertise, is often characterised and managed as a series of cost and/or headcount budget items, rather than what it really is - an investment in the risk management of the enterprise.

From a hydrometallurgical perspective, this paper will:

- outline the attributes, origin and development of process technology staff,
- address challenges and strategies to effectively source, deploy, train, maintain and manage the process expertise required throughout the life of a mining and metals venture, and
- present cost/benefit examples.

Keywords: Extractive Metallurgy, Hydrometallurgy, Project Risk Management, Process Expertise, Process Development, Technology Implementation, Technical Process Support, Process Optimisation, Training

INTRODUCTION

The level of success or failure of mining and metals projects and operations has always had healthy scrutiny. Often projects do not live up to expectations and determining and characterising the causes continues to be an area of intense study. Major hydrometallurgical (hydromet) projects are no exception; for example, many of the nickel laterite HPAL projects have not been economic successes for the initial owners.

Cunic[(1)] noted that 80 percent of a plant's life cycle costs will be committed by the end of the detailed design phase and that project owners must plan, design, build and purchase equipment based on not only the initial capital cost but also the long-term impact on the project life cycle. After facility and process designs have been finalised, the ability to affect the plant's life cycle costs are constrained and can be very expensive.

Thus the importance of the work prior to construction is critical and the importance of an objective, realistic feasibility study for projects cannot be overstated. Feasibility study methodologies and best practice have been discussed by Mackenzie and Cusworth[(3)], and Bacon[(2)] has outlined pitfalls of feasibility studies. Papers by Bacon[(2)], Campbell et al[(4,5)] and Wasmund et al[.6)] review the prerequisites for sound design of metallurgical process plants.

The aforementioned authors as well as Agarwal[(7)] and Lunt[(8)] specifically discuss overcoming the challenges of start-ups. Dobson et al[(9)] do the same, emphasising the value and training of competent personnel in the Cawse Nickel start-up. Valle et al[(10)] come to a similar conclusion in their paper on the Ambatovy start-up. Southwick[(11)] presents a number of technology cases, again emphasising the need for competent technical personnel, noting they can be scarce.

Many of these authors reference McNulty's work[(12,13,14)] in characterising new technology start-ups. In particular, the features of projects that have difficulty achieving design throughput and production are listed. Again, the availability of competent engineering, supervisory staff and technical support during commissioning and start-up feature prominently. "McNulty ramp-up curves" are now part of the lexicon of those striving to commercialise new metallurgical technology.

While the business risk to a project or new operation is most acute during construction, commissioning and ramp-up, consistently achieving targeted operating KPIs (Key Performance Indicators) during subsequent operations is important to ensure the continuing success of the enterprise.

Executing the strategies and tactics throughout a project's life require decisions to be made by people. Risk must be managed and that requires expertise. The feedstocks for ore beneficiation and subsequent extraction and recovery of metals have always had at least some unique and variable characteristics. Therefore the development and selection of a given project's extractive metallurgy, and its implementation, operation and optimisation are often critical to the project's success. Hydrometallurgical projects harness processes that entail, to a lesser or greater degree, technical risk. To manage this risk takes process expertise. In this paper, the author will argue that establishing and maintaining process expertise needs to be viewed as an investment in the risk management of the enterprise. This is becoming more critical as hydrometallurgical projects and operations face the challenges of today.

THE CHALLENGE

For some time ore bodies have been declining in grade, demanding increased scale to maintain economics. The global long term trends for copper and nickel grades as reported in the UNEP report, "Environmental Challenges of Anthropogenic Metals Flows and Cycles", are well shown in Figures 1 and 2[(15)].

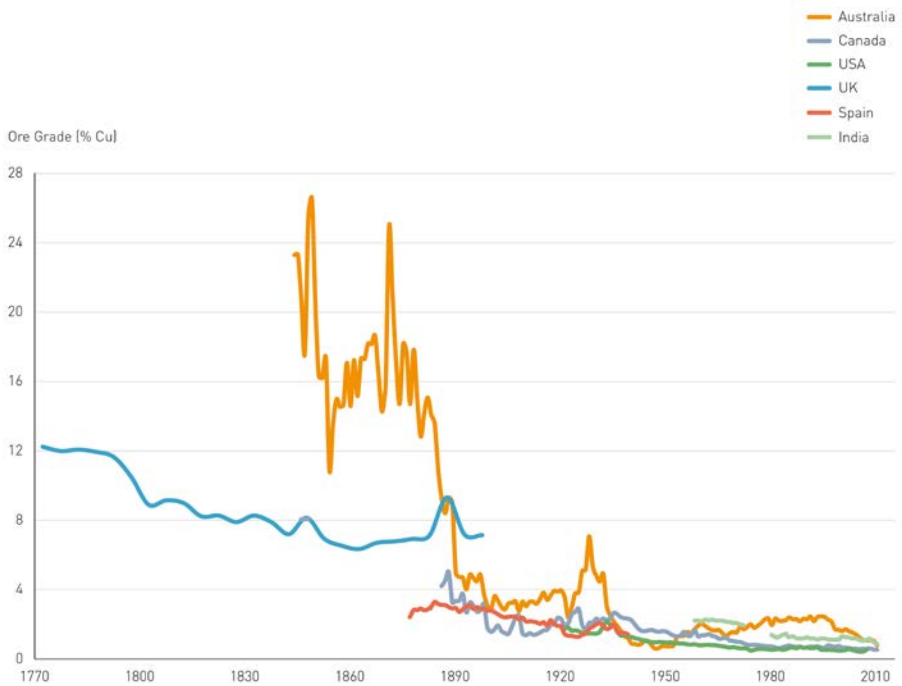

Figure 1 – Long-term Trends in Processed Copper Ore Grades[15]

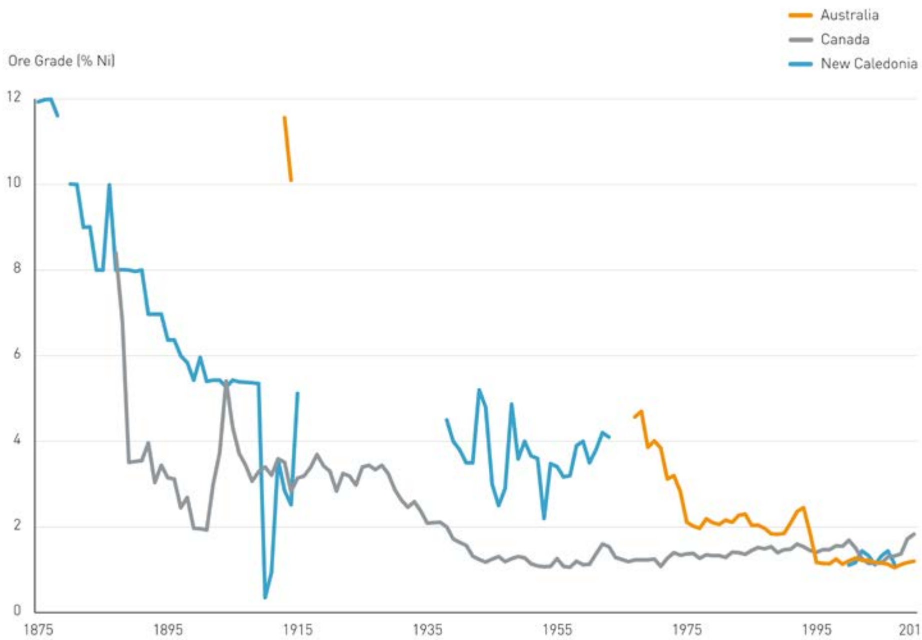

Figure 2 – Long-term Trends in Processed Nickel Ore Grades[15]

The UNEP report data for specific major mines is a further example of declining grades (Figure 3)[15].

Figure 3 – Long-term Trends in Processed Copper Ore Grades at Specific Mines[15]

These same resources are increasing in complexity, particularly in terms of by-products and recognised toxins. Metals and chemicals not recovered are either emissions or impounded as hazardous waste. The international copper, nickel and zinc study groups often present the challenge as the "Metal Wheel" chart in Figure 4[16].

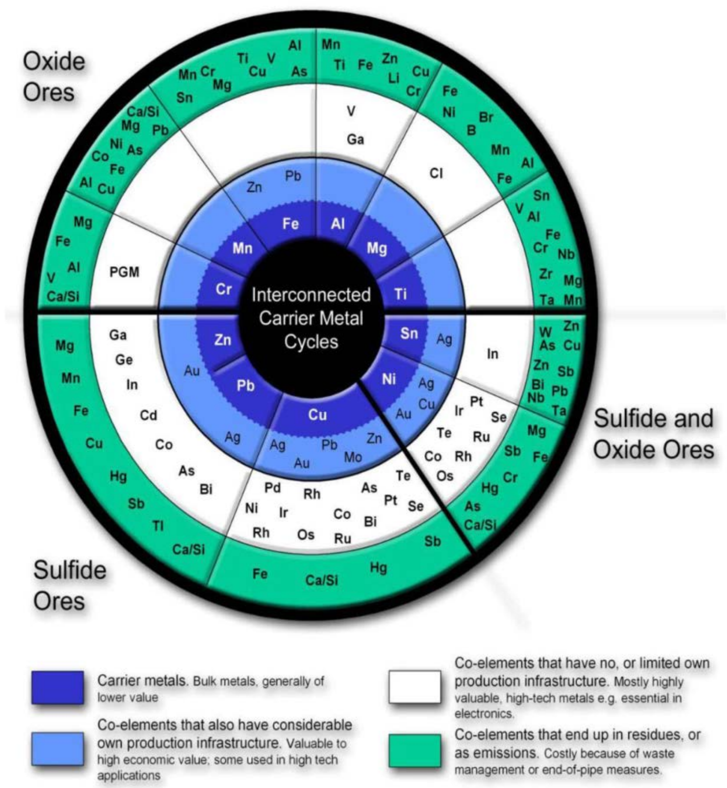

Figure 4 – Metal Wheel of Major Metals and their Co-products, By-products and Unrecovered Co-elements[16]

Copper can be considered the bellwether base metal regarding the increasing pressures of impurities. Undesirable elements are increasing in copper concentrates and intermediate products, challenging the industry and trade in concentrates (Figures 5 through 7)[16, 17].

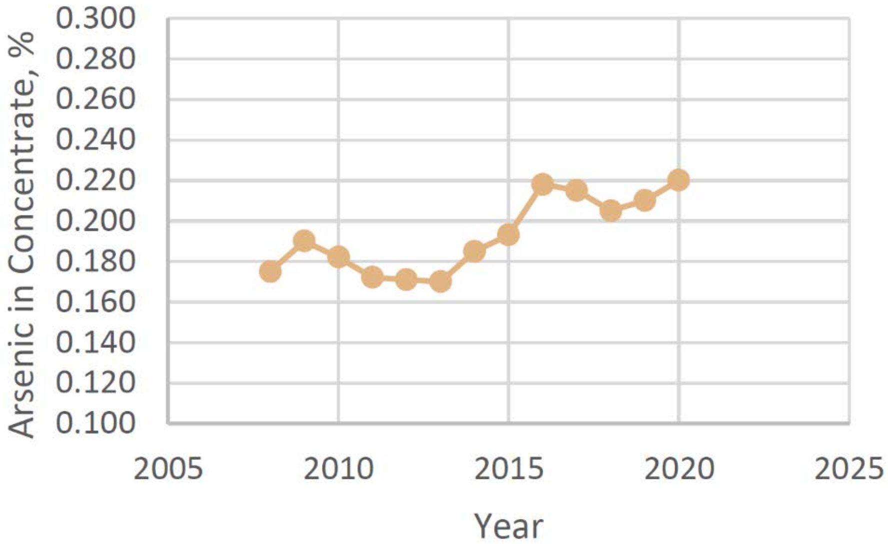

Figure 5 – Average Arsenic in Global Copper Concentrates[17]

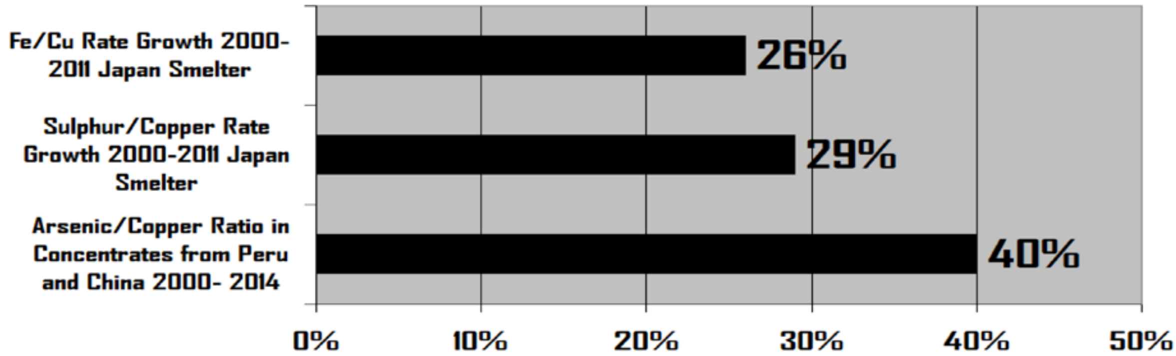

Figure 6 – Impurities Rate Growth in Recent Years in Copper Concentrates and Smelters (Metal Economics Research Institute, Japan, Estimates)[16]

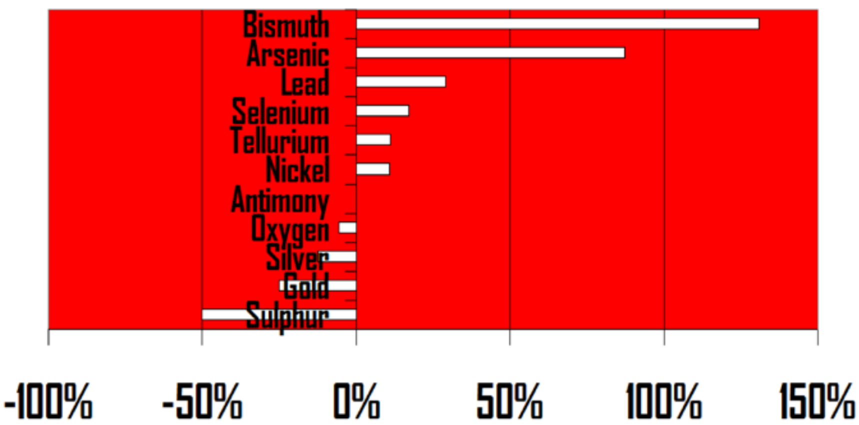

Figure 7 – Impurities Content of Copper Anodes of 30 Electrolytic Refineries, % Growth 2003-2016[16]

Hydrometallurgical processes can operate at high temperature and pressure and handle, generate and produce hazardous substances at a global industrial scale including, but not limited to: sulphuric acid, caustic soda, oxygen, hydrogen sulphide, sulphur dioxide, ammonia, steam, coal, natural gas and other fuel stocks. Such facilities cannot really be distinguished from other heavy chemical industrial operations, including oil and gas and petrochemical production plants that are recognised to have major process hazards among the biggest risks to its business (Figure 8). Additionally hydrometallurgical plants can have major impoundment and tailings dam facilities that need to be managed. Process safety management of these facilities is an important element of the overall risk management.

Figure 8 – Left to Right: Suncor Bitumen Upgrader in Ft. McMurray, Canada; Alcoa Alumina Refinery in Kwinana, Australia; Ambatovy Nickel Laterite Operation in Madagascar [18, 19, 20]

Furthermore, these projects are often remote from developed industrial infrastructure and workforces creating human resource challenges and personnel retention risk. Procurement of necessary materials and services can be a real challenge. The extent to which copper and nickel deposits are scattered around the globe is shown in Figures 9 and 10, respectively.

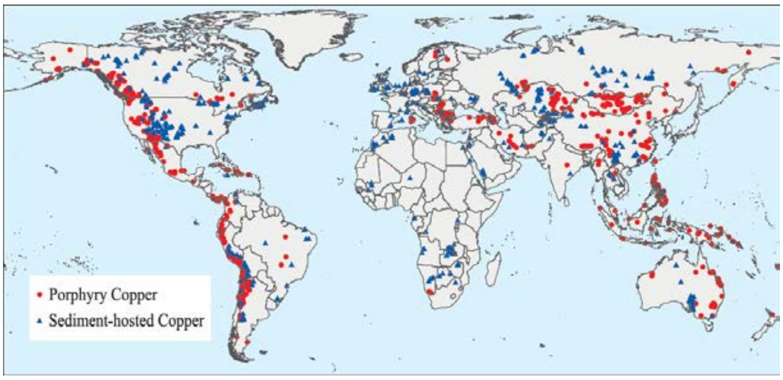

Figure 9 – Global Location of Copper Deposits[21]

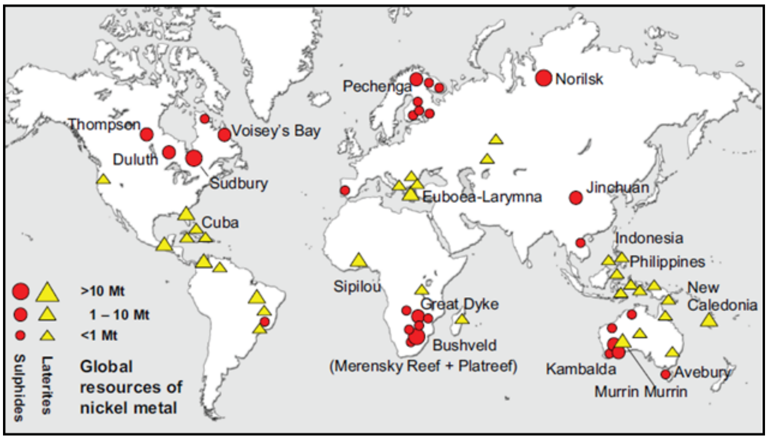

Figure 10 – Global Location of Nickel Deposits[22]

The prices of process inputs and the metal products are volatile. The constant USD prices of copper, nickel, cobalt and base metal index are compared to those of key inputs to mining and metals industries since 1981 in Figure 11. Interestingly, relative to 1981, with the exception of cobalt, metal prices have been at an advantage to input prices from 1987 through 2011. Copper has maintained this advantage to the present. More recently energy prices have dropped faster than that of metals.

Figures 12 and 13 track the relative year-to-year price changes of metals and inputs, respectively. Volatility of both are very evident. A 25% year-to-year change appears normal. Excluding sulphur, which has extraordinary relative variability, the average and median values of the presented year to year price change are 21% and 15%, respectively.

Furthermore, market watchers do not have a good record of forecasting base metal prices. Looking at the flagship base metal, copper, since January 2000, the consensus quarterly forecasts only finally converged with actual prices in 2015, and perhaps only coincidentally (Figure 14).

Thus, the attributes of today's mining and metal enterprises:

- declining grades,
- increasing metallurgical complexity,
- process safety,
- tightening environmental expectations,
- often remote projects, and
- volatility of input and product metal prices

translate to increasing and formidable business risk.

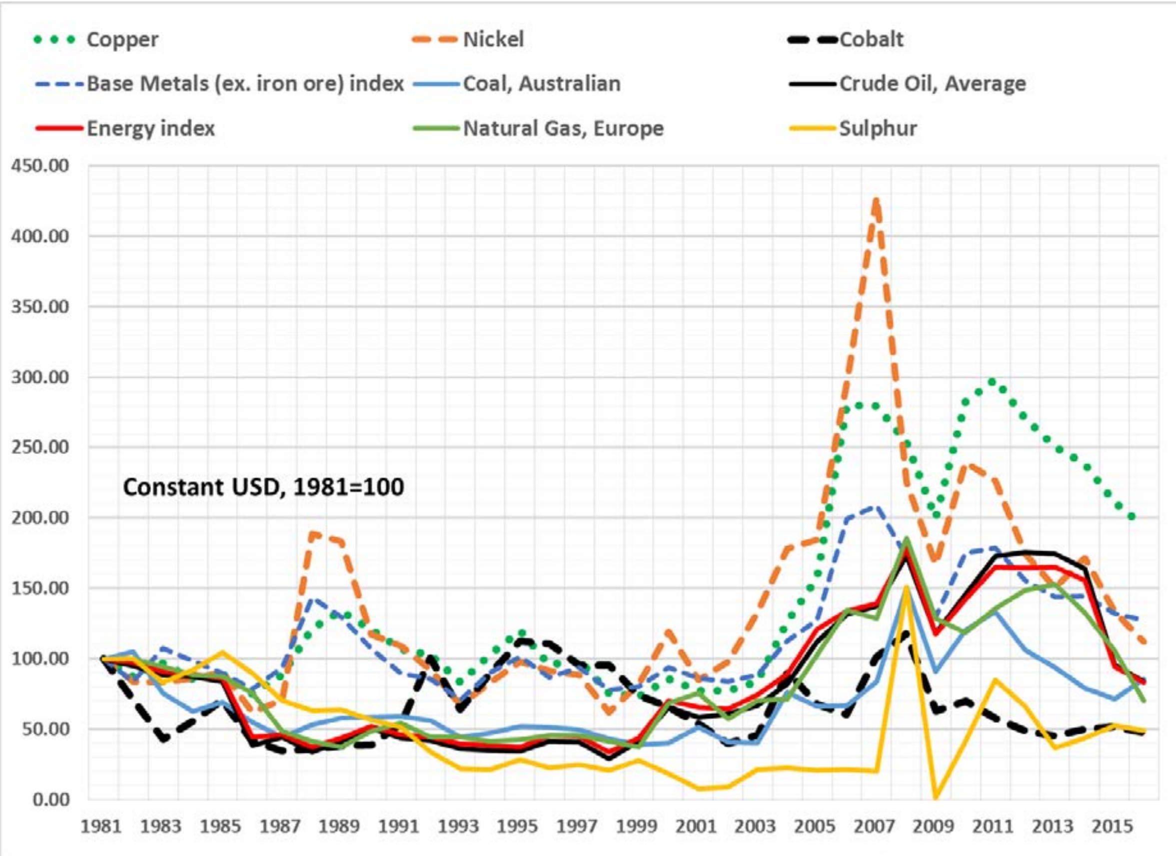

Figure 11 – Copper, Nickel Cobalt and Selected Input Prices[23, 24]

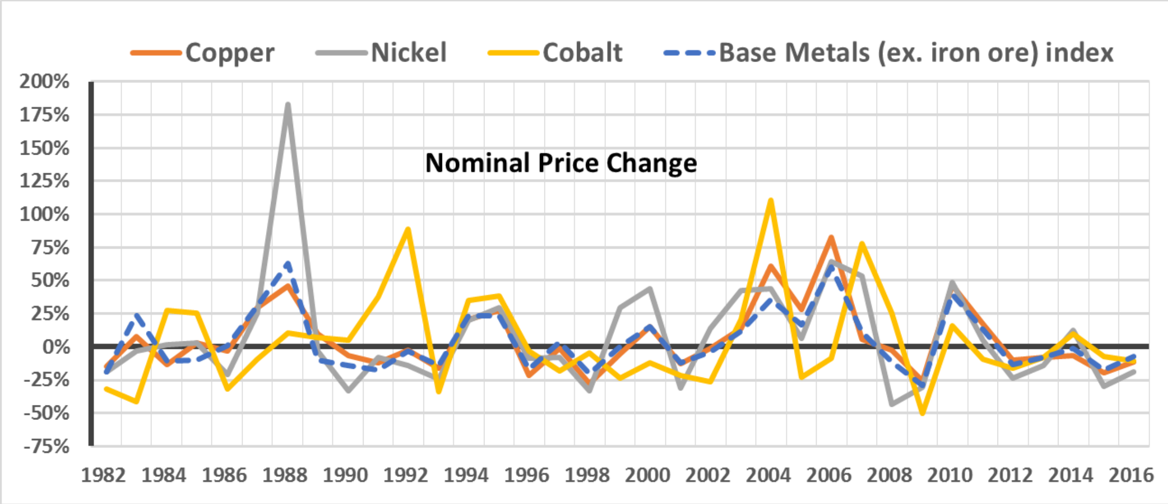

Figure 12 – Copper, Nickel, Cobalt & Base Metal Index Year to Year Price Changes(23, 24)

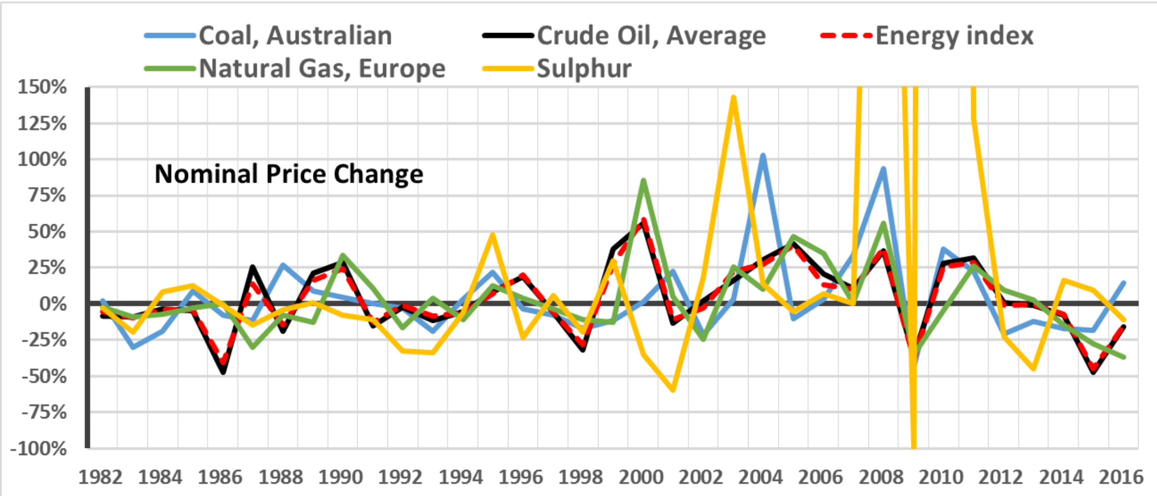

Figure 13 – Selected Input Year to Year Price Changes(23, 24)

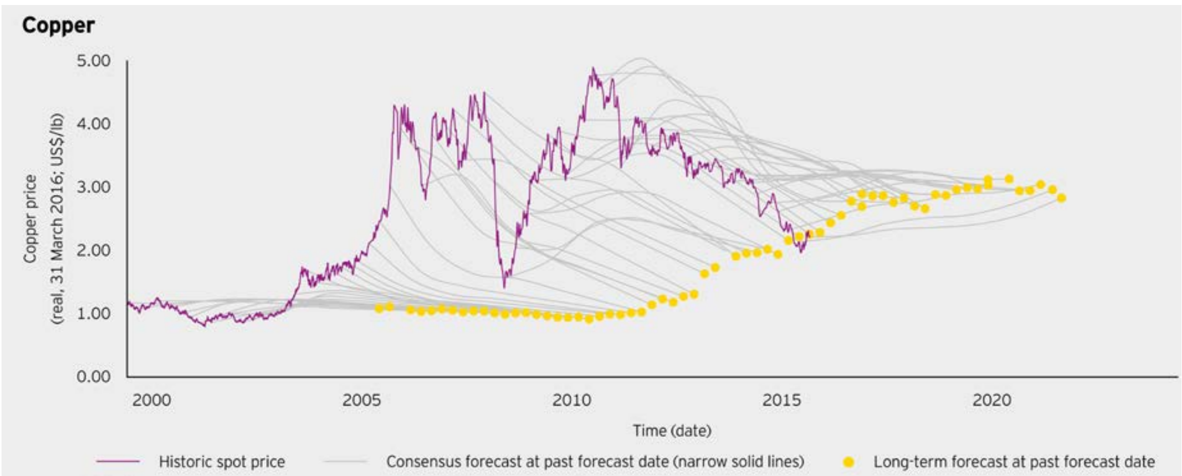

Figure 14 – Copper Spot Price and Consensus Quarterly Forecasts from 1 January 2000(25)

MEETING THE CHALLENGE: HOW ARE WE DOING?

How has the mining and metals sector fared in facing the previously described business risks? The MSCI World indices over the last 20 years or so give some insight. The indices below (Table 1) capture the large and mid-cap segments across 23 developed markets (thus excluding emerging and frontier markets).

Table 1 – Index Performance – Gross Returns (%) (March 31, 2017)[26,27,28]

					Annualised			
	1 Mo	3 Mo	1 Yr	YTD	3 Yr	5 Yr	10 Yr	Since Dec 30, 1994
MSCI World Metals & Mining	-1.72	6.85	40.55	6.85	-5.88	-7.30	-4.11	3.28
MSCI World Energy	0.17	-4.79	15.29	-4.79	-6.20	-0.26	1.65	9.02
MSCI World	1.14	6.53	15.43	6.53	6.12	9.99	4.81	7.30

The MSCI World & Metals & Mining Index represents a market capitalisation totalling USD 523 billion over 39 constituents representing diversified metals & mining, base metals, precious metals and steel players (the latter being 17% of the total)[26]. The MSCI World Energy Index represents a larger sector with USD 2.3 trillion market capitalisation, covering all parts of the oil, gas and coal industry[27]. The MSCI World Index covers approximately 85% of the free float-adjusted market capitalisation in each of 23 developed markets, totalling USD 35 trillion in value[28].

The volatility of energy and metals & mining is clear; these industries are not for the faint of heart. Since the end of 1994, the overall World and Energy indices have outperformed Mining & Metals substantially. The (simple) annualised gross returns since the end of 1994 of the World and Energy indices approximate cumulative increases in value of 162% and 205%, respectively. By comparison, the Metals & Mining index calculates to a cumulative increase of only 73%. It should be noted from Figure 11 that since the end of 1994, the Energy Price Index has roughly doubled, while the Base Metals Price Index has only increased by about 50%. As an interesting construct from Golden Dragon Capital shows (Figure 15), some metals & mining operators are regularly squeezed to just cover their cash costs[22].

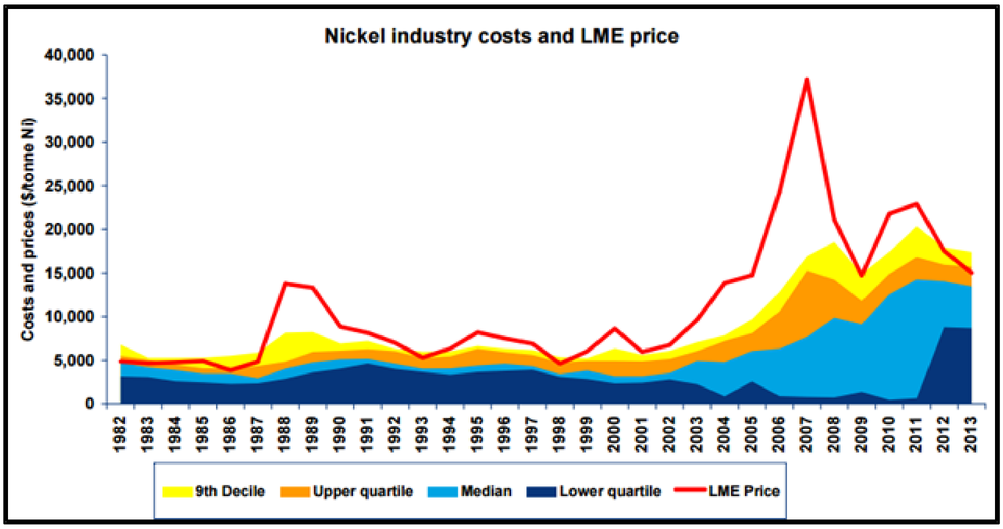

Figure 15 – Nickel Industry Net Direct Cash Costs and LME Price[22]

The mining industry has a chequered past delivering projects that live up to their economic expectations. Bacon in 2008 noted that 75% of projects exceed the upper limit of capital cost estimates in their feasibility study. Recent hydromet nickel laterite projects underscore this under-performance[(2)]. Things have not improved for project delivery. In 2014 Ernst & Young surveyed 108 mining and metals projects, all with a value of greater than USD 1 billion, representing investments of USD 367 billion. For those projects with available cost data, a stunning 69% were facing cost overruns with an average cost overrun of 62%. 50% of projects were reporting schedule delays even after remedial acceleration initiatives had been applied[(29)].

With respect to performance after initial project delivery, McNulty notes in his most recent update of plant ramp-up profiles that a mere 28% of 81 projects fit the profile of achieving name plate capacity in 36 months or less (McNulty Series 1 or better)[(14)].

Accompanying swelling costs, environmental pressures are increasing. Among the most visible regulatory targets are greenhouse gas emissions and water use. Declining grades coupled with the process configuration are the most important factors. That the impact is substantial is evident in Figures 16 and 17. Permits or taxes (or both) are pressuring the mining and metal operators to decrease the intensity of consumption of energy and water.

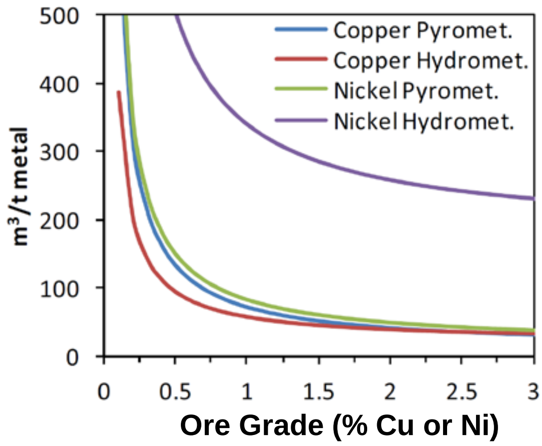

Figure 16 – Estimated Direct Water Consumption for Refined Metals vs. Ore Grade[(30)]

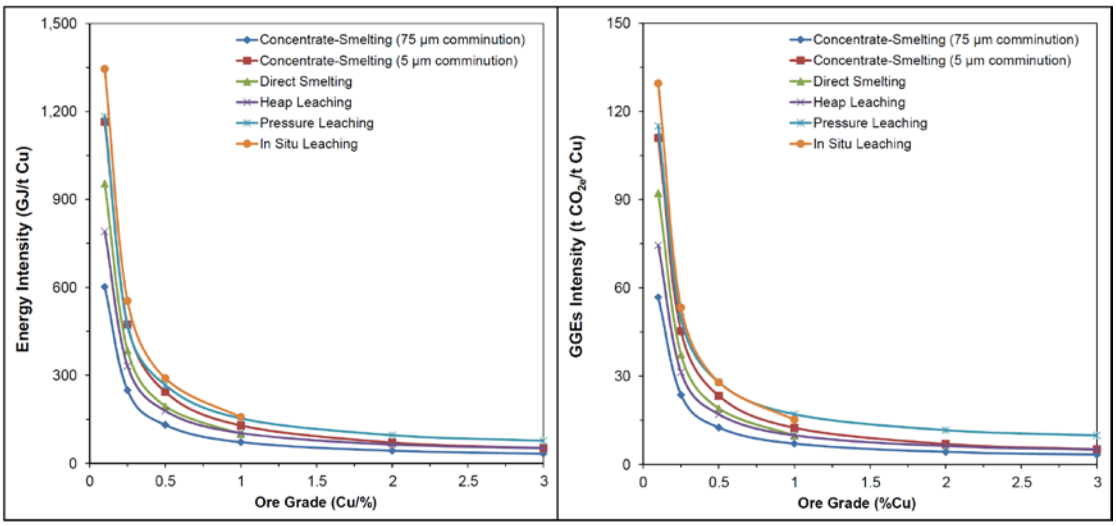

Figure 17 – Energy and Greenhouse Gas Emissions (GGEs) of Copper versus Ore Grade[(31,32)]

There is no better reminder that hydrometallurgical operations can be heavy industrial plants with all the attendant process risks than the explosion in the United States at the Gramercy alumina plant in July, 1999. The cause of the explosion, which injured 29 persons, was excessive pressure in flash tanks and a blow-off tank in the digestion area of the plant. The explosion caused catastrophic destruction to the digestion area. The forces of the explosion released more than 400,000 pounds of sodium hydroxide into the atmosphere. Residue settled on homes, buildings, and vehicles in the towns of Gramercy and Lutcher, located approximately 3 miles away. The explosion blew portions of the blow-off tank and four flash tanks hundreds of feet from the digestion area. The dome of Flash Tank No. 6, which weighed approximately 7,600 pounds, was propelled about 3,000 feet from its original location. Figures 18 and 19 show the extent of the damage(33).

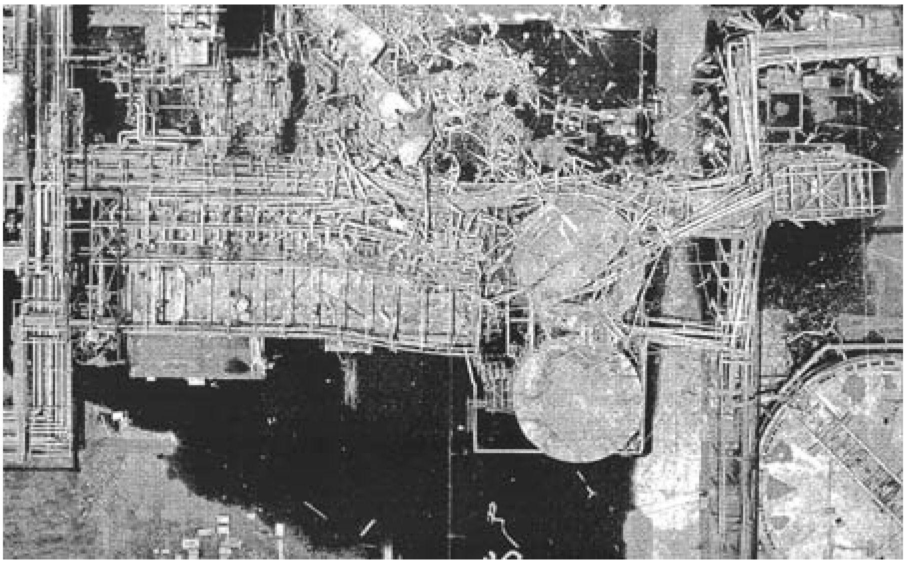

Figure 18 – Gramercy Alumina Plant - Aerial Photograph of Site (Post Explosion)(33)

Figure 19 – Gramercy Alumina Plant – Digester Area Before and After Explosion(33)

Mining and metals, including hydromet projects, have had less than stellar returns over the past two decades. Costs are rising relative to metals prices. Projects more often than not do not deliver anticipated returns. Lower grades are driving up the emission of GHGs and the consumption of water, two high profile and important environmental dimensions of today's industry. Hydrometallurgy like other heavy industrial enterprises has major process hazards and major accidents have occurred. These business risks have proven to be far more than theoretical and are linked to the processes employed and require process expertise to manage the risk.

HYDROMETALLURGICAL PROCESS EXPERTISE

Hydrometallurgy employs mainly inorganic aqueous chemistry to extract metals from ores, concentrates, and various waste products with the subsequent metals recovery from these solutions. By the time of Agricola, the father of modern metallurgy, in the 16th century, hydrometallurgy was known, though considered a sideline invented by alchemists in their search for gold(34). That aqua regia dissolved gold was discovered in the 9th century and the cementation of copper onto iron had already been practiced in Spain and China. However, successful industrialisation of hydrometallurgy only came about in the late 19th century with the application of cyanidation of gold and the Bayer process for the production of alumina, the latter the first major pressure hydromet process. Hydrometallurgy is the younger metallurgical sibling to extractive pyrometallurgy and the forming of metals.

A hydromet process, like any other industrialised chemical process has inputs and outputs, science that governs it, facilities that contain and control it and people and organisations that run it. This kind of process can be viewed as a series of concentric wheels, the "Process Wheel" (Figure 20) which also outlines the elements of the required process expertise.

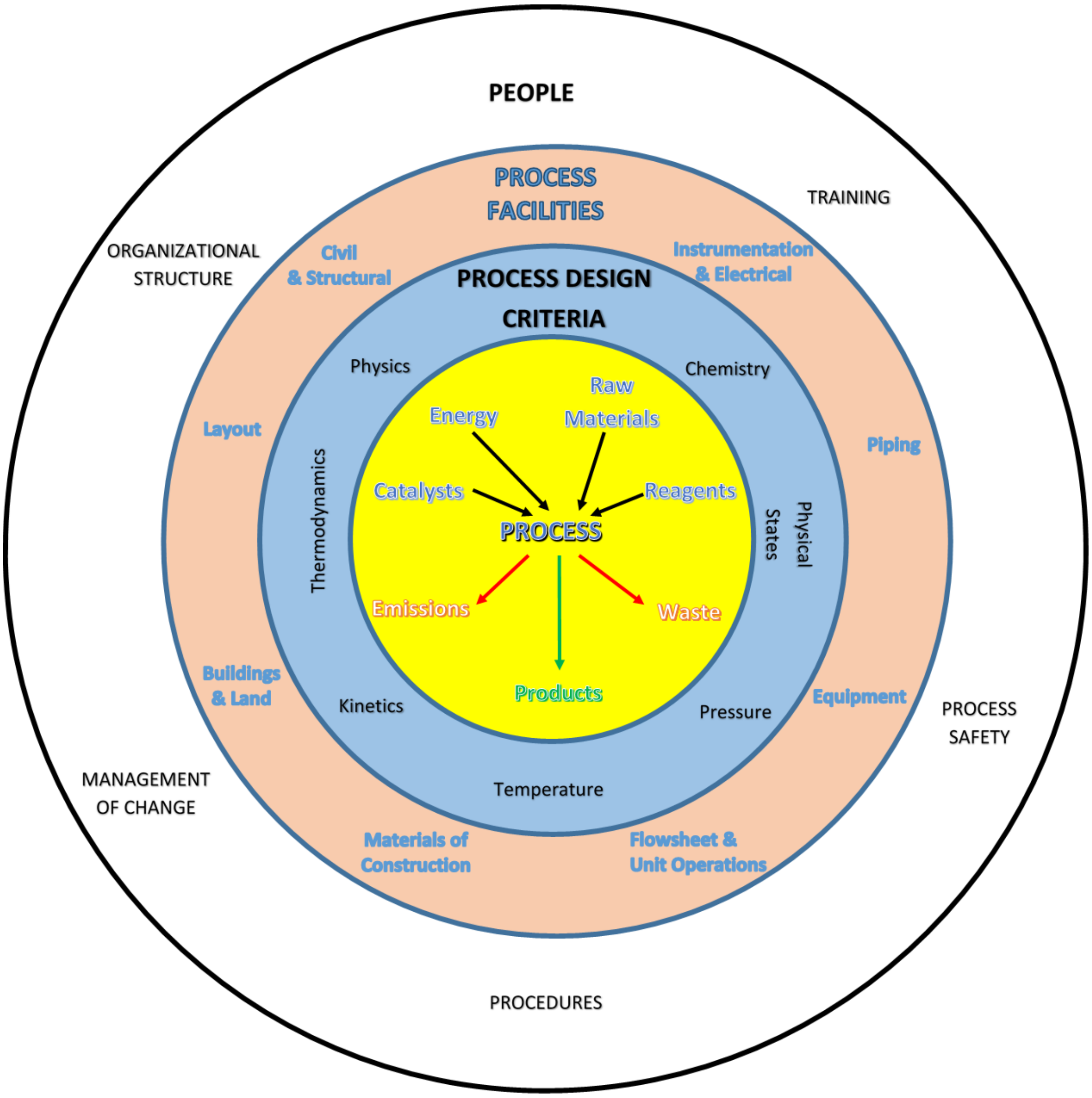

Figure 20 – The Process Wheel

Projects and ongoing operations reliant on hydrometallurgy treat resources and/or feeds that are at least to some extent a unique blend of minerals and elements. Therefore, a purpose-specific flowsheet must be developed and employed to:

- apply the classical suite of aqueous chemical unit operations of hydrometallurgy:
    - leaching, both atmospheric and pressure,
    - chemical precipitation and crystallisation – atmospheric, pressure and vacuum,
    - liquid/solids separation – thickeners, clarifiers, filters, centrifuges,
- apply chemical engineering separation unit operations - distillation, scrubbing and gas disentrainment,
- apply heat transfer operations – evaporation, condensation, drying,
- employ electro-hydrometallurgy – electrowinning, electrorefining,
- more recently, utilise a "4th organic phase" – activated carbon, ion exchange resins and solvents for unit operations such as carbon-in-leach, carbon-in-pulp, resin-in-pulp and solvent extraction,
- use a wide variety of gas/liquid/solid reagents – e.g. air, ammonia, oxygen, hydrogen, hydrogen sulphide, sulphur dioxide, carbon dioxide, caustic soda, sulphur, limestone, lime, etc.
- store, control and transfer solids, liquid and gas flows as well as their multiphase mixtures – aqueous liquid/solid/gas/organic,
- control emissions and minimise and safely impound waste and effluent, and
- through out it all, manage the all-encompassing water balance – sometimes the local environment makes the water scarce and/or of poor quality, sometimes there is too much, and at times within a meteorological cycle, both.

Hydrometallurgy, of course, is often combined with mineral processing and pyrometallurgy for the overall flowsheet of a metallurgical enterprise.

Thus, while the application of generic skills and principles apply, for hydromet processes the hydrometallurgical context counts heavily. Applying the above list to the "Process Wheel":

Process → Process Design Criteria → Process Facilities → People

highlights a distinctive framework of expertise.

The process expertise is held by the scientists, engineers, practitioners and management running and maintaining a hydromet process throughout the life of the project. Importantly this cadre includes not only technical and management professionals with extensive university schooling, but field operators and tradesman whose education is many years of hard won relevant experience, day-in-day-out, shift-in-shift-out, on the front line of the process. In the author's experience these veterans are often the best educated process expertise. John Marsden captures the spirit of how education supplants schooling in his "Top 10 things a metallurgical or mineral processing graduate should do"(35):

- accurately trace a pipe through a plant,
- work night shift as an operator,
- use a Marcy cup (correctly),
- work on a mill relining job – inside the mill,
- hose out a sanded thickener (completely),
- etc.

Regardless of the origin of the practitioner, there is a progression best characterised by classical trade nomenclature: apprentice → journeyman → master craftsman. Those that master the skill not only have the knowledge and experience, but have the maturity to connect the dots, and know what to ***not*** to (bother to) do. This wisdom comes with time; one needs to have been practicing long enough to experience circumstances that occur only infrequently but can present substantial risk or opportunity if one looks beyond the immediate appearances and symptoms. Those with the additional appropriate soft skills can become trainers, supervisors, managers, mentors and leaders ensuring the process continues to generate economic returns. Hydromet innovators (at all levels) use their deep expertise to successfully import ideas from other fields.

Malcolm Gladwell in his book "Outliers: The Story of Success" coins the "10,000 Hour Rule" - that to achieve world class expertise takes a great investment in practice within the field in question(36). While some critics have argued this is simplistic, the reality is that extensive practice, while not on its own sufficient, is necessary to develop process expertise. True expertise in hydrometallurgy (by nature of the subject's details) is not fungible with that from distantly related or other process fields.

WHERE PROCESS EXPERTISE IS USED

The "value chain" was coined more than 30 years ago by Michael Porter, a Princeton graduate in aeronautical and mechanical engineering who went on to a PhD and professorship in business and economics at Harvard. Porter, one of the most cited and influential authors in business and economic strategy, introduced the value chain as a tool highlighting a company's strategically relevant activities in order to focus on the sources of competitive advantage that can result in higher prices or lower costs and ultimately earn margins. By determining and analysing their business's value chain, leaders and managers consider these activities not as costs but as steps that add value to a product or service[37].

Porter's generic value chain comprises:

- Primary activities that in series physically create the product, its sale and transfer to the customer as well after sale assistance. These would be inbound logistics, operations, outbound logistics, sales & marketing and after sales service.
- Activities that support the primary activities and each other by providing procurement, technology, human resource management and various corporate functions.

In later work Porter developed the powerful concept of "Shared Value" to take corporations beyond the single dimension of profits that today are softened by endeavours such as corporate social responsibility programmes. Shared Value has policies and practices that enhance the competitiveness of a company while simultaneously advancing social and economic conditions in the communities in which it operates. Porter presented a typical value chain for creating Shared Value in mining that this author has altered somewhat below (Figure 21)[38].

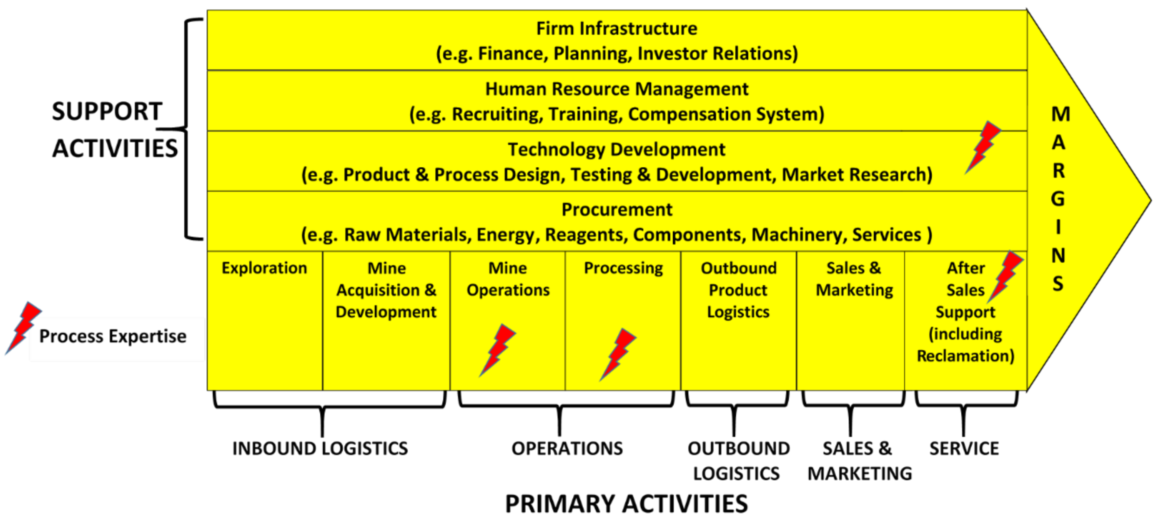

Figure 21 – The Mining Value Chain (after Michael Porter)[38]

The primary activities have to be capable to deliver value; if not, everything else is academic. For a mining and metals enterprise dependent on hydrometallurgy, it is clear that hydromet process expertise factors in the primary activities. Not only is hydrometallurgy obviously relevant in operations and its process safety, but as the customer of the mine, aids to define mine exploitation and planning. This expertise also helps solve issues with the consumer of the metallurgical product (either in product application or as feedback for continuous improvement in the preceding primary activities). Running the enterprise throughout its life to manage waste, effluent and the water balance for effective environmental management and ultimate reclamation can take significant hydromet process expertise. Furthermore, while hydromet technology is not the only technology that figures in the support activities, strength here can be a strategic differentiator. Therefore, process expertise is a key element and enabler of the primary activities that generate margins as well as technology development.

But mines and their downstream processing facilities have to first be successfully established. Mackenzie and Cusworth in their paper "Use and Abuse of Feasibility Studies" present a useful diagram of the framework of the development of a mining and metals project (Figure 22)[3].

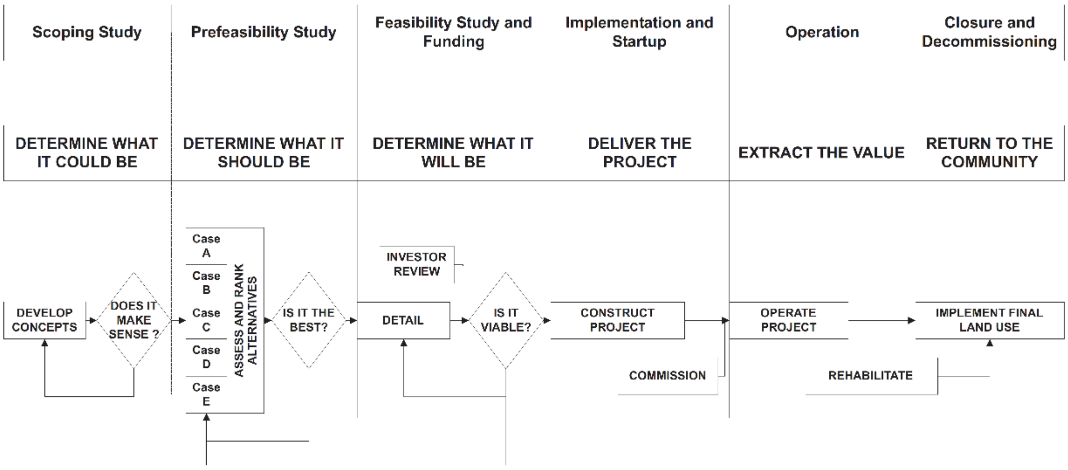

Figure 22 – The Project Development Framework[3]

Process and technical issues often dominate scoping and prefeasibility studies as the form of the project and the likely flowsheet are selected from a number of options. At the early stage of hydromet projects, the development and selection of the process is critical to the project's success and the relevant process expertise mitigates this project risk. Though the total project cost expenditures are still relatively low, the influence on project risk by the quality of initial assessment, resource sampling and process testwork and its evaluation is very high.

> "Investments of time, focus and expert review yield the highest return early in the life cycle when the ability to influence outcomes is greatest. Most of a project's key and defining decisions are made during these initial phases, as the delivery strategy and methodology are established, making this the most critical time to plan, get the foundations right and optimise prior to moving into delivery."[29]

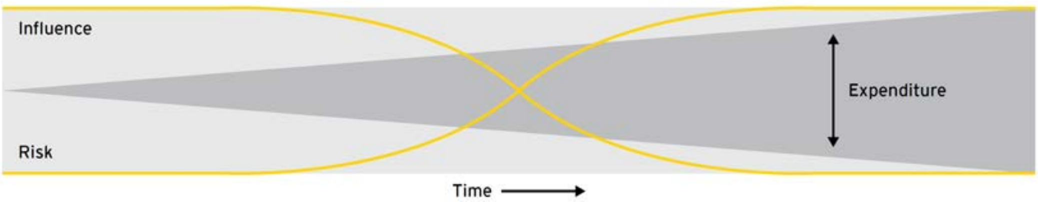

Figure 23 – Relationship between the Project Life Cycle and the Ability to Influence the Risk Profile and Expenditure[29]

Figure 23 models how early decisions have the greatest influence on project outcomes. Decisions at this time can significantly impact the future risk profile, for example to limit testwork by cutting back on continuous or integrated piloting. As the projects advances, the risks and expenditures increase and the mitigation options become progressively more limited.

If the project has met the hurdle criteria for a feasibility study, commercial and project delivery issues rise to the top. However even at this stage and subsequent project delivery, process expertise is required to ensure that the process intent and the design envelope are not corrupted by cost-cutting and "value engineering". Again, if the process does not deliver, everything else is academic.

As already discussed, commissioning and ramp-up are particularly critical phases; most of the facilities life-cycle cost decision have been made, the capital sunk and the cumulative cash flow profile is (hopefully) approaching its nadir.
Process related risk to metallurgical enterprises does not end with successfully commissioning. Mackenzie and Cusworth describing the operational phase in Figure 22 as extracting the value is apt.

The primary activities in Porter's value chain with their embedded process expertise must remain value added steps to generate margins. Due to volatility of input and product prices, the rate of investment recovery will vary and will be at risk. Sub-optimal performance over time, and failing to keep up with sustaining capital to keep the facilities vital will exacerbate the risk. The process and technology must work, be maintained, remain robust and evolve as the resource and economics dictate. Process safety and environmental stewardship must be upheld.

Thus, process expertise mitigates business risk in all stages of a hydromet project's life: determining the right process, engineering and delivering the project, starting-up and operating the facilities and even the final decommissioning and remediation.

VALUING HYDROMETALLURGICAL PROCESS EXPERTISE

Campbell et al[5], Halbe[39] and Kennedy et al[40] have presented economic evaluations of successful and failed metallurgical project start-up scenarios. The first two papers focussed exclusively on hydrometallurgical projects. All three used McNulty's characterisation of mining and metals projects start-ups into four series as a basis for economic evaluation (Figure 24) [12, 13, 14].

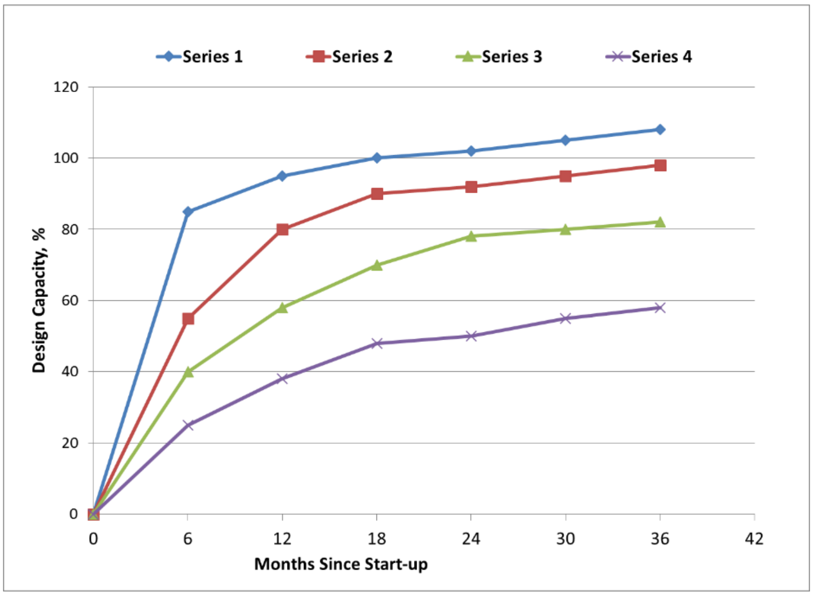

Figure 24 – The McNulty Curves,
% of Design Capacity versus Months since Commissioning[12]

According to McNulty, the most successful projects that achieved name plate capacity in 36 or less months - Series 1 - generally relied on mature technology, and/or were particularly well prepared and run projects. It is instructive to directly quote McNulty's summary of the less successful projects (Series 2, 3 and 4) in his last update (2014)[14].

> "Progression from Series 2 through Series 4, the flattest profile, reflected increases in the following exposures to risk:
>
> - Mineralogy and physical characteristics of the ore were not completely defined;
> - Process chemistry was poorly defined or misunderstood;
> - If technology had been licensed, there were few or no predecessors;
> - Laboratory testing was limited in scope and/or quality;
> - Pilot-scale process simulation was incomplete or nonexistent;
> - Prototype equipment was used;
> - Process conditions were unusually aggressive, with high temperatures and/or pressures, and often resulted in severe unpredicted corrosion;

- Impact of process conditions on product quality received inadequate attention;
- Safety margins in equipment sizes were reduced or eliminated in response to projected cost overruns or 'value engineering';
- Management and supervisory personnel were inexperienced and operators were not sufficiently trained."

Each of McNulty's summary points can be linked to the Process Wheel and/or Mackenzie and Cusworth's Project Development Framework, and all the increased exposures to risk can be mitigated with process expertise. For McNulty Series 3 and 4 start-ups, the primary activities in Porter's Value Chain fail to add value in time to make the project economic for the original owners. Following Campbell's and Halbe's approach, economic analysis shows how crippling a Series 3 or 4 start-up can be (Tables 2 and 3, below).

A good example of the value of hydromet process expertise was presented by Valle, et al in a paper on completing the Ambatovy ramp-up in Madagascar[10]. Over about a year, a team of almost 20 seasoned operators, technologists, metallurgists and engineers were mobilised to aid the ramp-up and improve the quality of the nickel product. To do this in Madagascar was not cheap, around USD 250,000 per person per year or an annualised cost of USD 5 M. However, during the initiative, nickel product quality went from zero to essentially 100% on-spec and production increased by 12,000 tonnes/year representing over USD120M/y in revenue.

Tables 2 and 3 summarise simple economic modelling of a USD 1 billion project with a 20 year life as Series 1, 2, 3, and 4 start-ups, as well as a Series 2 start-up with a deterioration of 5% of product value (as decreased production, recovery or quality or any combination). Appendices A through E, at the end of this paper, present more details of this model.

Using a hurdle rate of 12%, for the plant modelled, Series 1 and 2 give decent returns. However, it would take a CAPEX reduction of USD 380M for a Series 2 plant to yield the net present value of a Series 1 plant. A Series 3 plant fails to meet the hurdle rate and hence has a negative net present value. A Series 2 plant has a gross profit of more than USD 50M greater than a Series 3 plant and it would take a CAPEX reduction of USD 359M for a Series 3 plant to yield the net present value of a Series 2 plant. A Series 4 plant is clearly an immediate failure and would probably be shut down or sold at a great loss after 3 or 4 years.

The above results are not unexpected and have been directionally confirmed by previous papers[5,39]. However, even a modest slip in performance can be extremely costly. A Series 2 plant that has a deterioration of 5% of product value (as decreased production, recovery or quality or any combination) after completion of ramp-up may lose less than 1% return on investment, but earns USD 20M less gross profit per year. The slip in performance in this Series 2 scenario is the equivalent of USD 85M in the original capital expenditure.

Table 2 – Basic Assumptions for Simple Economic Model of USD 1 Billion Hydromet Plant

Initial Investment Parameters	
CAPEX (USD)	(1,000,000,000)
Total Investment (USD)	(1,000,000,000)
Depreciation Life (in years)	10
Project Life (in years)	20
Enterprise Salvage Value (USD)	-
Revenue and Cost Assumptions	
Fixed Cost per tonne (USD) @name plate	2,500
Variable Cost per tonne (USD)	2,500
Total Cost per tonne (USD) @name plate	5,000
Sale Price per tonne (USD)	16,000
Gross Profit Margin % @name plate	68.8%
Annual Sustaining CAPEX (USD)	75,000,000
Closeout Support Costs (USD)	250,000,000
Capacity, Tax, Hurdle Rate, and Growth Rate Assumptions	
Name Plate Annual Capacity (tonnes)	30,000
Tax Rate	30%
WACC/Hurdle Rate	12.0%
Working Capital Metrics	
DSO (Days Sales Outstanding)	30
Inventory Days	60
DPO (Days Payables Outstanding)	60

Table 3 –Simple Economic Model of Various Scenarios of USD 1 Billion Hydromet Plant

Scenario	Simple Payback (y)	Net Present Value @12% (M USD)	Internal Rate of Return (%)	Profitability Index @12%	Annual Gross Profit after Ramp-up (M USD)	Reduction in CAPEX required to achieve NPV of next best Series (M USD)
Series 1 Ramp-up	5.0	536	19.5	1.54	371	-
Series 2 Ramp-up	6.1	220	15.2	1.22	310	380
Series 2 Ramp-up with subsequent drop of 5% nameplate	6.4	149	14.3	1.15	290	85
Series 3 Ramp-up	7.7	(78)	10.8	0.92	253	359
Series 4 Ramp-up	13.3	(502)	2.8	0.50	168	511

Profitability Index (PI) = (Net Present Value of future cash flow) / investment

Ernst & Young present two levers for companies to enhance their capital productivity[29]:

- Minimised and predictable "input" through project delivery, and
- Maximised and sustainable "output" through earlier asset operationalisation (e.g. schedule acceleration) or operational efficiency (e.g. improved equipment availability and utilisation of processes and skills).

For hydromet projects, clearly process expertise is a major factor of the latter “lever”. By the economic modelling above, the magnitude of risk that hydromet expertise addresses clearly can be very large, great enough to completely negate the promised economics and even shutdown an operation long before its projected life expectancy.

ACCESSING AND SUSTAINING HYDROMETALLURGICAL PROCESS EXPERTISE

Hydromet projects and facilities come in all shapes and sizes with owners of a full range of on-the-ground capability. There is no single approach to accessing and sustaining the required process expertise; this is context dependent. However, considering a number of factors will help define an approach at each stage, including operation after commissioning:

- Is the hydromet technology in all its major aspects an easily accessible mature technology?
- Is the hydromet technology owned and controlled by the project owner?
- Does the owner already operate directly similar technology at another site?
- Does the owner have technical testing resources and facilities, and if so, to what extent?
- Does the owner have existing technical support at other operating sites?
- Does the owner have a project engineering group?

At one end of the spectrum, the owner may already have other sites operating directly similar technologies and have significant in-house testing, technical and project support. Even if the technology is totally imported and licensed, the owner will have experienced resources that, if well interfaced with the technology provider throughout the project design and delivery, can incorporate the process expertise into what already exists.

At the other end, the project owner may not yet be an operator and must import expertise and develop from scratch in-house capability. This does not automatically increase risk, just the level of mitigation. McNulty noted that successful Series 1 projects that licensed the underlying technology had the licensors provide seasoned technical specialists during process development, engineering, design, and commissioning, as well as training the licensees’ operators and supervisors(14).

In the case where the owner is applying its own hydromet technology similar reasoning applies. If newly developed, it is important that sufficient testwork and piloting occurs and that however this is done (in-house or contracted services), all stages of development involve those destined to run the facility. The deeper understanding of the process and resulting practical training prove invaluable in start-up and early operations. This team is the core of the future facility’s competency. Collaboration and partnership with academia and engineering companies can bulk up the process expertise. Finally, to be sure that the effort does not suffer from “group think”, independent expert peer reviews can be very valuable. After commissioning, retaining the expertise at hand effectively supports optimisation and expansion projects.

This approach was used by Sherritt Gordon for the development of their nickel ammonia leach - hydrogen reduction technology in the late 1940’s and early 1950’s. At the time Sherritt was not an operator of hydrometallurgy, but proceeded through a series of thorough and meticulous piloting campaigns. Sherritt did not work alone. They partnered in development with Frank Forward of the University of British Columbia or UBC (primarily the ammonia leach) and the Chemical Construction Company or Chemico (the recovery of nickel by reduction with hydrogen under pressure). Sydney Nashner of Chemico took over as manager of the pilot plant, subsequently worked in Chemico on the commercial plant design and became the first general manager of new facilities in Fort Saskatchewan, Canada. Sherritt endowed the Sherritt Gordon Chair of Metallurgy at UBC permitting Frank Forward to devote more time to the process. Sherritt engaged the Battelle Memorial Institute to provide continuous independent peer reviews of the process development and engineering(41,42).

The Sherritt Refinery achieved 90% capacity in 8 months and reached design the following year (1955). Already 70 employees from the research division had relocated from Ottawa to Fort Saskatchewan to participate in the commissioning and early operations. In 1955, the rest of research and the pilot plant were relocated to the operating site(41). The research division continued to support the operations, expansions and developed and commercialised the cobalt pentamine process to also recover cobalt metal at the site. Almost 40 years later Sherritt’s process expertise was instrumental in turning around the HPAL operation at Moa, Cuba and retooling the Canadian refinery to treat Ni-Co mixed sulphides as its primary feed.

The design, start-up and operation of Western Mining's nickel refinery at Kwinana, Australia (now BHP Nickel-West) and the Impala Base Metal Refinery in Springs, South Africa are examples of hydromet technology licensers effectively starting-up and subsequently maintaining successful operations. Both licensed technology from Sherritt and used Sherritt's facilities and resources extensively for test work, demonstration and training. Both paid careful attention to training from the outset and through commissioning. Both had Series 1 or better start-ups(43, 44, 45, 46). Both had subsequent expansions and improvements, relying largely on their own now developed process expertise while at times searching out specific support from Sherritt(45, 47, 48).

Thus, there are a number of approaches, but at the minimum, the operator must acquire enough process expertise to become an "intelligent customer" of hydromet technology, and then build from there with continued hands on experience in a way to ensure continuity of the expertise at the facility.

The previous characterisation of hydrometallurgical process expertise and the above successes point to approaches to source, deploy, train and sustain process expertise:

- Demonstrably celebrate all types of process expertise and keep it vital. "Walk this talk" in recognition, rewards and compensation at all levels of the business. Create a viable and attractive advancement path for experts. If the organisation obviously values process expertise, employees will be prepared to make the investment to become an expert and continuity is easier to maintain.
- Emphasise hands-on training, and circulate personnel at various stages of their career to keep the connection to the process fresh.
- Build and maintain a process expertise pipeline with the patience it requires. Import veteran expertise to seed the pipeline if required. Plan mentoring by senior subject matter experts into succession management. Invest in knowledge management systems to secure and preserve expertise. Hydromet process expertise is specialised and takes time to build. Remember the "10,000 hour rule".
- Stay the course. The mining and metals sector's ranking of skills availability as a strategic risk seems to be proportional to the metals prices, resulting in "hiring at any cost" followed by deep across the board cuts. This approach, as Ernst & Young argue in "It is only a ceasefire – the war for talent will continue", leaves mining and metals players exposed to risks posed by long term trends(49). Ernst & Young call for a more sophisticated response by adopting a "long play" stratagem. In fact it is contended that "an investment in talent will be as critical to the future success of mining companies as investment in exploration"(49). Ernst & Young further recommend consciously maintaining an oversupply of critical skilled workers to be better positioned to meet the requirements ahead of the economic curve. For those depending on hydrometallurgical operations, hydromet process expertise is one of these critical elements of the business's talent pool.
- Involve all levels of (the prospective) operation and maintenance in all stages of process development projects to develop knowledge, skills and training ahead of commissioning. Build the operating teams far enough in advance to take full advantage of the foregoing.
- Leverage outside process expertise by building and investing in partnerships with academia, engineering companies, technology providers and industrial consortiums and keep them up. Targetted collaborative efforts such as AMIRA's P266 "Improving Thickener Technology" in Australia are effective to build specific unit operation expertise. The same can occur with national research organisations. Good models of industry wide collaboration are the Kellogg Innovation Network Catalyst for Mining(50) and FSG's Shared Value Initiative(38). Partnerships are a great way to train, advance expertise, import concepts from other sectors and to level resources throughout the full life cycle of a project. Furthermore, real constraints on the resources of a single operator to realise a process expertise pipeline can be largely mitigated through partnerships.

CONCLUSIONS

Hydrometallurgical facilities are invariably run by mining companies. As presented, ongoing business risks to the mining sector remain and are mounting: volatile input and metal product prices, lower grade resources with increasing complexity, remote locations, environmental concerns including waste and effluent management, GHG emissions and water use, increasing expectations of process safety, and difficulties in gaining a sustainable social license to operate. These risks are real: mining sector returns have lagged other sectors, projects continue to blow past the expected costs and then in some cases do not operate to the promised expectations, and major process safety related accidents have occurred.

One would expect that over time innovation would improve the mining sector's performance. However there has been a long-term underinvestment in innovation in mining, declining since 1997 to around 0.5% of revenue today, compared to 2 to 2.5% for the oil and gas industry[50,51]. Cost reduction has historically been favoured over innovation as the route to business improvement. The strategic priority has been low and that would include building and sustaining hydromet process expertise for those that operate hydrometallurgical facilities to ultimately get their metal product to market.

Yet, hydrometallurgical process expertise mitigates business risk in all stages of a hydromet project's life: determining the right process, engineering and delivering the project, starting-up and operating the facilities and even the final decommissioning and remediation – these are primary activities in Porter's value chain. Regardless of how well the project was brought to commissioning, the initial ramp-up and ongoing operation still depend on the process expertise, and its maintenance, continued development and training ensure continued performance. Hydromet process expertise is not a "silver bullet" to these projects' risk, but it is a necessary element. Consequently building and maintaining hydromet process expertise is a key investment in risk management.

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APPENDIX A: USD 1 BILLION HYDROMET PLANT – SERIES 1 RAMP-UP

Plant with Series 1 Start-up

	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 19	Year 20	Year 21	Total
Tonnes Produced		20,400	30,000	33,000	33,000	33,000	33,000	33,000	33,000	33,000	-	644,400
Price/tonne		16,000.000	16,000.000	16,000.000	16,000.000	16,000.000	16,000.000	16,000.000	16,000.000	16,000.000		
Revenue		326,400,000	480,000,000	528,000,000	528,000,000	528,000,000	528,000,000	528,000,000	528,000,000	528,000,000	-	10,310,400,000
Fixed Cost per tonne		3,676.471	2,500.000	2,272.727	2,272.727	2,272.727	2,272.727	2,272.727	2,272.727	2,272.727		
Fixed Cost		(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	-	(1,500,000,000)
Variable Cost per tonne		2,500.000	2,500.000	2,500.000	2,500.000	2,500.000	2,500.000	2,500.000	2,500.000	2,500.000		
Variable Cost		(51,000,000)	(75,000,000)	(82,500,000)	(82,500,000)	(82,500,000)	(82,500,000)	(82,500,000)	(82,500,000)	(82,500,000)	-	(1,611,000,000)
Total COGS		**(126,000,000)**	**(150,000,000)**	**(157,500,000)**	**(157,500,000)**	**(157,500,000)**	**(157,500,000)**	**(157,500,000)**	**(157,500,000)**	**(157,500,000)**	-	**(3,111,000,000)**
COGS per tonne		**6,176.47**	**5,000.00**	**4,772.73**	**4,772.73**	**4,772.73**	**4,772.73**	**4,772.73**	**4,772.73**	**4,772.73**		
Gross Profit		**200,400,000**	**330,000,000**	**370,500,000**	**370,500,000**	**370,500,000**	**370,500,000**	**370,500,000**	**370,500,000**	**370,500,000**	-	**7,199,400,000**
		61.4%	68.8%	70.2%	70.2%	70.2%	70.2%	70.2%	70.2%	70.2%		69.8%
Operating Expense												
Annual Sustaining CAPEX		(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(250,000,000)	(1,750,000,000)
Depreciation		(100,000,000)	(100,000,000)	(100,000,000)	(100,000,000)	(100,000,000)	(100,000,000)	(100,000,000)	-	-	-	(1,000,000,000)
Other Income (Expense)		-	-	-	-	-	-	-	-	-	-	-
Total Operating Expense		(175,000,000)	(175,000,000)	(175,000,000)	(175,000,000)	(175,000,000)	(175,000,000)	(175,000,000)	(75,000,000)	(75,000,000)	(250,000,000)	(2,750,000,000)
Profit Before Taxes		25,400,000	155,000,000	195,500,000	195,500,000	195,500,000	195,500,000	195,500,000	295,500,000	295,500,000	(250,000,000)	4,449,400,000
Taxes		(7,620,000)	(46,500,000)	(58,650,000)	(58,650,000)	(58,650,000)	(58,650,000)	(58,650,000)	(88,650,000)	(88,650,000)	75,000,000	(1,334,820,000)
Net Income		17,780,000	108,500,000	136,850,000	136,850,000	136,850,000	136,850,000	136,850,000	206,850,000	206,850,000	(175,000,000)	3,114,580,000
Working Capital Investment		**(27,200,000)**	**(12,800,000)**	**(4,000,000)**	**-**	**-**	**-**	**-**	**-**	**-**	**44,000,000**	**-**
Add back depreciation/amortization		100,000,000	100,000,000	100,000,000	100,000,000	100,000,000	100,000,000	100,000,000	-	-	-	1,000,000,000
Total Investment	**(1,000,000,000)**											
Project Cash Flow	**(1,000,000,000)**	**90,580,000**	**195,700,000**	**232,850,000**	**236,850,000**	**236,850,000**	**236,850,000**	**236,850,000**	**206,850,000**	**206,850,000**	**(131,000,000)**	**3,114,580,000**
Cumulative Project Cash Flow	**(1,000,000,000)**	**(909,420,000)**	**(713,720,000)**	**(480,870,000)**	**(244,020,000)**	**(7,170,000)**	**229,680,000**	**466,530,000**	**3,038,730,000**	**3,245,580,000**	**3,114,580,000**	
Simple Payback	5.03											
NPV	536,185,932		NPV Rate	12%								
IRR	19.5%											
PI (Profitability Index) =(NPV of future cash flow)/investment	1.54											

APPENDIX B: USD 1 BILLION HYDROMET PLANT – SERIES 2 RAMP-UP

Plant with Series 2 Start-up

	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 19	Year 20	Year 21	Total
Tonnes Produced		14,700	26,400	28,500	28,500	28,500	28,500	28,500	28,500	28,500	-	554,100
Price/tonne		16,000.000	16,000.000	16,000.000	16,000.000	16,000.000	16,000.000	16,000.000	16,000.000	16,000.000		
Revenue		235,200,000	422,400,000	456,000,000	456,000,000	456,000,000	456,000,000	456,000,000	456,000,000	456,000,000	-	8,865,600,000
Fixed Cost per tonne		5,102.041	2,840.909	2,631.579	2,631.579	2,631.579	2,631.579	2,631.579	2,631.579	2,631.579		
Fixed Cost		(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	-	(1,500,000,000)
Variable Cost per tonne		2,500.000	2,500.000	2,500.000	2,500.000	2,500.000	2,500.000	2,500.000	2,500.000	2,500.000		
Variable Cost		(36,750,000)	(66,000,000)	(71,250,000)	(71,250,000)	(71,250,000)	(71,250,000)	(71,250,000)	(71,250,000)	(71,250,000)	-	(1,385,250,000)
Total COGS		**(111,750,000)**	**(141,000,000)**	**(146,250,000)**	**(146,250,000)**	**(146,250,000)**	**(146,250,000)**	**(146,250,000)**	**(146,250,000)**	**(146,250,000)**	-	**(2,885,250,000)**
COGS per tonne		**7,602.04**	**5,340.91**	**5,131.58**	**5,131.58**	**5,131.58**	**5,131.58**	**5,131.58**	**5,131.58**	**5,131.58**		
Gross Profit		**123,450,000**	**281,400,000**	**309,750,000**	**309,750,000**	**309,750,000**	**309,750,000**	**309,750,000**	**309,750,000**	**309,750,000**	-	**5,980,350,000**
		52.5%	66.6%	67.9%	67.9%	67.9%	67.9%	67.9%	67.9%	67.9%		67.5%
Operating Expense												
Annual Sustaining CAPEX		(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(250,000,000)	(1,750,000,000)
Depreciation		(100,000,000)	(100,000,000)	(100,000,000)	(100,000,000)	(100,000,000)	(100,000,000)	(100,000,000)	-	-	-	(1,000,000,000)
Other Income (Expense)		-	-	-	-	-	-	-	-	-	-	-
Total Operating Expense		(175,000,000)	(175,000,000)	(175,000,000)	(175,000,000)	(175,000,000)	(175,000,000)	(175,000,000)	(75,000,000)	(75,000,000)	(250,000,000)	(2,750,000,000)
Profit Before Taxes		(51,550,000)	106,400,000	134,750,000	134,750,000	134,750,000	134,750,000	134,750,000	234,750,000	234,750,000	(250,000,000)	3,230,350,000
Taxes		15,465,000	(31,920,000)	(40,425,000)	(40,425,000)	(40,425,000)	(40,425,000)	(40,425,000)	(70,425,000)	(70,425,000)	75,000,000	(969,105,000)
Net Income		(36,085,000)	74,480,000	94,325,000	94,325,000	94,325,000	94,325,000	94,325,000	164,325,000	164,325,000	(175,000,000)	2,261,245,000
Working Capital Investment		**(19,600,000)**	**(15,600,000)**	**(2,800,000)**	**-**	**-**	**-**	**-**	**-**	**-**	**38,000,000**	**-**
Add back depreciation/amortization		100,000,000	100,000,000	100,000,000	100,000,000	100,000,000	100,000,000	100,000,000	-	-	-	1,000,000,000
Total Investment	**(1,000,000,000)**											
Project Cash Flow	**(1,000,000,000)**	**44,315,000**	**158,880,000**	**191,525,000**	**194,325,000**	**194,325,000**	**194,325,000**	**194,325,000**	**164,325,000**	**164,325,000**	**(137,000,000)**	**2,261,245,000**
Cumulative Project Cash Flow	**(1,000,000,000)**	**(955,685,000)**	**(796,805,000)**	**(605,280,000)**	**(410,955,000)**	**(216,630,000)**	**(22,305,000)**	**172,020,000**	**2,233,920,000**	**2,398,245,000**	**2,261,245,000**	
Simple Payback	6.11											
NPV	220,055,326		NPV Rate	12%								
IRR	15.2%											
PI =(NPV of future cash flow)/investment	1.22											

APPENDIX C: USD 1 BILLION HYDROMET PLANT – SERIES 2 RAMP-UP WITH SUBSEQUENT DROP OF 5% NAMEPLATE

Plant with Series 2 Start-up with subsequent drop of 5% nameplate

	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 19	Year 20	Year 21	Total
Tonnes Produced		14,700	26,400	28,500	27,000	27,000	27,000	27,000	27,000	27,000	-	528,600
Price/tonne		16,000.000	16,000.000	16,000.000	16,000.000	16,000.000	16,000.000	16,000.000	16,000.000	16,000.000		
Revenue		235,200,000	422,400,000	456,000,000	432,000,000	432,000,000	432,000,000	432,000,000	432,000,000	432,000,000	-	8,457,600,000
Fixed Cost per tonne		5,102.041	2,840.909	2,631.579	2,777.778	2,777.778	2,777.778	2,777.778	2,777.778	2,777.778		
Fixed Cost		(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	-	(1,500,000,000)
Variable Cost per tonne		2,500.000	2,500.000	2,500.000	2,500.000	2,500.000	2,500.000	2,500.000	2,500.000	2,500.000		
Variable Cost		(36,750,000)	(66,000,000)	(71,250,000)	(67,500,000)	(67,500,000)	(67,500,000)	(67,500,000)	(67,500,000)	(67,500,000)	-	(1,321,500,000)
Total COGS		**(111,750,000)**	**(141,000,000)**	**(146,250,000)**	**(142,500,000)**	**(142,500,000)**	**(142,500,000)**	**(142,500,000)**	**(142,500,000)**	**(142,500,000)**	-	**(2,821,500,000)**
COGS per tonne		**7,602.04**	**5,340.91**	**5,131.58**	**5,277.78**	**5,277.78**	**5,277.78**	**5,277.78**	**5,277.78**	**5,277.78**		
Gross Profit		**123,450,000**	**281,400,000**	**309,750,000**	**289,500,000**	**289,500,000**	**289,500,000**	**289,500,000**	**289,500,000**	**289,500,000**	-	**5,636,100,000**
		52.5%	66.6%	67.9%	67.0%	67.0%	67.0%	67.0%	67.0%	67.0%		66.6%
Operating Expense												
Annual Sustaining CAPEX		(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(250,000,000)	(1,750,000,000)
Depreciation		(100,000,000)	(100,000,000)	(100,000,000)	(100,000,000)	(100,000,000)	(100,000,000)	(100,000,000)	-	-	-	(1,000,000,000)
Other Income (Expense)		-	-	-	-	-	-	-	-	-	-	-
Total Operating Expense		(175,000,000)	(175,000,000)	(175,000,000)	(175,000,000)	(175,000,000)	(175,000,000)	(175,000,000)	(75,000,000)	(75,000,000)	(250,000,000)	(2,750,000,000)
Profit Before Taxes		(51,550,000)	106,400,000	134,750,000	114,500,000	114,500,000	114,500,000	114,500,000	214,500,000	214,500,000	(250,000,000)	2,886,100,000
Taxes		15,465,000	(31,920,000)	(40,425,000)	(34,350,000)	(34,350,000)	(34,350,000)	(34,350,000)	(64,350,000)	(64,350,000)	75,000,000	(865,830,000)
Net Income		(36,085,000)	74,480,000	94,325,000	80,150,000	80,150,000	80,150,000	80,150,000	150,150,000	150,150,000	(175,000,000)	2,020,270,000
Working Capital Investment		**(19,600,000)**	**(15,600,000)**	**(2,800,000)**	**2,000,000**	-	-	-	-	-	**36,000,000**	-
Add back depreciation/amortization		100,000,000	100,000,000	100,000,000	100,000,000	100,000,000	100,000,000	100,000,000	-	-	-	1,000,000,000
Total Investment	**(1,000,000,000)**											
Project Cash Flow	**(1,000,000,000)**	**44,315,000**	**158,880,000**	**191,525,000**	**182,150,000**	**180,150,000**	**180,150,000**	**180,150,000**	**150,150,000**	**150,150,000**	**(139,000,000)**	**2,020,270,000**
Cumulative Project Cash Flow	**(1,000,000,000)**	**(955,685,000)**	**(796,805,000)**	**(605,280,000)**	**(423,130,000)**	**(242,980,000)**	**(62,830,000)**	**117,320,000**	**2,009,120,000**	**2,159,270,000**	**2,020,270,000**	
Simple Payback	6.35											
NPV	149,307,838		NPV Rate	12%								
IRR	14.3%											
PI =(NPV of future cash flow)/investment	1.15											

APPENDIX D: USD 1 BILLION HYDROMET PLANT – SERIES 3 RAMP-UP

Plant with Series 3 Start-up

	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 19	Year 20	Year 21	Total
Tonnes Produced		10,800	21,000	24,300	24,300	24,300	24,300	24,300	24,300	24,300	-	469,200
Price/tonne		16,000.000	16,000.000	16,000.000	16,000.000	16,000.000	16,000.000	16,000.000	16,000.000	16,000.000		
Revenue		172,800,000	336,000,000	388,800,000	388,800,000	388,800,000	388,800,000	388,800,000	388,800,000	388,800,000	-	7,507,200,000
Fixed Cost per tonne		6,944.444	3,571.429	3,086.420	3,086.420	3,086.420	3,086.420	3,086.420	3,086.420	3,086.420		
Fixed Cost		(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	-	(1,500,000,000)
Variable Cost per tonne		2,500.000	2,500.000	2,500.000	2,500.000	2,500.000	2,500.000	2,500.000	2,500.000	2,500.000		
Variable Cost		(27,000,000)	(52,500,000)	(60,750,000)	(60,750,000)	(60,750,000)	(60,750,000)	(60,750,000)	(60,750,000)	(60,750,000)	-	(1,173,000,000)
Total COGS		**(102,000,000)**	**(127,500,000)**	**(135,750,000)**	**(135,750,000)**	**(135,750,000)**	**(135,750,000)**	**(135,750,000)**	**(135,750,000)**	**(135,750,000)**	-	**(2,673,000,000)**
COGS per tonne		**9,444.44**	**6,071.43**	**5,586.42**	**5,586.42**	**5,586.42**	**5,586.42**	**5,586.42**	**5,586.42**	**5,586.42**		
Gross Profit		**70,800,000**	**208,500,000**	**253,050,000**	**253,050,000**	**253,050,000**	**253,050,000**	**253,050,000**	**253,050,000**	**253,050,000**	-	**4,834,200,000**
		41.0%	62.1%	65.1%	65.1%	65.1%	65.1%	65.1%	65.1%	65.1%		64.4%
Operating Expense												
Annual Sustaining CAPEX		(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(250,000,000)	(1,750,000,000)
Depreciation		(100,000,000)	(100,000,000)	(100,000,000)	(100,000,000)	(100,000,000)	(100,000,000)	(100,000,000)	-	-	-	(1,000,000,000)
Other Income (Expense)		-	-	-	-	-	-	-	-	-	-	-
Total Operating Expense		(175,000,000)	(175,000,000)	(175,000,000)	(175,000,000)	(175,000,000)	(175,000,000)	(175,000,000)	(75,000,000)	(75,000,000)	(250,000,000)	(2,750,000,000)
Profit Before Taxes		(104,200,000)	33,500,000	78,050,000	78,050,000	78,050,000	78,050,000	78,050,000	178,050,000	178,050,000	(250,000,000)	2,084,200,000
Taxes		31,260,000	(10,050,000)	(23,415,000)	(23,415,000)	(23,415,000)	(23,415,000)	(23,415,000)	(53,415,000)	(53,415,000)	75,000,000	(625,260,000)
Net Income		(72,940,000)	23,450,000	54,635,000	54,635,000	54,635,000	54,635,000	54,635,000	124,635,000	124,635,000	(175,000,000)	1,458,940,000
Working Capital Investment		**(14,400,000)**	**(13,600,000)**	**(4,400,000)**	-	-	-	-	-	-	**32,400,000**	-
Add back depreciation/amortization		100,000,000	100,000,000	100,000,000	100,000,000	100,000,000	100,000,000	100,000,000	-	-	-	1,000,000,000
Total Investment	**(1,000,000,000)**											
Project Cash Flow	**(1,000,000,000)**	**12,660,000**	**109,850,000**	**150,235,000**	**154,635,000**	**154,635,000**	**154,635,000**	**154,635,000**	**124,635,000**	**124,635,000**	**(142,600,000)**	**1,458,940,000**
Cumulative Project Cash Flow	**(1,000,000,000)**	**(987,340,000)**	**(877,490,000)**	**(727,255,000)**	**(572,620,000)**	**(417,985,000)**	**(263,350,000)**	**(108,715,000)**	**1,476,905,000**	**1,601,540,000**	**1,458,940,000**	
Simple Payback	7.70											
NPV	(78,335,757)		NPV Rate	12%								
IRR	10.8%											
PI =(NPV of future cash flow)/investment	0.92											

APPENDIX E: USD 1 BILLION HYDROMET PLANT – SERIES 4 RAMP-UP

Plant with Series 4 Start-up

	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 19	Year 20	Year 21	Total
Tonnes Produced		7,200	13,500	18,000	18,000	18,000	18,000	18,000	18,000	18,000	-	344,700
Price/tonne		16,000.000	16,000.000	16,000.000	16,000.000	16,000.000	16,000.000	16,000.000	16,000.000	16,000.000		
Revenue		115,200,000	216,000,000	288,000,000	288,000,000	288,000,000	288,000,000	288,000,000	288,000,000	288,000,000	-	5,515,200,000
Fixed Cost per tonne		10,416.667	5,555.556	4,166.667	4,166.667	4,166.667	4,166.667	4,166.667	4,166.667	4,166.667		
Fixed Cost		(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	-	(1,500,000,000)
Variable Cost per tonne		2,500.000	2,500.000	2,500.000	2,500.000	2,500.000	2,500.000	2,500.000	2,500.000	2,500.000		
Variable Cost		(18,000,000)	(33,750,000)	(45,000,000)	(45,000,000)	(45,000,000)	(45,000,000)	(45,000,000)	(45,000,000)	(45,000,000)	-	(861,750,000)
Total COGS		**(93,000,000)**	**(108,750,000)**	**(120,000,000)**	**(120,000,000)**	**(120,000,000)**	**(120,000,000)**	**(120,000,000)**	**(120,000,000)**	**(120,000,000)**	-	**(2,361,750,000)**
COGS per tonne		**12,916.67**	**8,055.56**	**6,666.67**	**6,666.67**	**6,666.67**	**6,666.67**	**6,666.67**	**6,666.67**	**6,666.67**		
Gross Profit		**22,200,000**	**107,250,000**	**168,000,000**	**168,000,000**	**168,000,000**	**168,000,000**	**168,000,000**	**168,000,000**	**168,000,000**	-	**3,153,450,000**
		19.3%	49.7%	58.3%	58.3%	58.3%	58.3%	58.3%	58.3%	58.3%		57.2%
Operating Expense												
Annual Sustaining CAPEX		(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(75,000,000)	(250,000,000)	(1,750,000,000)
Depreciation		(100,000,000)	(100,000,000)	(100,000,000)	(100,000,000)	(100,000,000)	(100,000,000)	(100,000,000)	-	-	-	(1,000,000,000)
Other Income (Expense)		-	-	-	-	-	-	-	-	-	-	-
Total Operating Expense		(175,000,000)	(175,000,000)	(175,000,000)	(175,000,000)	(175,000,000)	(175,000,000)	(175,000,000)	(75,000,000)	(75,000,000)	(250,000,000)	(2,750,000,000)
Profit Before Taxes		(152,800,000)	(67,750,000)	(7,000,000)	(7,000,000)	(7,000,000)	(7,000,000)	(7,000,000)	93,000,000	93,000,000	(250,000,000)	403,450,000
Taxes		45,840,000	20,325,000	2,100,000	2,100,000	2,100,000	2,100,000	2,100,000	(27,900,000)	(27,900,000)	75,000,000	(121,035,000)
Net Income		(106,960,000)	(47,425,000)	(4,900,000)	(4,900,000)	(4,900,000)	(4,900,000)	(4,900,000)	65,100,000	65,100,000	(175,000,000)	282,415,000
Working Capital Investment		**(9,600,000)**	**(8,400,000)**	**(6,000,000)**	**-**	**-**	**-**	**-**	**-**	**-**	**24,000,000**	**-**
Add back depreciation/amortization		100,000,000	100,000,000	100,000,000	100,000,000	100,000,000	100,000,000	100,000,000	-	-	-	1,000,000,000
Total Investment	**(1,000,000,000)**											
Project Cash Flow	**(1,000,000,000)**	**(16,560,000)**	**44,175,000**	**89,100,000**	**95,100,000**	**95,100,000**	**95,100,000**	**95,100,000**	**65,100,000**	**65,100,000**	**(151,000,000)**	**282,415,000**
Cumulative Project Cash Flow	**(1,000,000,000)**	**(1,016,560,000)**	**(972,385,000)**	**(883,285,000)**	**(788,185,000)**	**(693,085,000)**	**(597,985,000)**	**(502,885,000)**	**368,315,000**	**433,415,000**	**282,415,000**	
Simple Payback	13.34											
NPV	(502,773,239)		NPV Rate	12%								
IRR	2.8%											
PI =(NPV of future cash flow)/investment	0.50											