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THE FUTURE OF NI-CO-CU PROCESSING IN THE AGE OF LITHIUM-ION BATTERIES

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ABSTRACT

Batteries were first invented in the mid-1700s, based on the so-called Leiden (or Leyden) Jar capacitor, with the term having been coined by Benjamin Franklin in 1748. However, it was not until the early 1990s that lithium-ion batteries became a commercial reality, with the major components of these batteries being cobalt and, to a lesser extent, nickel. Since then, the advent of electric, battery-powered vehicles has seen an increased demand for both of these metals, to such an extent that some projections indicate a shortfall of cobalt by as soon as 2020. This presents the industry with a unique, and very serious, challenge, especially as far as cobalt is concerned.

Virtually all cobalt production is as a by-product of copper and nickel processing. Any increase, therefore, necessarily means a much higher (on a tonnage, not percentage, basis) corresponding increase in copper and nickel production. This is further exacerbated by the fact that in 2017, total annual cobalt production was only 110,000 tonnes, compared to 2.1 million tonnes for nickel and 19.7 million tonnes for copper, and that the cobalt to metal ratio in the ore is typically 1:100 for copper, although there are areas of the DRC where it is 1:10, and 1:10 for nickel. Based on current production data, known land-based reserves of cobalt will last for 70 years, and those for copper and nickel for approximately 40 years. Any increase in demand will, therefore, reduce this time frame. Furthermore, 58% of world cobalt production in 2017 emanated from the DRC, most of which was sold into China. This is bringing mining practices in the DRC into focus, and particularly artisanal mining using child miners. The social desire to eliminate such practices has contrasted with the very real economic hardships experienced by these miners in one of the world’s poorest, yet, ironically, mineral-richest countries.

As with a previous time when the cobalt price hit US$30/lb in the early 1980s, much effort is now being directed to replacing cobalt in batteries as it was then in super magnets and alloys. Indeed, some battery manufacturers are trying to eliminate its use completely. However, the unique (and far superior) structural properties of cobalt oxides suggest that this will again be as unsuccessful as it was in the 1980s, at least in the near term when cobalt supply is expected to be at breaking point.

The paper briefly reviews the interconnectedness of the cobalt, nickel and copper markets, and presents a basic understanding of the role of cobalt in batteries, and why it seems unlikely, at the present time at least, to be replaced on a large scale. A summary of current, past and proposed cobalt/nickel and cobalt/copper processing flowsheets is given, together with a discussion of where new sources of cobalt might arise from. In this respect, the challenges facing the nickel (and consequently, by-product cobalt) industry are reviewed, where with sulphide reserves becoming depleted, increased focus will be on laterites. Processing of laterites is not easy, and with HPAL laterite plants struggling to be viable, this will likely further distress the supply of both cobalt and nickel. Similarly, the lack of any major new copper discoveries is stressing the copper markets. Finally, it is conjectured that the main short-term source of cobalt supply will be from recycled batteries themselves, since market forces, environmental regulations and simple resource sustainability mandate that this must be so. That being the case, there follows a discussion of battery recycling technology, which is very much more complex than might at first be envisioned, has not been well-managed to date, and is attracting a lot of not necessarily positive attention. In the longer-term, however, it is likely that harvesting of deep-sea manganese nodules and cobalt crusts will become the main source of supply.

Keywords: cobalt, copper, nickel, battery(ies), supply-demand, DRC, Cuba, China, recycling, lithium-ion, laterites, deep-sea nodules.

INTRODUCTION – THE AGE OF LITHIUM-ION BATTERIES

The advent of lithium-ion batteries, and associated smart phones, tablets and lap-top computers, has revolutionised the way in which we live. Despite their name, lithium-ion batteries also contain substantial amounts of cobalt, as well as nickel and copper, and it is the availability of these three metals, especially cobalt, rather than lithium, which is likely to be the determining factor as to the speed of development of the anticipated upcoming "Electric Future."

The first batteries were invented in the mid-1700s, the so-called Leyden (or Leiden) jars, which were a form of electric capacitor and still see limited use today. The term "battery" is attributed to Benjamin Franklin, who, when not being a Founding Father of the USA, was an accomplished physicist, particularly in the field of electricity. In 1748, he is reported as likening a collection of these Leyden jars to a battery of cannon(1). The battery, as we are familiar with the term today, was invented in 1799 by Alessandro Volta, the Voltaic Pile, which was the first cell capable of generating a steady, continuous flow of electricity(2). The well-known, and widely used, nickel-cadmium (NiCad) rechargeable battery was, somewhat surprisingly, invented as long ago as 1899(1), but it was not until the late 1970s/early 1980s that lithium-ion batteries came on the scene with the advent of the LCO (lithium cobalt oxide) cathode material(3). It was still another decade before such batteries became a commercial reality, however, when Sony started using them in mobile phones(4). It would be fair to state, therefore, that the "Age of Lithium-Ion Batteries," in the sense that we mean the lithium-ion batteries which use significant amounts of cobalt and nickel, has been with us for no more than thirty years. However, it is really only in the last decade with the almost universal use of smart mobile phones, tablet computers and the drive to reduce our dependence on fossil fuels and the associated atmospheric pollution, by replacing, at least partially, conventional transport with electric vehicles (EVs), that it has really taken off. Following the lead of Tesla, all the major car manufacturers are developing their own versions of electric vehicles, and it is anticipated that ~32% of all cars will electric by the year 2030(5). The question is whether the growth of EVs will be able to mirror that of the automobile, whether history will, in a sense, repeat itself. This paper suggests that it will be very difficult to do so.

The internal combustion engine was first introduced at the end of the 1850s, and the first modern engine in 1876(6). 1885 saw the advent of the commercial, petrol (or gasoline)-powered car, introduced by Karl Benz(7), but it was the best part of another thirty years before the car became commonplace. Figure 1 shows a picture of 5th Avenue in New York City in 1900, where there is not an automobile in sight, whereas Figure 2, on the other hand, shows the same thoroughfare just over a decade later, in 1913, with no horse in sight(8). This was due, in large part, to the development of the Model T Ford in 1908, which subsequently became the first mass-produced car, with well over 15 million having been produced by 1927(7). No doubt Tesla would be very pleased if their Model 3, or even the Model Y, has the same impact.

Figure 1. New York in 1900 - no cars(8)

The evolution of the motor car would not have been possible, however, without the widespread availability of oil. Fortunately (or perhaps unfortunately, depending on perspective), there was never a shortage of oil, and there are many locations around the world where it has been found. Furthermore, oil is a primary product, and is therefore not dependent on the recovery of another mineral for its production. Although the evolution of electric vehicles is still in its infancy, there is, thus, a striking similarity to the original evolution of motor vehicles, which relied entirely on the widespread availability of this single commodity (oil, refined to petroleum or gasoline). Electric vehicles, at least in their current configuration, will rely very much on another single commodity, namely cobalt (and, to a much lesser extent, nickel and lithium).

Figure 2. New York in 1913 – no horses(8)

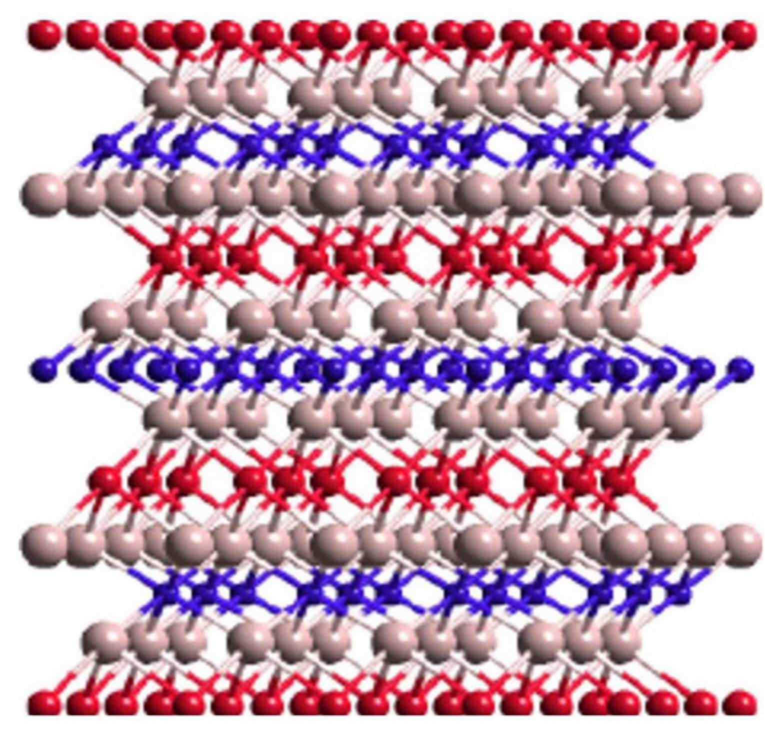
However, here is where the comparisons with oil start to diverge. Despite organisations such as OPEC (Organization of Petroleum Exporting Countries), oil is found in many locations around the world, and is not subject to control by any one supplier. On the other hand, the situation for cobalt is quite different, with a majority of the world's supply coming from a mineral-rich but economically very poor African country, the Democratic Republic of Congo (DRC), formerly known as Zäire, and before that as the Belgian Congo. Furthermore, over 50% of the world's known land-based reserves reside in the same geographical area, now largely controlled by China, which clearly raises a number of supply-demand problems that will have to be addressed in one way or another.

Hence, it is apropos to examine the relationship between lithium-ion batteries and the extractive metals industry which supplies the raw materials, and it is the intent of this paper to present a balanced perspective in that respect.

LITHIUM-ION BATTERY CHEMISTRY

Fundamentals

To start with, it is worth a (very) brief review of lithium-ion battery chemistry in order to be able to understand why cobalt, and to a lesser extent, nickel, are so important, and more importantly, why total substitution of cobalt is not likely, at least, not in the near future. As noted, the first lithium-ion battery was patented in the early 1980s, and was based on the so-called LCO (lithium cobalt oxide, or lithium cobaltate, $LiCoO_2$) chemistry. Fundamentally, lithium-ion batteries work on the principle of intercalation, wherein lithium ions are inserted into and removed from a layered structure. Anodes are typically graphite, which is probably the most common material capable of intercalation. The cathodes, a lithium-transition metal oxide also form a layered structure, and as such lithium ions are thus able to migrate from the cathode to the anode and vice-versa. Simply put, when fully-charged, the lithium ions are 'tied' to an electron within the structure of the anode. When the battery discharges, the intercalated lithium ions are released from the anode, and travel through the electrolyte solution to be absorbed (intercalated) into the cathode. A lithium-ion battery starts its life in a state of full discharge: all its lithium ions are intercalated within the cathode and its chemistry does not yet have the ability to produce any electricity. As the battery is charged, an oxidation reaction occurs at the cathode, as it loses some negatively charged electrons. To maintain the charge balance in the cathode, an equal number of positively charged intercalated lithium ions are dissolved into the electrolyte solution, which travel over to the anode, where they are intercalated within the graphite. This reaction also deposits electrons into the graphite anode, to 'tie-up' the lithium ion. Figure 3 shows this in schematic form(9).



Lithium-cobalt-oxide is an intercalation compound- it forms two dimesional layers that allows lithium ions to easily enter and leave the structure- in this drawing, the black speres represent lithium atoms, the tan spheres represent oxygen atoms, and the red spheres represent cobalt atoms (Image source: Argonne National Laboratory)

Figure 3. Schematic of Lithium-Ion Intercalation(9)

The cobalt-based cathode structure can withstand about 60% of the lithium to be removed before it begins to change (degrade) over long periods of time. It is this high degree of stability which is desirable, especially for EVs, and which makes cobalt so attractive. Other structures are not able to do this as well. Replacing the cobalt with cheaper and more abundant nickel still creates an intercalation structure, but one that is prone to releasing oxygen, which can be a fire hazard, and which is unable to release anywhere nearly as many lithium ions. Aluminium, which will absorb the oxygen, can be added to the structure to reduce the hazard and stabilize the structure, but it also lowers the capacity of the cell(9). Argonne National Laboratory experience indicates that at least some cobalt is needed in the cathode structure because it helps the performance rate at which the power is delivered. Electric vehicles need to have batteries that accept lithium ions at a high rate during charging and deliver lithium ions at a high rate during discharge, and a minimum of about 10% cobalt appears to be necessary to enhance these rate properties of the battery(9). It seems unlikely, therefore, that complete substitution of cobalt can be achieved with present battery technologies.

Since the stability and integrity of the structure is crucial to the battery, recycling technologies which simply aim to reconstitute the original cathode, by replacing the lithium, for example(10), will not be effective, since with spent batteries, the essential integrity of the structure will have been compromised or degraded.

Types of Lithium-Ion Battery

Several formulations of batteries have been developed, each having its own specialised end-use, but none that can easily replace the cobalt-based batteries needed for EVs. The properties of the most common of these are summarised in Table 1(11), where it appears that only the NMC and NCA formulations are suitable for powering electric vehicles. Given, therefore, that cobalt appears to be essential at the present time for the ongoing development of EV battery technology, this presents something of a conundrum. This is highlighted in Figure 4, which shows the evolving end-use of cobalt as the “Age of Lithium-Ion Batteries” has taken hold(12). Whereas just over a decade ago, batteries accounted for 20% of cobalt use, today it is at 62% and growing. Such a scenario clearly puts pressure on the demand side.

Table 1. Summary of Most Common Lithium-Ion Battery Properties(11)

Chemistry	Lithium Cobalt Oxide	Lithium Manganese Oxide	Lithium Nickel Manganese	Lithium Iron Phosphate	Lithium Nickel Cobalt Aluminum Oxide	Lithium Titanate
Short form	Li-cobalt	Li-manganese	NMC	Li-phosphate	Li-aluminum	Li-titanate
Abbreviation	$LiCoC_2$ (LCO)	$LiMn_2O_4$ (LMO)	$LiNiMnCoO_2$(NMC)	$LiFePo_4$ (LFP)	$LiNiCoAlO_2$(NCA)	Li_2TiO_3 (LTO)
Nominal voltage	3.60V	3.70V (3.80V)	3.60V (3.70V)	3.20, 3.30V	3.60V	2.40V
Full charge	4.20V	4.20V	4.20V (or higher)	3.65V	4.20V	2.85V
Full discharge	3.00V	3.00V	3.00V	2.50V	3.00V	1.80V
Minimal voltage	2.50V	2.50V	2.50V	2.00V	2.50V	1.50V (est.)
Specific Energy	150–200Wh/kg	100–150Wh/kg	150–220Wh/kg	90–120Wh/kg	200-260Wh/kg	70–80Wh/kg
Charge rate	0.7–1C (3h)	0.7–1C (3h)	0.7–1C (3h)	1C (3h)	1C	1C (5C max)
Discharge rate	1C (1h)	1C, 10C possible	1–2C	1C (25C pule)	1C	10C possible
Cycle life (ideal)	500–1000	300–700	1000–2000	1000–2000	500	3,000–7,000
Thermal runaway	150°C (higher when empty)	250°C (higher when empty)	210°C(higher when empty)	270°C (safe at full charge)	150°C (higher when empty)	One of safest Li-ion batteries
Maintenance	Keep cool; store partially charged; prevent full charge cycles, use moderate charge and discharge currents					
Packaging (typical)	18650, prismatic and pouch cell	prismatic	18650, prismatic and pouch cell	26650, prismatic	18650	prismatic
History	1991 (Sony)	1996	2008	1996	1999	2008
Applications	Mobile phones, tablets, laptops, cameras	Power tools, medical devices, powertrains	E-bikes, medical devices, EVs, industrial	Stationary with high currents and endurance	Medical, industrial, EV (Tesla)	UPS, EV, solar street lighting
Comments	High energy, limited power. Market share has stabilized.	High power, less capacity; safer than Li-cobalt; often mixed with NMC to improve performance.	High capacity and high power. Market share is increasing. Also NCM, CMN, MNC, MCN	Flat discharge voltage, high power low capacity, very safe; elevated self-discharge.	Highest capacity with moderate power. Similar to Li-cobalt.	Long life, fast charge, wide temperature range and safe. Low capacity, expensive.

However, in order for EVs to be both practical and efficient, battery technology has to improve and at the same time use less cobalt, the latter mainly for reasons of supply as will be discussed later in this paper. Figure 5 shows the evolution of the amount of cobalt in Tesla EVs, suggesting that, at the present time, 4.5 kg per car is about as low as it can be, whilst Figure 6 shows BMW's vision of how batteries will develop over the next decade(13). In both of these scenarios, the low-cobalt NCM or NCA batteries are projected to be the ongoing technology of choice. Tesla, along with Panasonic, has announced that it intends to develop a cobalt-free battery, but such is considered to be at least a decade from becoming a reality(14). BMW, on the other hand, is looking towards the solid-state battery, as is Volkswagen.

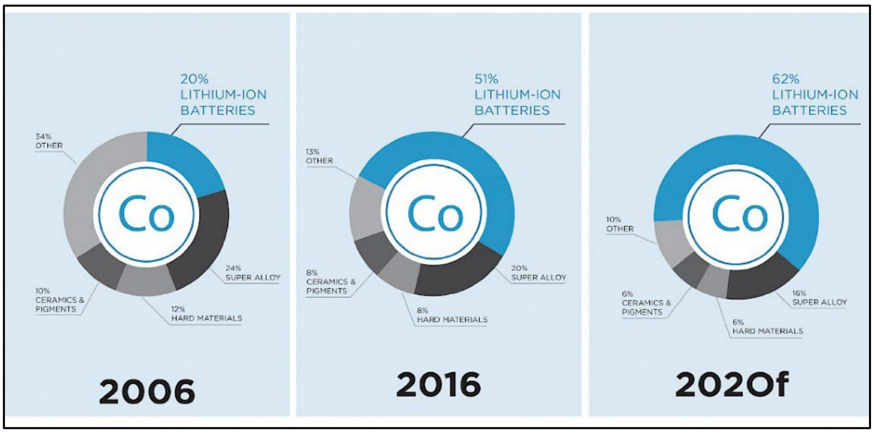


Figure 4. The Evolving End-Use of Cobalt(12)

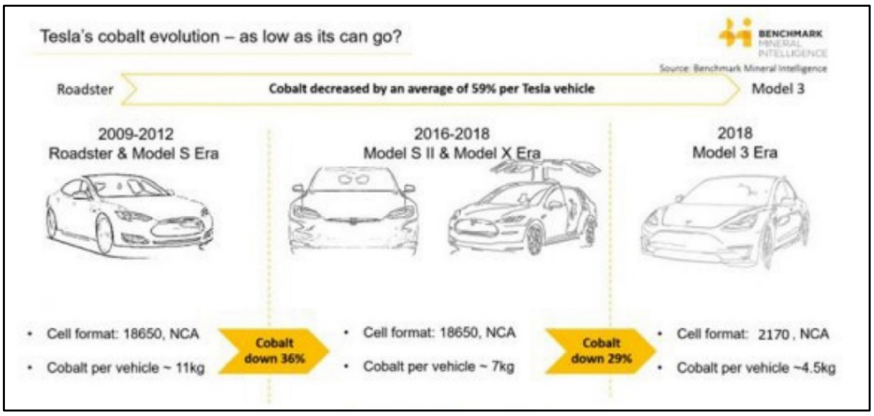


Figure 5. Progressive Decreasing Amount of Cobalt in Tesla EVs(13)

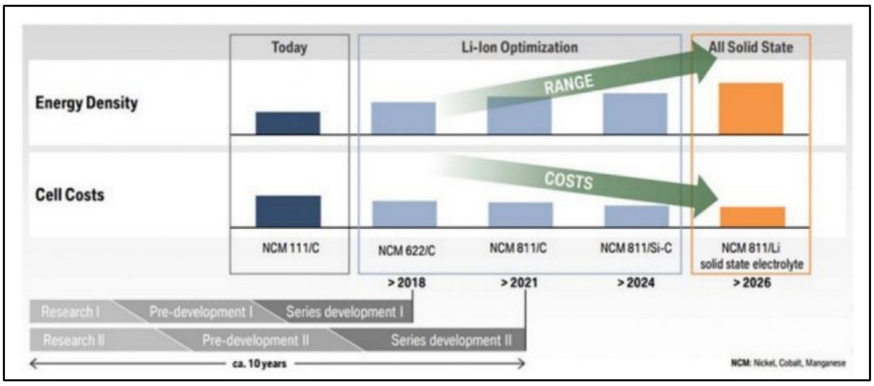


Figure 6. Material Development and Cell Roadmap, BMW(13)

Batteries of the Future

There is much ongoing development work on batteries, and how they might develop in the future. The Australian Academy of Science has summarised these as involving new anode materials, such as silicon and graphene, and novel battery chemistries such as lithium-air, aluminium-air, which are intended to be the next generation of zinc-air batteries(15). Such batteries are a long way off, and do not, so far, give any indications that they will be able to replace the current cobalt-based batteries.

The EV industry in particular is, however, pinning a great deal of hope on the so-called solid-state batteries, as with BMW and Volkswagen above, with the aim of finding a cost-effective and efficient solid-state battery for electric vehicles, which would be equivalent to finding the golden fleece in Greek mythology(16). VW believes that a solid-state battery would increase the range of a Volkswagen E-Golf to approximately 750 km compared to the present 300 km. This battery technology also has further advantages over the present lithium-ion technology: higher energy density, enhanced safety, better fast charging capability, and, above all, they take up significantly less space. A solid-state battery is also expected to reach a much higher energy density than current cells of the same size, and thus a current-size battery package would be able to achieve a range comparable to that of conventional petrol (gasoline) vehicles. Additionally, it is believed that by replacing the current volatile organic electrolytes, they will be inherently safer. The aim is to have such batteries by 2026 (Figure 6).

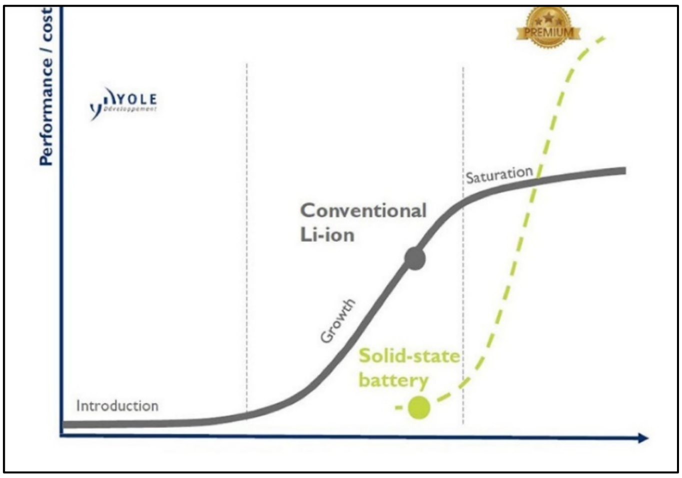


Figure 7. Solid-State Batteries Projection(16)

SUPPLY-DEMAND RELATIONSHIPS

At the Beginning of the "Age of Lithium-Ion Batteries"

Before addressing the current supply-demand situation, it is interesting to observe what the situation was at the beginning of the 1990s when the first lithium-ion batteries were commercialised. In the preceding decade, with the advent of super-alloys and super-magnets, both of which were/are highly dependent on cobalt, there had been panic and concern as to whether there would be sufficient availability to meet demand, somewhat similar to the current angst relative to lithium-ion batteries. Much effort was put into finding substitutes for cobalt, notably with nickel as it always is, and although some minor substitutions were adopted, the panic eventually subsided and the inflated cobalt prices returned to more traditional levels, again very similar to what has been observed with cobalt price over the past few years, as shown below(17).

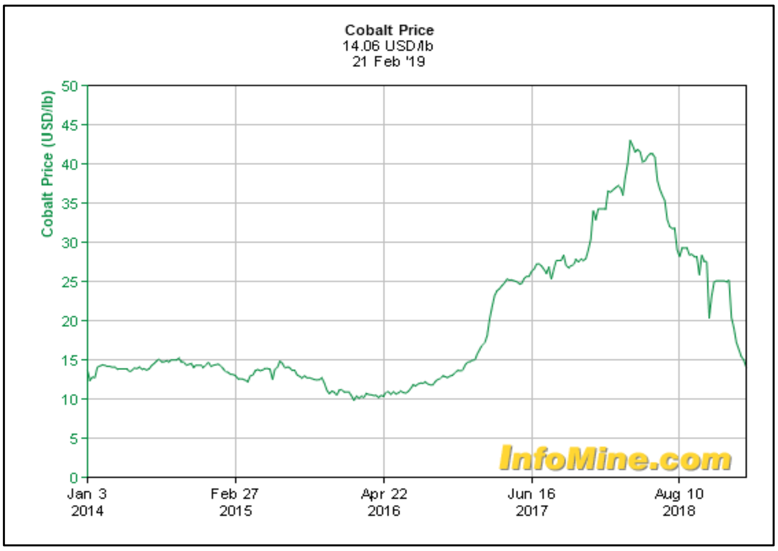


Figure 8. Five-Year Cobalt Price(17)

In 1990, the world demand for cobalt was 24,000 tonnes/year, with estimated reserves being 2.4 million tonnes, so that at the then consumption rates, there were 100 years of identified reserves(18). Then, as now, the Central African Copperbelt accounted for 60% of the supply, but unlike today, the distribution ratio between Zambia and Zaïre (as the DRC was then known) was approximately 1:2. In projecting future trends and uses for cobalt, lithium-ion batteries were not even mentioned, with most growth expected to come from super-alloys. Relative to the then current supply, it was estimated that the Copperbelt could increase supply by 6000 tonnes annually, with other sources being Cuba

(1600 tonnes or greater, as export to Canada), and potentially 4500 tonnes from Russia. It was also noted that there was at least 400 years of supply "under the sea." The paper concluded that "All in all, Cobalt appears to be steady and here to stay."

Fast forward a decade to 2000, and still before the "Age of Lithium-Ion Batteries" had really begun, at the first ALTA conference of the "noughties," a general paper reviewing HPAL projects on nickel laterites stated(19):

> *"… many projects are too heavily dependent on this (cobalt) credit to compensate for low nickel grades. The relatively tight cobalt market may not be able to cope with the planned tonnages that will flow from the new laterite producers and this may put the price under pressure. Compounding this will be the ultimate return to normality in both the Zambian and Congolese industries …*
>
> *… Consequently laterite projects that are overtly dependent on cobalt credits to enhance viability may not prove viable. … However, in response to low cobalt prices demand must be stimulated by new uses for the metal and rescue the day. It is clear that the industry must focus on developing the cobalt market and someone has to pay for it."*

How times have changed! There was indeed great concern that by-product cobalt from the embryo nickel laterite projects would swamp the market, and, as noted in the above quotation, the concept of massive demand from lithium-ion batteries was still not even on the horizon. In fact, there was concern that there just was not enough demand and uses for cobalt, and that this would have a major negative impact on these new nickel laterite projects. Everything was geared to nickel and the burgeoning steel industry, especially in China, but with an unfortunate and necessary need for cobalt by-product credits in order for projects to be economically viable. It is probably fair to say, however, that with the many potential and actual HPAL projects which failed, cobalt was simply not a factor in the end. Operational issues, particularly those associated with the HPAL autoclaves(20,21), and the massive cost overruns were much more the issues.

Current (2018) Production and Reserves

Given the present and projected importance of cobalt, therefore, it is appropriate to look at current (and future) supply-demand relationships in the context of the "Age of Lithium-Ion Batteries." Despite being fairly widespread in the earth's crust, at 0.002%, making it the 33rd most abundant element, most of the world's cobalt is recovered as by-product of copper and nickel processing. At present, there is only one primary cobalt mine, the Bou Azzer deposit in Morocco, although others are being actively considered, as will be discussed later in this paper.

Table 2 shows the recent mine production of each of copper(22), nickel(23) and cobalt(24) as reported by the United States Geological Survey (USGS). Certain observations are immediately obvious, in that copper production is an order of magnitude greater than that of nickel, which itself is 20 times that of cobalt. Cobalt production is dominated by the DRC, which produces nearly 60% of global supply, the majority of which undergoes final refining in China. Of this cobalt refined in China, 80% is consumed by lithium-ion battery manufacture(24). Cobalt production is now some 4.5 times that of what it was in 1990(18), and considerably greater than what was believed possible at that time or what was feared in 2000(19). The relative production from the two African Copperbelt countries, however, is now 30:1 in favour of the DRC, compared to 2:1 in 1990.

Table 3 summarises the estimated confirmed land-based reserves of these three metals. It is apparent that, as for world production, the DRC, with approximately 50%, dominates the known reserves of cobalt. Of the other countries, Australia appears to hold a dominating position for all three metals. However, the USGS notes that these Australian reserves are those reported by the major companies, and the JORC (Joint Ore Reserves Committee)-compliant reserves are considerably less, being 24 million tonnes for copper, 6 million for nickel and 390,000 for cobalt, in other words, about 30% of the numbers in Table 3.

Table 2. World Mine Production of Copper(22), Nickel(23) and Cobalt(24), tonnes

	Copper		Nickel		Cobalt	
	2016	**2017**	**2016**	**2017**	**2016**	**2017**
Australia	948,000	920,000	204,000	190,000	5,500	5,000
Brazil	-	-	160,000	140,000	-	-
Canada	708,000	620,000	236,000	210,000	4,250	4,300
Chile	5,500,000	5,330,000	-	-	-	-
China	1,900,000	1,860,000	98,000	98,000	-	-
Colombia	-	-	41,600	49,000	-	-
Congo (DRC)	846,000	850,000	-	-	64,000	64,000
Cuba	-	-	51,600	51,000	4,200	4,200
Guatemala	-	-	54,000	68,000	-	-
Indonesia	727,000	650,000	199,000	400,000	-	-
Madagascar	-	-	49,000	45,000	3,800	3,800
Mexico	752,000	755,000	-	-	-	-
New Caledonia	-	-	207,000	210,000	3,390	2,800
Papua New Guinea	-	-	-	-	2,190	3,200
Peru	2,350,000	2,390,000	-	-	-	-
Philippines	-	-	347,000	230,000	4,100	4,000
Russia	-	-	222,000	180,000	5,500	5,600
South Africa	-	-	49,000	49,000	2,300	2,500
United States	1,430,000	1270,000	24,100	23,000	690	650
Zambia	763,000	755,000	-	-	3,000	2,900
Other countries	4,160,000	4,300,000	150,000	150,000	7,600	5,900
World total (rounded)	**20,100,000**	**19,700,000**	**2,090,000**	**2,100,000**	**111,000**	**110,000**

Table 3. Estimated World Reserves of Copper(22), Nickel(23) and Cobalt(24), ’000 tonnes

Country	Copper	Nickel	Cobalt
Australia	88,000	19,000	1,200
Brazil	-	12,000	-
Canada	11,000	2,700	250
Chile	170,000	-	-
China	27,000	2,900	-
Colombia	-	1,100	-
Congo (DRC)	20,000	-	3,500
Cuba	-	5,500	500
Guatemala	-	1,800	-
Indonesia	26,000	4,500	-
Madagascar	-	1,600	150
Mexico	46,000	-	-
New Caledonia	-	N/A	N/A
Papua New Guinea	-	-	51
Peru	81,000	-	-
Philippines	-	4,800	280
Russia	-	7,600	250
South Africa	-	3,700	29
United States	45,000	130	23
Zambia	20,000	-	270
Other countries	260,000	6,500	560
World total (rounded)	**790,000**	**74,000**	**7,100**

For cobalt, it is notable that whereas demand has increased 4.5 times since 1990, identified reserves have increased just under three times, and rather than there being 100 years of reserves, at the present rate of consumption, there is now just seventy years, which, of course, is consistent, this being thirty years later. In the context of the “Age of Lithium-Ion Batteries,” doubling consumption, which is the minimum anticipated, therefore, will reduce this to a mere thirty-five years. Similarly for nickel and copper, at current production rates (Table 2), there are just under 40 years of identified reserves left.

Nickel is becoming increasingly dependent on laterites, which account for 60-70% of identified reserves(23). However, laterites are not easy to process, and more so, are highly capital-intensive, and the many problems associated with HPAL (High Pressure Acid Leaching), the currently-preferred technology, have been well documented. Equally, copper is also facing a supply problem. Anglo American estimates that working on the assumption that the growth rate of copper over the next 13 years is 2% a year, which in historic terms is not high, the world would need the equivalent of another 13 Collahuasi copper mines by 2030(25). At 560,000 tonnes, Collahuasi is the world's second largest copper mine. If it is also factored in that the assumption that global copper consumption would rise from the current 3 kg per person to 4 kg per person, which again is not considered unreasonable, it would then need the equivalent of another 22 Collahuasi mines to come on stream. Clearly, this is not going to happen.

Crystal-Ball Gazing - Forecasting the Supply-Demand Situation

Whilst there is unanimity of agreement that there will be an increased demand for cobalt, not all commentators agree on the scale of this increase, nor how much of a problem it will be. There are a number of factors at play here, not the least of which is battery chemistry itself. At the end of 2016, there were an estimated two million EVs in existence(26). Contrast this with, also in 2016, seventy million new petrol (gasoline)-driven cars being produced in a single year(27), then it is clear that EV production is very much in its infancy, and the critical factor will be at what rate this is going to grow. Most estimates, such as that by the Commodities Research Unit (CRU) in a study undertaken for Glencore(5), are calling for approximately 30% of all new vehicles to be electric by the year 2030. Taking the optimistic Tesla estimate of only 4.5 kg of cobalt per car noted above(13), then 20 million EVs (30% of seventy million, also noted above) will require an extra 90,000 tonnes of cobalt, or close to current world production.

This is not too dissimilar to an estimate published by Morgan Stanley in 2017, as shown in Figure 9(28). This graph only projects to 2025, so extrapolating to 2030 gives a figure similar to that above.

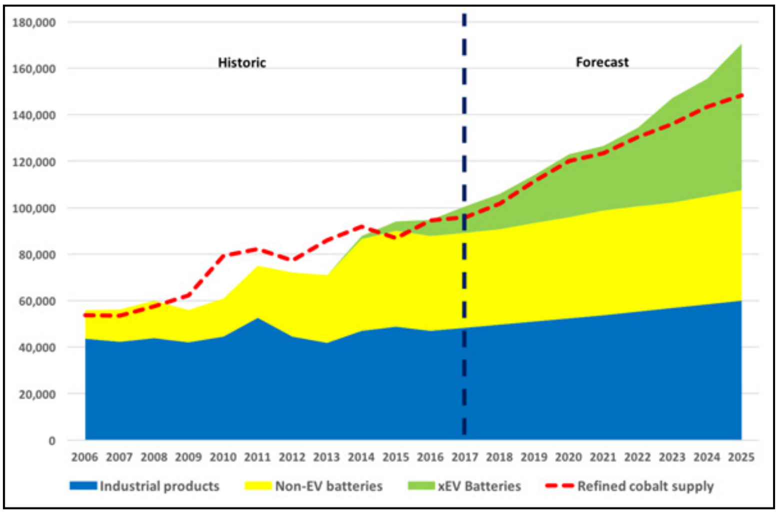


Figure 9. Annual Cobalt Supply and Demand, tonnes – Morgan Stanley(28)

Conversely, the CRU study commissioned by Glencore referenced above, has estimated that based on an EV market share of less than 32% in 2030, forecast metal requirements are roughly 4.1m tonnes of additional copper (18% of 2016 supply, which as Anglo American notes above, is not there), 56% more nickel production or 1.1m tonnes compared to 2016, and 314,000 tonnes of cobalt, a three-fold increase from 2016 supply(5). Glencore said at the time that the company will aim to double its cobalt output to 63,000 tonnes by 2020, mostly as a result of restarting its Katanga mine in the Congo. However, more recent developments in February, 2019, suggest that this may be problematic due to the laying off of workers, especially expatriates, and the ongoing tensions between the company and the government(29). Katanga would also lift copper production to over 1.6m tonnes by then from 1.3m tonnes in 2017. Glencore is also planning to grow nickel production by more than 20% to 142,000 tonnes over the same time frame.

Western Areas Limited, WA, in its 2018 year-end corporate presentation has estimated that, based on average NMC battery chemistry, the typical future electric vehicle will contain 40-50 kg Ni, 50-75 kg Cu and 5-15 kg Co per car(30). The low end for cobalt is about the same as that for Tesla with its NCA batteries noted above, and the high-end more in keeping with the CRU estimate.

Analysis by researchers at the Helmholtz Institute Ulm (HIU) of the Karlsruhe Institute of Technology (KIT) in Germany shows that the availability of cobalt (and also lithium) could become seriously critical. Cobalt-free battery technologies, including post-lithium technologies based on non-critical elements such as sodium, but also magnesium, zinc, calcium and aluminium, represent possibilities to decrease the dependency upon and avoid the criticality of supplies in the long term(31). Their scenario-based analysis until 2050 for various applications of batteries shows that a shortage and price increase of cobalt are highly likely to occur, since cobalt demand by batteries alone might be twice as high as today's identified land-based reserves. This conclusion is in keeping with the simple analysis based on production (Table 2) and reserves (Table 3) discussed above. In contrast, today's identified lithium reserves are expected to be much less strained, but production will have to be significantly increased (possibly more than ten times, depending on the scenario) to match future demand.

Options for Increased Production of Cobalt

There are, however, more optimistic (from the perspective of supply), but also somewhat naïve, outlooks, in that as prices are driven higher, other miners will look to bring new production capacity online to meet this demand(32). In this scenario, it is believed that there is significant opportunity for new production to come online, and that in situations where cobalt is currently a by-product, the increase in price will now promote it to be the major commodity, at least in terms of revenue if not tonnage. Unfortunately, such optimistic viewpoints fail to take into account (i) the time and cost required to bring new production on-line, and (ii) the fact that there simply are not the identified reserves.

In whatever way it is looked at, the supply of cobalt is linked to that of nickel and copper, and since it seems unlikely that, with present knowledge, the foreseeable batteries of the future EVs will be entirely cobalt-free, there will need to be increased supplies of cobalt to meet demand, whereas the situation for nickel and copper (and also manganese), whilst still being cause for concern, is perhaps not quite so pressured. Because virtually all of the world's cobalt is mined as a by-product, any attempts to increase its supply inevitably will result in a substantial increase in the supply of copper and/or nickel. As will be noted later, sufficiently significant increases in the supply of cobalt from the DRC (i.e. copper mining) is unlikely, especially in the short term, for a variety of reasons. Similarly, increasing its supply from nickel operations, predominantly laterites, also seems logistically unlikely. Laterite projects are highly capital-intensive, and if, for example, increasing cobalt supply by 100,000 tonnes/annum is needed, this would result in the equivalent extra production of at least 1 million tonnes of nickel, or 50% of current world production. Whilst this is equivalent to the CRU/Glencore estimate referenced above for nickel, it is not so for cobalt, and it is possible that such an increase in production could depress the price of nickel to a level that is not economically sustainable – a "catch-22" situation, such as what happened in the early "noughties."

It is also worth noting that nickel plants, unlike even primary copper smelting, are always relatively modest in size, 50,000 tonnes/annum being considered a large plant, so that equivalent cobalt is 5000 tonnes or less. These plants also require substantial capital investment, in the order of billions of dollars, especially from laterites if based on HPAL technology, so it is unrealistic to expect there to be enough projects to come on line to meet the projected shortfalls.

Existing Operations

Nevertheless, existing commercial laterite projects are announcing increases in production. The Ramu Project in Papua New Guinea has announced an expansion, costing US$1.5 billion, to generate 34,000 tonnes of nickel and 3,300 tonnes of cobalt annually(33). Vale has indicated that it intends to invest a further US$500 million at Goro, this despite the project not only being over-budget and years late when it started up in 2010, but also having accumulated nearly US$1.3 billion in losses during the period 2014 to 2016 alone. This decision has been made purely because of the anticipated EV revolution(34). Vale has also announced a US$2 billion expansion at Voisey's Bay, increasing cobalt production from the current 1800 tonnes to 2600, and nickel by 45,000 tonnes(35).

Meta Nikel Kobalt has announced that it will increase production fourfold at its Gördes Project in Turkey(36). The plant will produce 40,000 tonnes of nickel (up from 10,000), but the cobalt amount was not stated, and will be combined with a 25,000MW battery plant, for a total investment of US$4.5 billion. Other major producers, such as Sumitomo and PT Inco, are also looking at possible projects, but there is nothing definitive announced as yet(37).

Africa

Cobalt production in Africa is dominated by the Central African Copperbelt, straddling the DRC and Zambia, with the majority of production emanating from the former. There are and have been other operations on the continent, including the aforementioned Bou Azzer mine in Morocco, and from 1973-2016, BCL (Bamangwato Concessions Limited) in Botswana. BCL operated the Selebi-Phikwe smelter, which produced a nickel-copper-cobalt matte that was refined by Glencore (Falconbridge) at Kristiansand in Norway. Botswana also hosted the Tati Nickel Mine, which was not successful, although it has recently come out of liquidation(38).

In South Africa, two of the major platinum producers, Impala and Anglo Platinum(39), also produce significant tonnages of nickel, copper and cobalt. The Nkomati mine, which hosts one of the largest potential nickel reserves in South Africa is currently under care and maintenance, and African Rainbow Minerals, the operator, is currently deciding whether to reopen it(40). Further north, the Kasese Cobalt Company (KCCL) was formed in 1992 as a corporate entity with the government of Uganda to recover cobalt from an unstable stockpile of a cobalt-rich sulphide concentrate (pyrite), and the processing plant was commissioned in 2000(41). The project was reported to cost US$153 million, but it is unsure as to whether the plant has operated after the Kilembe Copper plant stopped production. There have been no official cobalt statistics showing any export of material from Uganda.

The Democratic Republic of the Congo (DRC)

As noted, most of the world's cobalt comes from the DRC (Democratic Republic of the Congo), capital Kinshasa, a landlocked country in central Southern Africa, and not to be confused with the neighbouring Republic of Congo, capital Brazzaville, to the west. Figure 10 shows the general location of the DRC, and Figure 11 the location of the Copperbelt, which straddles the DRC and Zambia, where this cobalt is found.

Figure 10. Central Southern Africa, Showing Location of DRC (Google Maps)

The DRC is the second-largest country in Africa, being almost the size of western Europe. However, despite its vast mineral wealth, it has one of the lowest GDPs in the world(42), and it is also one of the most corrupt countries(43). Given both its mineral wealth potential and its climate (ideal for agriculture), it ought to be one of the most prosperous countries on the planet. The revisions to the Mining Code early in 2018(44), and the elections held at the end of 2018 appear to have done nothing to alleviate any of the problems in the country, and, if anything, have only exacerbated them. As noted in Figure 10 and Figure 11, the mineral wealth of the country is located on the opposite side to the administrative capital, Kinshasa, and just to the south of opposition/rebel strongholds located near the Rwanda/Burundi border.

Indeed, in the 1980s when the price of cobalt first saw a dramatic increase to the US$30/lb level, so much so prompting the extractive metals industry to host a stand-alone conference dedicated entirely to cobalt alone(45), and later in the 1990s, the metals processing plants were subject to invasion by these rebels. There is neither road nor rail link from Kinshasa to the Copperbelt, so the latter area is somewhat isolated and a long way from any port. However, in 2015, the Haut-Katanga Province was ratified, with an administrative capital of Lubumbashi, suggesting a degree of autonomy from Kinshasa may be possible(46).

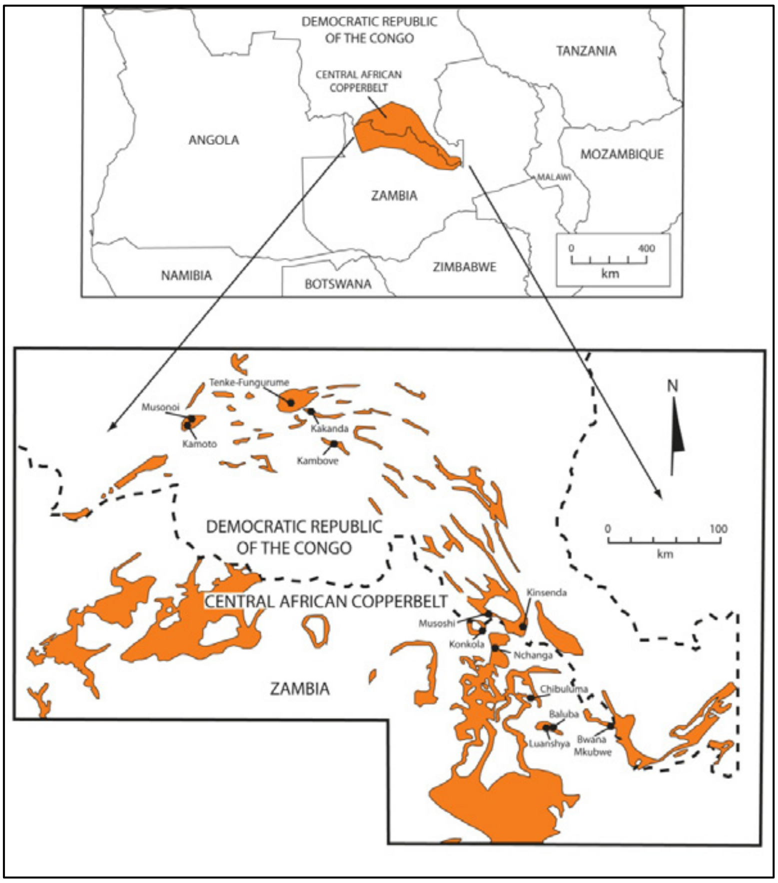


Figure 11. Location of Central African Copperbelt, DRC and Zambia(47)

Additionally, apart from these political, geographical and infrastructure issues, there are other obstacles which mitigate against the DRC significantly increasing output, these being ones of health. Ebola outbreaks are common, but its control is hampered by rebel attacks(48). Indeed, such attacks appear to be on the increase, to the extent that medical professionals are now having to resort to disguises(49). The central and southern African countries have the highest incidence of AIDS in the world, which has had a devastating effect on the workforce, to the extent that the S. African platinum companies now post AIDS-related statistics in their Annual Reports.

Additionally, since the WHO (World Health Organization) mandated against the spraying of DDT, malaria has become endemic, having spread from the north of the country in the 1970s as far south as northern South Africa(50). Whereas formerly, maybe 5% of the population suffered symptoms attributable to DDT, now the majority of the population is at risk from contracting malaria. The former situation, whilst not desirable in any sense, would, however, seem to be more preferable. Ivanhoe Mines is actively working with the government to combat the malaria problem in the DRC(51).

Up to 20% of the cobalt recovered in the DRC is as a result of artisanal mining, mostly by children, and the majority is sold into China, which country accounts for close to 80% of the supply of the cobalt sulphate needed for lithium-ion battery manufacture(52). Thus, there is a potential supply-demand problem. This artisanal mining is the subject of controversy, with the cobalt recovered therefrom being classified as a “conflict mineral.” On the one hand, for these very poor children miners, who are paid typically US$9 per day, it is a source of much-needed income, but conversely, it is also clearly exploitation. However the issue is resolved, it is clearly one which could have a significantly negative short-term impact on the supply of cobalt. Major companies are now implementing “chains-of-custody” in an effort to combat this exploitation.

Despite the real and potential difficulties of operating in the DRC, there are, nevertheless, many companies now doing so. Of these, the major players are Glencore, whose Mutanda mine generates 110,000 tonnes of copper and 23,000 tonnes of cobalt, and Freeport-McMoran/Lundin Mining/Gécamines at Tenke Fungurume with a similar amount of copper and 8200 tonnes of cobalt(53). However, recently Lundin has announced that it has sold its interest to Umicore for US$150 million(54). Others include the Shituru Mining Corporation (Chinese owned) which re-opened the historic Shituru mine in 2012(55), Canadian-based Katanga Mining and the Belgian Forrest Group. The latter is interesting in that it plans to treat the slag dumps from the old copper smelters, generating alliages blanc (white metal), a copper, cobalt, iron alloy for further processing(56), in a process similar to that developed at Nkana(57) and installed at Chambishi(58). As noted above, Ivanhoe Mines are also active, but on two copper-only projects, and ones which are in relatively early-stage exploration.

Zambia

For many years, there were two operating cobalt plants in Zambia, along with those in the DRC (or Zaïre as it was known for a time)(59), which allowed Zambia to produce at a level equivalent to 50% of that from the DRC. The two Zambian plants were/are Nkana in Kitwe(60,61) and Chambishi, mid-way between Kitwe and Chingola (Nchanga), the site of the pioneering major copper SX/EW plant of the early 1970s, which is still operating(58,62,63,64,65). The former cobalt plant, along with the Nkana copper smelter, is no longer in operation. According to its 2018 Annual Report, Chambishi is still operating, but using feed material from the DRC(66). The Chambishi expansion in 2000 was based on treating slag dumps, notably the one in Kitwe (Figure 12), which had been built up since 1932(58). In the early days, copper mineral processing and smelting on the Copperbelt was somewhat inefficient by modern standards, with the result that substantial amounts of cobalt reported to the slags(59). Consequently, slag dating back to the early days of smelting was very high in cobalt, in some cases as high as 3%, making the slag dumps some of the richest, if albeit relatively low tonnage, cobalt resources in the world(67).

Figure 12. Nkana Slag Dump, Kitwe, Zambia

Chambishi processed slag from 2000-2010, when it stopped due to depressed metal prices(68). The remaining dump (Figure 12) is still in existence and has, unsurprisingly, attracted “illegal” mining similar to the artisanal miners in the DRC. Sadly and equally unsurprisingly, this mining has resulted in tragedy, with several miners having been killed as the dump collapsed(69). Ironically, the Zambian Observer published an article showcasing a headline stating that Black Mountain, as the dump is known, “is not a disaster in waiting” the day prior to the disaster(68). Like much of the rest of the Copperbelt, both in the DRC and in Zambia, the dump is now under Chinese control(68).

Australia

As would be expected, there are several new projects developing in Australia, along similar lines to those in N. America referenced below. The most advanced appears to be that of Clean Teq’s nickel, cobalt, scandium Sunrise Project in New South Wales, formerly known as Syerston(70). A DFS was completed in mid-2018 for the production of 18,730 tonnes of nickel and 3200 tonnes of cobalt, both as battery-grade sulphate salts(71). Several updates were delivered at this conference.

Other projects include the Thackaringa Cobalt Project, located 25km southwest of Broken Hill, New South Wales(72), Torrens Mining Cu-Co Project in South Australia(73), the Mount Thirsty Co-Ni-Mn JV in WA, which is currently undergoing a PFS(74), and GME Resources NiWest Project, adjacent to Murrin Murrin, which proposes a heap leach to produce 19,200 tonnes of nickel and 1400 tonnes of cobalt in battery grade sulphate salts annually(75). Additionally, Panoramic Resources has signed an off-take agreement with Chinese company Sino Nickel for all of its concentrate production from its Savannah Project in WA(76). Savannah was placed on care and maintenance in May 2016 as nickel prices plummeted, but a subsequent feasibility study in 2017 on restarting the project found that it would be viable, requiring a capital investment of A$36-million and could produce 10,800 tonnes of nickel, 6,100 tonnes of copper and 800 tonnes of cobalt annually.

North America

There are potentially-mineable, well-known areas where cobalt exists, two of these being the Idaho Cobalt Belt in the US, and the Ontario Cobalt Camp in Canada, the latter situated around the aptly-named town of Cobalt. Both of these areas have very high concentrations of arsenic, which have posed problems in processing, and the former has previously hosted cobalt production in the past from the Blackbird mine. Calera Mining Company operated for a short while after WW2, since cobalt was deemed a strategic metal and a source of US domestic supply desirable, but was eventually closed down as being uneconomic. Noranda, as this division of Glencore was then known, acquired and attempted to reactivate the mine in the 1980s, spurred on by the rise in price of cobalt to ~US$30/lb due to the expansion of the superalloys market. A process was developed(77), with an operating cost of US$2.10/lb of Co for treatment of the concentrate. Unfortunately, the Blackbird deposit is very difficult to mine, with cobalt occurring in discrete, non-contiguous pockets or zones, with the result that the mining costs were estimated to be over US$20/lb of Co, and the project was abandoned as the price of cobalt dropped back to more traditional levels(78).

More recently, eCobalt Solutions has indicated that it plans to mine 1200 tonnes/day at its Idaho Cobalt Project, in the same area as Blackbird(79). The company plans to produce 1500 tonnes of cobalt per year, starting in 2020, in a concentrate containing <0.5% As(80). This will be achieved via a roasting process, assuming permits are granted, with the arsenic trioxide/sulphide subsequently being sequestered by the Dundee Sustainable Technologies vitrification process(81,82). It has to be said that reverting to roasting of arsenical concentrates seems to be a return to the dark ages in terms of environmental and OHSA aspects. Pressure leaching or chloride-based processes would certainly seem to offer a more environmentally-attractive option. In the author’s opinion, vitrification of arsenic has been attempted before, and demonstrated not to be viable long term – vitrification is always susceptible to de-vitrification (second law of thermodynamics) with the subsequent mobilization of the arsenic, and there are no compelling data to show that it is effective long-term(83).

In Canada, there is much activity in and around the Ontario Cobalt Belt as well as in the North West Territories. The Cobalt, Ontario area has been mined extensively in the past, from 1904 to 1985, but, despite its name, it was for silver, and the last of these silver mines closed almost 30 years ago. Historically, the ores contained 8-100 oz/ton silver, together with ~1% nickel and 2% cobalt, making them some of the richest-known cobalt ores(84). However, the current global push for the town’s namesake metal is now breathing new life into this area, 500 kilometers north of Toronto(85). There are at least five junior exploration companies, the most advanced of which appears to be First Cobalt, which also has a project, Iron Creek, in the Idaho Belt(86). The company has not issued targets for production, but intends to initiate a PEA in 2019(87). It recently announced that it has entered into a Memorandum of Understanding with Glencore, wherein the latter will supply feedstock to reopen the refinery(88). Other companies exploring this area include Canada Cobalt Works(89), Cruz Cobalt Corporation(90), Cobalt Power Group(91), and Quantum Cobalt Corporation(92). Another Canadian Company, Fortune Minerals, has revived its NICO Project (nickel, cobalt and bismuth) in the North-West Territories(93), and is aiming to produce 1850 tonnes/annum of cobalt in a concentrate, with a projected start-up in 2022(94).

There is also a large, often-overlooked, already-mined resource, namely the Sudbury Tailings from the operations of both Vale (Inco) and Glencore (Falconbridge)(95,96). Since the early 1990s, Glencore alone has disposed of 8 million tonnes (dry basis), with an average grade of ~0.8% Ni(96). The cobalt content was not given, but unpublished data have shown 0.03-0.05% Co and nickel contents as high as 1.2%. As with other deposits in N. America, there is, however, a substantial arsenic content, which together with a substantial pyrrhotite content (~75%) has acted as a disincentive for re-processing. A chloride-based approach to re-treating these tailings was proposed in 2010(95), and more recently, a bioleaching process has been proposed(97,98). The chloride approach can recover, in addition to nickel, cobalt and the PGMs, useful products of iron and sulphur, as well as the intrinsic energy contained in the tailings. Additionally, it fixes 100% of the contained arsenic as scorodite, widely recognized as being the most effective arsenic-fixation method. Bioleaching, whilst being able to recover nickel and possibly cobalt, is not able to achieve anything else, and more importantly, will generate a tailings volume appreciably greater than that already there due to the oxidation of iron and sulphur to form ferric hydroxide and gypsum. Moreover, as noted in the Terraframe paper in this conference, bioleaching of pyrrhotite generates substantial heat, which has to be controlled(99). Terraframe has had issues with just 11% pyrrhotite in the ore, so that materials with 75% pyrrhotite would seem to be impractical by this approach.

Deep-Sea Manganese Nodules and Cobalt Crusts

Interest in the potential exploitation of polymetallic seabed nodules generated a great deal of activity, interest in and excitement among prospective mining consortia in the 1960s and 1970s. Almost half a billion dollars was invested in identifying potential deposits and in research and development of technology for mining and processing the nodules(100). These initial undertakings were carried out primarily by four multinational consortia composed of companies from the United States, Canada, the United Kingdom, the Federal Republic of Germany, Belgium, the Netherlands, Italy, Japan and two groups of private companies and agencies from France and Japan. There were also three publicly sponsored entities from the Soviet Union, India and China(100).

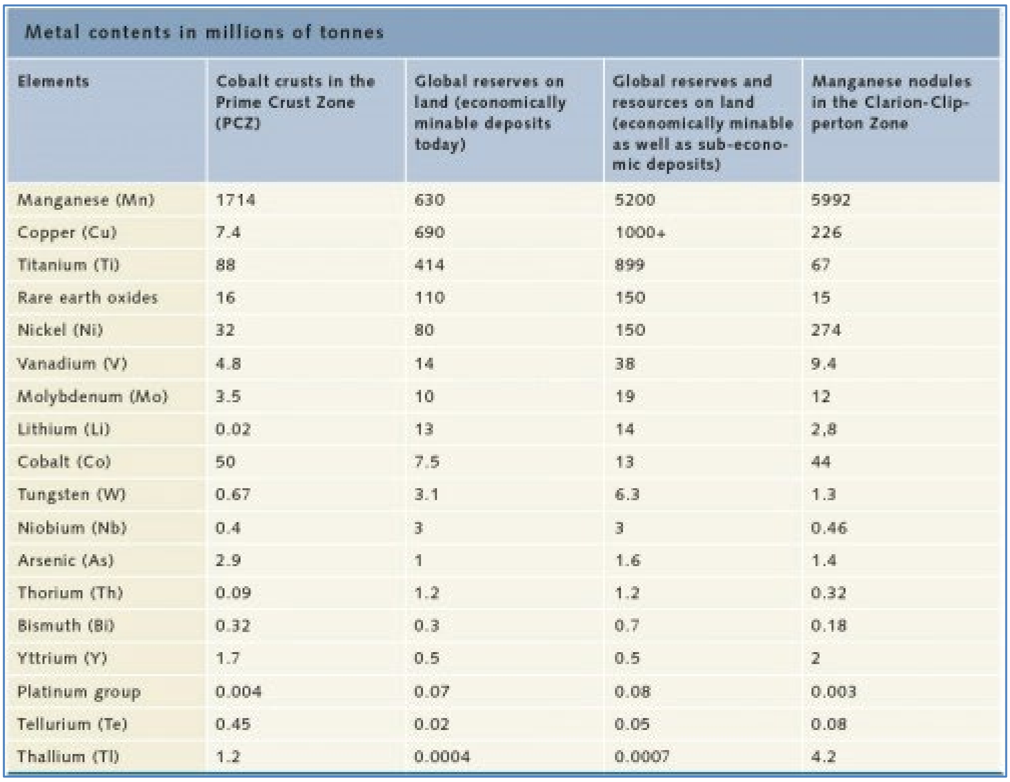
In the late-seventies, two of the international joint ventures succeeded in collecting several hundred tonne quantities of manganese nodules from the abyssal plains (18,000 feet, >5.5 km depth) of the eastern equatorial Pacific Ocean. Significant quantities of nickel (the primary target at the time) as well as copper and cobalt were subsequently extracted from this "ore" using both pyrometallurgical and hydrometallurgical methods.

An Economist report suggests that harvesting of deep-sea nodules is once again definitely back on the agenda(101). Two companies, Nautilus Minerals founded in 1987(102) and Neptune Minerals founded in 2011(103) have been formed to exploit these nodules. However, neither appears to have had much success, with Nautilus recently (January 2019) applying for creditor protection(104). Neptune is a private company, but there has been no news of it since 2015. Nevertheless, Nautilus, in particular, has demonstrated that harvesting seabed nodules appears to be technically feasible.

However, any future mining of nodules will need to be authorised by the International Seabed Authority (ISA) and would need to quantify any impact in advance via an Environmental Impact Statement. This, of course, introduces a very contentious topic, namely as to whether deep sea mining should be allowed from an environmental perspective(105). There are, as might be expected, a diversity of opinions about the impact seabed mining might have on the local ecosystem, and the fact is that nobody really knows. One theory is that since the nodules are generally found in the proximity of hydrothermal vents, which are constantly active, then harvesting of nodules would not, in fact, cause any disruption different to that what is already there(101).

In the context of the availability of cobalt in particular, Table 4 below shows that the reserves of both manganese and cobalt on the ocean floor far exceed those identified on land(106).

Table 4. Comparison of Land-Based and Sea-Based Metal Reserves(106)



Metal contents in millions of tonnes

Elements	Cobalt crusts in the Prime Crust Zone (PCZ)	Global reserves on land (economically minable deposits today)	Global reserves and resources on land (economically minable as well as sub-economic deposits)	Manganese nodules in the Clarion-Clipperton Zone
Manganese (Mn)	1714	630	5200	5992
Copper (Cu)	7.4	690	1000+	226
Titanium (Ti)	88	414	899	67
Rare earth oxides	16	110	150	15
Nickel (Ni)	32	80	150	274
Vanadium (V)	4.8	14	38	9.4
Molybdenum (Mo)	3.5	10	19	12
Lithium (Li)	0.02	13	14	2,8
Cobalt (Co)	50	7.5	13	44
Tungsten (W)	0.67	3.1	6.3	1.3
Niobium (Nb)	0.4	3	3	0.46
Arsenic (As)	2.9	1	1.6	1.4
Thorium (Th)	0.09	1.2	1.2	0.32
Bismuth (Bi)	0.32	0.3	0.7	0.18
Yttrium (Y)	1.7	0.5	0.5	2
Platinum group	0.004	0.07	0.08	0.003
Tellurium (Te)	0.45	0.02	0.05	0.08
Thallium (Tl)	1.2	0.0004	0.0007	4.2

Ultimately, however, it is almost certain that harvesting and processing of these nodules will occur, especially as cobalt-based batteries increasingly become a part of everyday life. Many researchers have worked on seabed nodules, and the variety of approaches mirrors the complexity and variety of primary methods of cobalt, nickel and manganese recovery. The following references comprise a critical review of an acid-based process and an ammonia-based process(107, 108).

Supply-Demand Discussion

Cobalt (and lithium) are fundamental components of present lithium-ion batteries. Both elements, but cobalt in particular, additionally suffer from strong geographical concentration, moreover in countries which are reported to be less politically stable. New battery technologies based on low-cost, abundant and, at best, non-toxic elements, are under development, but would seem to be a long-way from being commercially-realised. The particular problem for cobalt supply is that it is produced almost entirely as a by-product, and therefore the economics of its extraction are very much dependent on those of the primary metals, copper and nickel. Whilst there are numerous projects, both expansions from existing operations and potential new primary mines, these necessarily take time, and each can only deliver a small fraction of the total amount of cobalt needed.

Apart from Glencore, which has indicated it aims to double its production in the DRC (25-30,000 tonnes), the others will produce in the range of 1000-4000 tonnes/annum of cobalt, which does not come anywhere near the 100,000-300,000 additional tonnes indicated earlier in this paper. Further, most of this potential new cobalt production will require time to come on-line, especially from non-existing operations, such that the pressure on cobalt supply, assuming that the EV revolution goes ahead, is not going to be eased.

A further aspect to consider is that if production is, at the very minimum, doubled from current levels, then the known identified land-based reserves of cobalt will be exhausted in just over thirty years at best, and more than likely, even sooner. This situation can only be mitigated against by one or both of two possibilities. Much more attention will have to be paid to recycling, and not just from an environmental viewpoint, but more importantly from a sustainability stance. The other option is the harvesting of deep-sea nodules, which contain far more cobalt (and manganese) reserves than anything land-based. Again, though, this is a long-term option, but maybe one which can be developed before land-based reserves are exhausted.

COBALT (AND COPPER, NICKEL) RECOVERY FLOWSHEETS

As noted above, most of the world’s cobalt is recovered as a by-product from copper or nickel processing. Typically, the ratio of copper to cobalt is in the order of 100:1, but there are areas in the DRC where this can be as low as 10:1, whereas for nickel it is generally 10:1. Copper ores, however, are generally amenable to differential flotation, so that separate copper and cobalt concentrates can be produced which mitigates somewhat against this ratio(59).

This variety has, however, led to many different processing flowsheets for cobalt (and nickel), in contrast to the processing of other metals. The following section presents some of these flowsheets, mostly for reference (it is not meant to be exhaustive, as such is well beyond the scope of this paper), but also to demonstrate both the variety and complexity of cobalt chemistry in particular. Almost uniquely, cobalt (and nickel) refining flowsheets are carried out in all of sulphate, chloride, mixed sulphate-chloride, ammonia and nitric acid media, by roasting/atmospheric leaching, POX (pressure oxidative leaching), HPAL (high pressure acid leaching) and, more recently, bacterial and heap leaching. The Head of Outokumpu Research, in the company’s monthly newsletter, declared in 1974 that “an interest in cobalt chemistry could drive a person mad!”(109). The following certainly are testament to this … or not.

Operating Plant Flowsheets

The flowsheets here show the diversity of cobalt/nickel and cobalt/copper processing, and are presented largely, but not entirely, in alphabetical order. This is essentially an update of a very general review carried out in 1997(110), and of a more recent one, equally general(111). Emphasis has been placed on cobalt recovery, since it is clearly this metal that is currently the driving factor behind the “Age of Lithium-Ion Batteries.” Smelting flowsheets have not been included, since they generally create an intermediate, which requires further refining by hydrometallurgical methods. It should be mentioned in this context, however, that ferronickel smelting of laterites not only is highly energy intensive(112), but also does not recover the associated cobalt(113). There is no right or wrong way, and each process has its advantages and drawbacks.

Ammonia-Based Circuits

One of the earliest cobalt/nickel refining circuits was that, now known as Corefco, developed by Sherritt (Gordon) at the University of British Columbia and Fort Saskatchewan in the 1950s. Subsequently, there have been similar flowsheets used in other operations, including two in both Australia and Cuba.

Corefco (Sherritt), Fort Saskatchewan

The unique aspect of this process was the manipulation of ammonia chemistry to effect cobalt, nickel and copper separation. All three metals form a range of ammine complexes, which formed the basis of the original soluble cobaltic pentammine process. The process has been modified several times since inception, with the hexamine process the most recent variation(114). Figure 13 shows the process as it was in 1997(115).

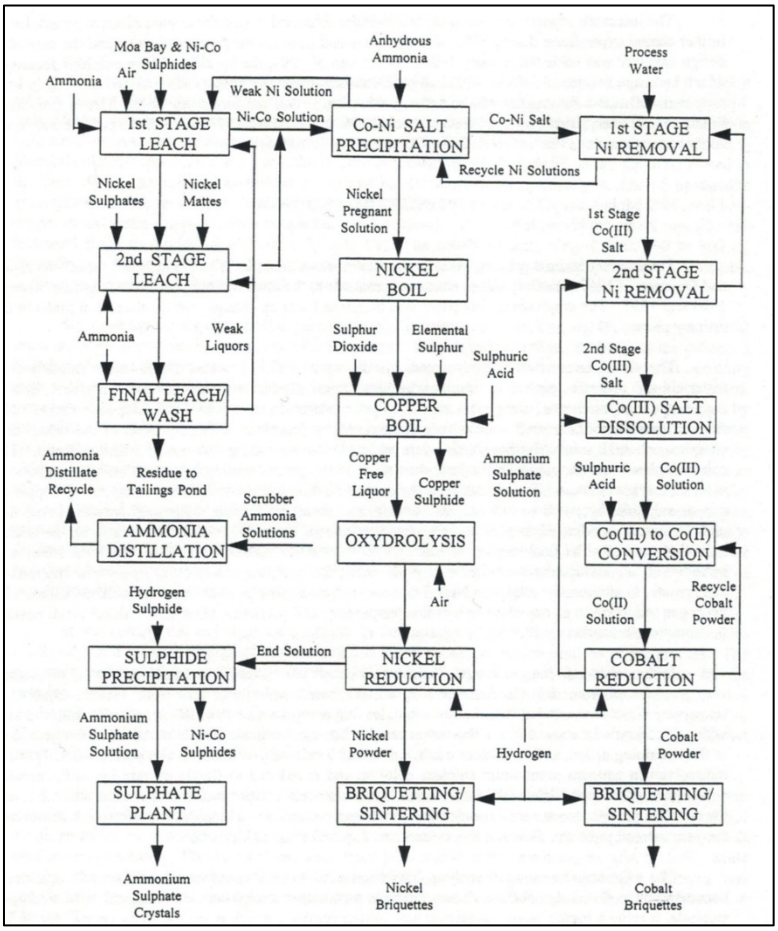


Figure 13. Corefco (Sherritt) Refinery Flowsheet, 1997(115)

Subsequently, modifications were made to the ammonia leaching circuit to accommodate changing amounts of nickel and cobalt in the feed(116), as shown in Figure 14. The refinery is largely fed with mixed sulphides derived from the Moa Joint Venture in Cuba(117,118), the flowsheet for which is covered in the laterite HPAL group of processes, and is shown later in Figure 30.

Nickel West (BHP), Kwinana

The only other purely ammonia-based refining flowsheet known to be currently operating is that of Nickel West (BHP) at Kwinana, which operates a circuit similar to that of Sherritt, as shown in Figure 15(119).

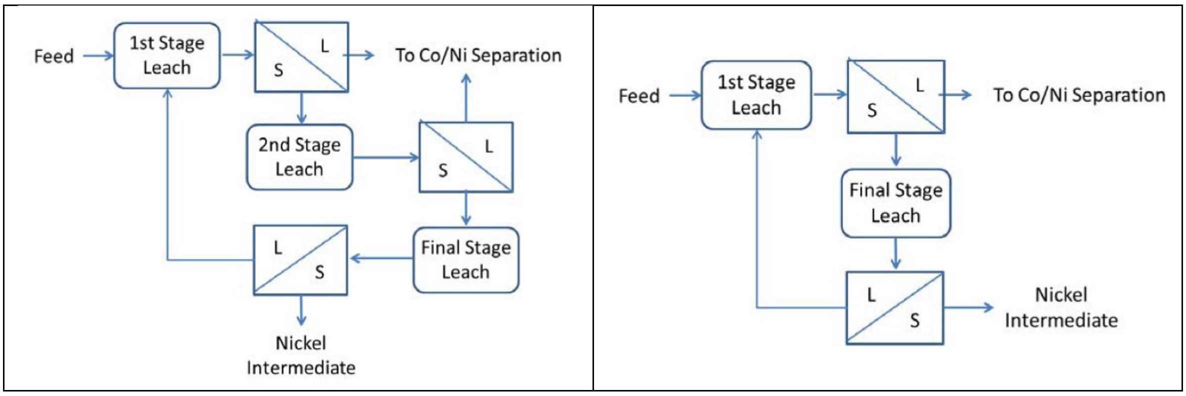


Figure 14. Modifications to Corefco Leaching Circuit, 2009 (left) and 2015 (right)(116)

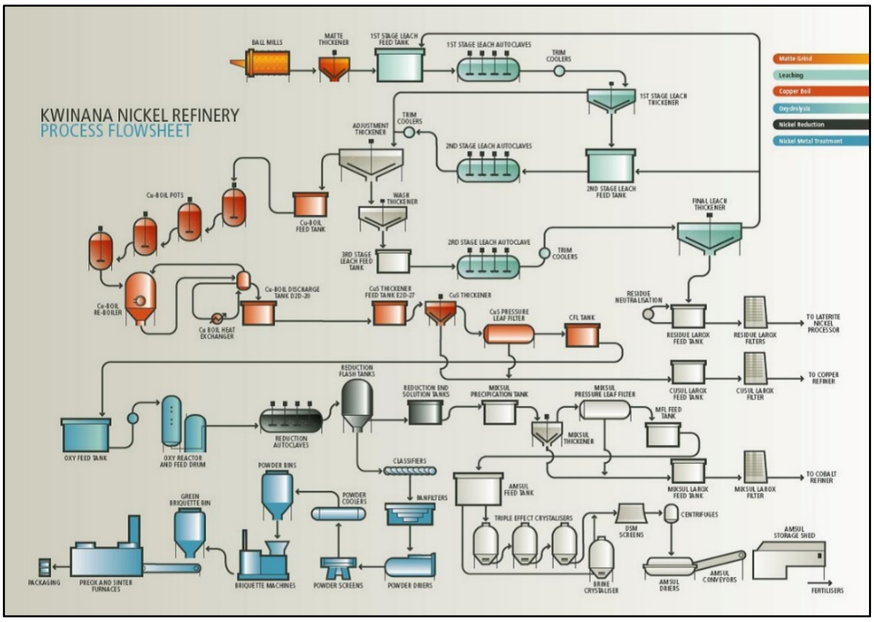


Figure 15. BHP Nickel West, Kwinana Refining Flowsheet(119)

Queensland Nickel

Queensland Nickel (QNI) also operated an ammonia-based refining flowsheet for several years, from 1974 to January, 2016, at Yabulu, near Townsville, the defining feature of which was the ASX (ammoniacal solvent extraction) step for the separation of cobalt and nickel(120,121). Figure 16 shows the flowsheet. The plant is currently (February, 2019) on care and maintenance, although there are concerted efforts being made to re-open it(122).

Cuban Plants

Two ammonia-based plants operated for a while in Cuba, these being Nicaro and Punta Gorda(123). The former was closed in 2012(124), but the latter is currently undergoing debottlenecking with a view to increasing production to around 36,000 tonnes of Ni+Co(125). The flowsheets are not reproduced here, but can be found in an article by Habashi(126). Consideration is also being given to mining the San Felipe deposit, which is reported to have 300 million tonnes of nickel together with associated cobalt(127).

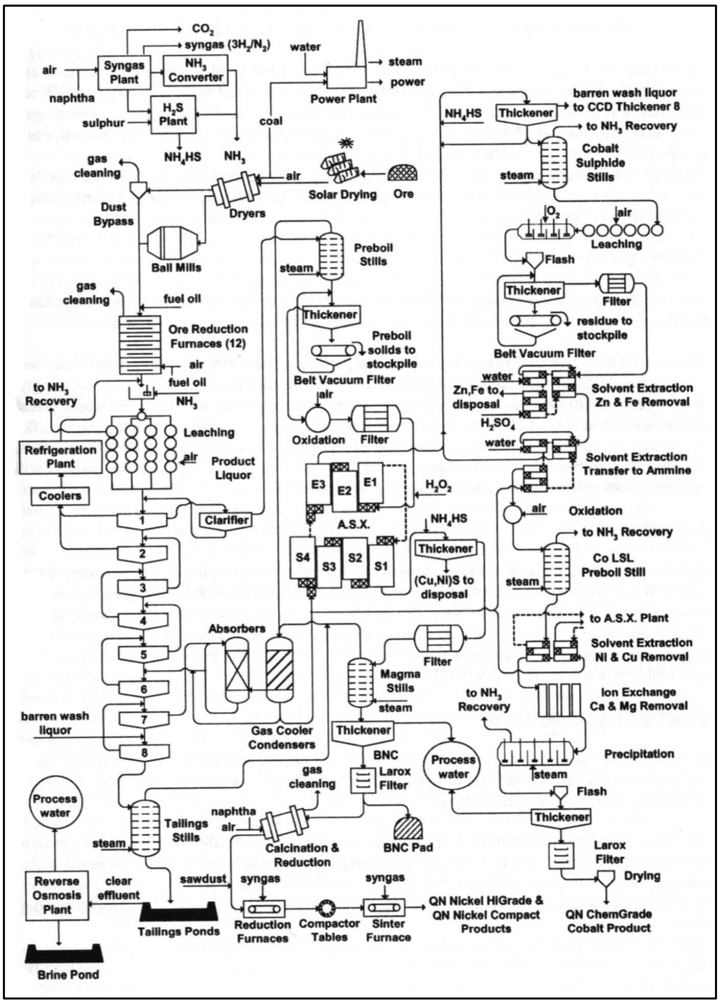


Figure 16. Queensland Nickel (QNI) Yabulu Refining Flowsheet, 2003(121)

Bacterial Leaching Circuits

Bacterial leaching has proved to be effective for refractory gold (the BIOX® Process), but less so for base metals. Billiton, later BHPBilliton, adapted the BIOX® Process for copper (BioCOP®) and later for nickel (BioNIC® – a somewhat unfortunate acronym, intended to be pronounced bio-nick!). An initial copper leaching pilot project in Chile, comprising a Joint Venture between BHPBilliton and Codelco, known as Alliance Copper, resulted in the building of a 20,000 tpa copper plant(128), but, the project was ultimately terminated in October 2006, having not achieved its objectives. Similar processes were mooted for nickel and zinc, but never went anywhere. However, more recently, there have been three projects for nickel. Of these, Mondo Minerals Nickel in Finland attained commercial operation on a waste stream from a talc operation(129,130), whilst Western Areas in Australia has piloted a Bioheap® process, essentially to remove arsenic from a nickel sulphide waste stream(131,132), and Terraframe is reactivating a project in Finland(133). The Western Areas project has reached the Engineering and Procurement stage, and is currently (February 2019) ramping up and debottlenecking. Apart from Terraframe, none of these projects, however, is a primary process for processing nickel arisings, and Western Levels has very little cobalt in its feed.

BioNIC®

BioNIC® (Figure 17) was extensively piloted(134,135), but never caught on as a commercial reality. The pilot plant data show very low cobalt levels in solution, relative to nickel, suggesting that perhaps cobalt was not readily recovered.

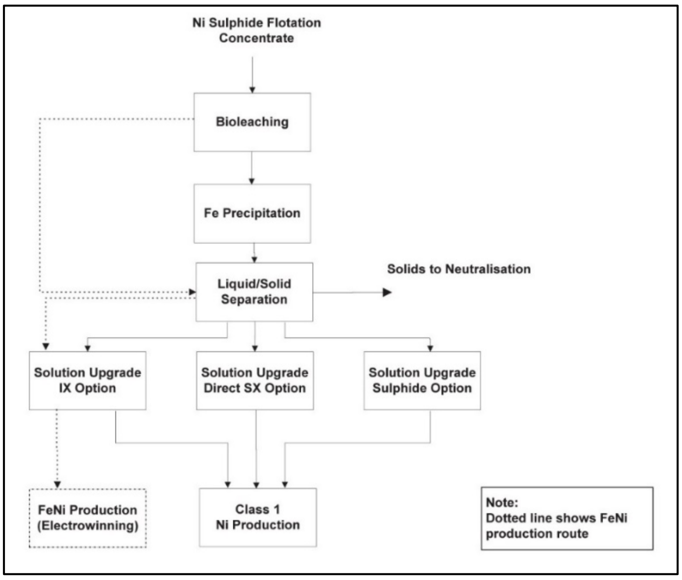


Figure 17. BioNIC® Flowsheet, 1988(135)

Mondo Minerals Nickel, Finland

The Mondo plant treats a by-product stream from a talc operation, and as with Western Areas mentioned above, the bioleaching plant is not large, producing approximately 1000 tonnes of nickel and 40-50 tonnes of cobalt annually(129,130).

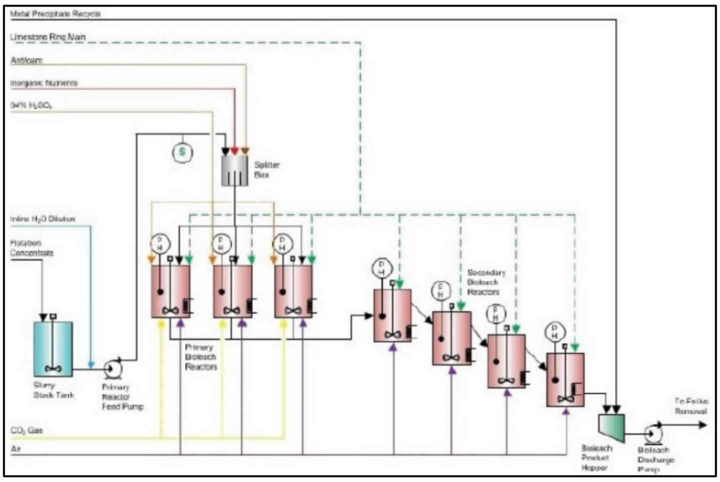


Figure 18. Mondo Nickel Bioleach Circuit(129)

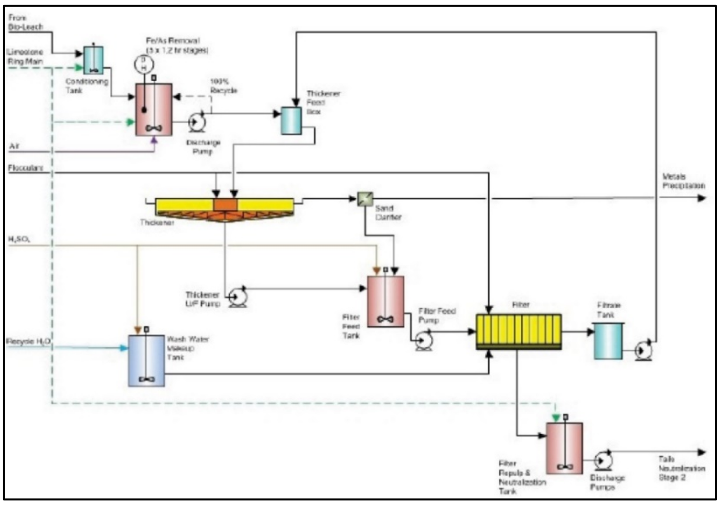


Figure 19. Mondo Nickel Iron-Arsenic Removal Circuit(129)

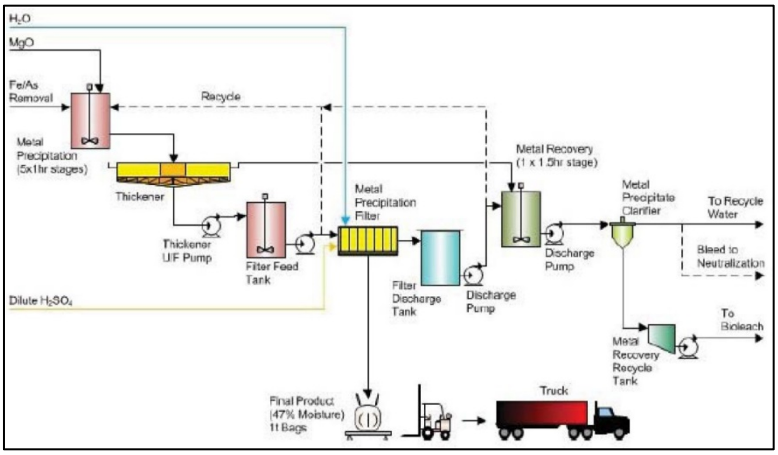


Figure 20. Mondo Nickel Metal Precipitation Circuit(129)

The project was originally estimated to have an IRR of 19-22%, but this was using a nickel price of US$20,000/tonne, which is very much on the high side of current prices. In the last quarter of 2018, Mondo Minerals was acquired by the British speciality chemicals company Elementis plc, from U.S. private equity firm Advent International(136). In view of the decline in the nickel price during the second half of 2018, the new owners took the decision to suspend operations, and the plant is being kept in "care and maintenance mode". The production stop is considered to be temporary. Prior to the cessation of the operation, good progress had been made in ramping up the production, and the throughput in the bioleach plant was just below the design value.

Terraframe, Finland (formerly Talvivaara Project)

This project originally set out to prove, amongst other things, that bioleaching was possible in boreal (i.e. very cold) conditions, such as what is experienced in northern Finland, but its primary objective was to exploit what is the largest nickel deposit in Europe(137). This was originally a pioneering sulphide heap bioleaching operation recovering Ni, Co, Cu and Zn. It suffered major environmental and financial problems, and closed in late 2014, but was restarted by Terrafame in 2015(133). The processing flowsheet to a mixed sulphide product is shown in Figure 21.

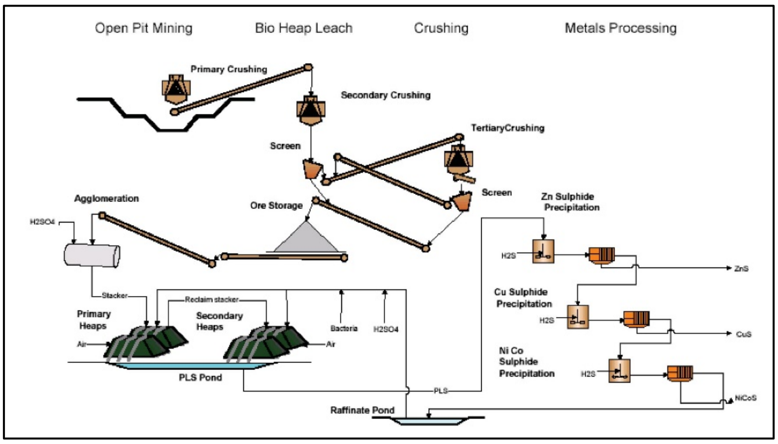


Figure 21. Terraframe (formerly Talvivaara) Heap Leach Process(137)

According to the latest information, the company produced over 27,000 tonnes of nickel in a mixed nickel/cobalt sulphide product in 2017(138). Furthermore, in keeping with the growing trend to produce battery chemicals, Terraframe has committed to invest €240 million in the further processing of the current nickel-cobalt mixed sulphide product into sulphate salts. Terraframe's goal is to start the commercial production of battery chemicals at the beginning of 2021(138). It has to be said that this is, by far, the most successful of the bioleach operations. In addition, Terraframe also recovers over 60,000 tonnes of zinc.

Chloride-Based Circuits

Chloride-based circuits generally give a better quality of cobalt (and nickel) metal as opposed to mixed chloride-sulphate, sulphate alone or hydrogen reduction. The metal produced is also "softer" since it does not suffer from hydrogen embrittlement, and does not have to undergo vacuum degassing, unlike metal generated in sulphate circuits. Chloride circuits were originally adopted since Co/Ni separation was far superior and much easier to what could be achieved in a sulphate medium, prior to the development of the solvent extraction reagent Cyanex® 272. Cobalt forms a strong anionic chloro complex, whereas nickel is almost unique in that it does not form such a complex under normal process conditions. Thus, nickel behaves as a cation, whereas cobalt behaves as an anion, thereby facilitating separation. This is in contrast to the ammonia-based circuits referenced above, wherein both metals form ammine complexes.

Glencore (Falconbridge), Kristiansand, Norway

Operating since 1910, Glencore Nikkelverk is the largest nickel refinery in the western world producing (in 2016) 92,00 tonnes of nickel, 39,000 tonnes of copper, but only 4,700 tonnes of cobalt, in addition to 115,000 tonnes of sulphuric acid. It has traditionally processed matte from Sudbury in Canada and until recently, from BCL in Botswana. The plant is extremely impressive, and additionally has a classical platinum-group metal refinery.

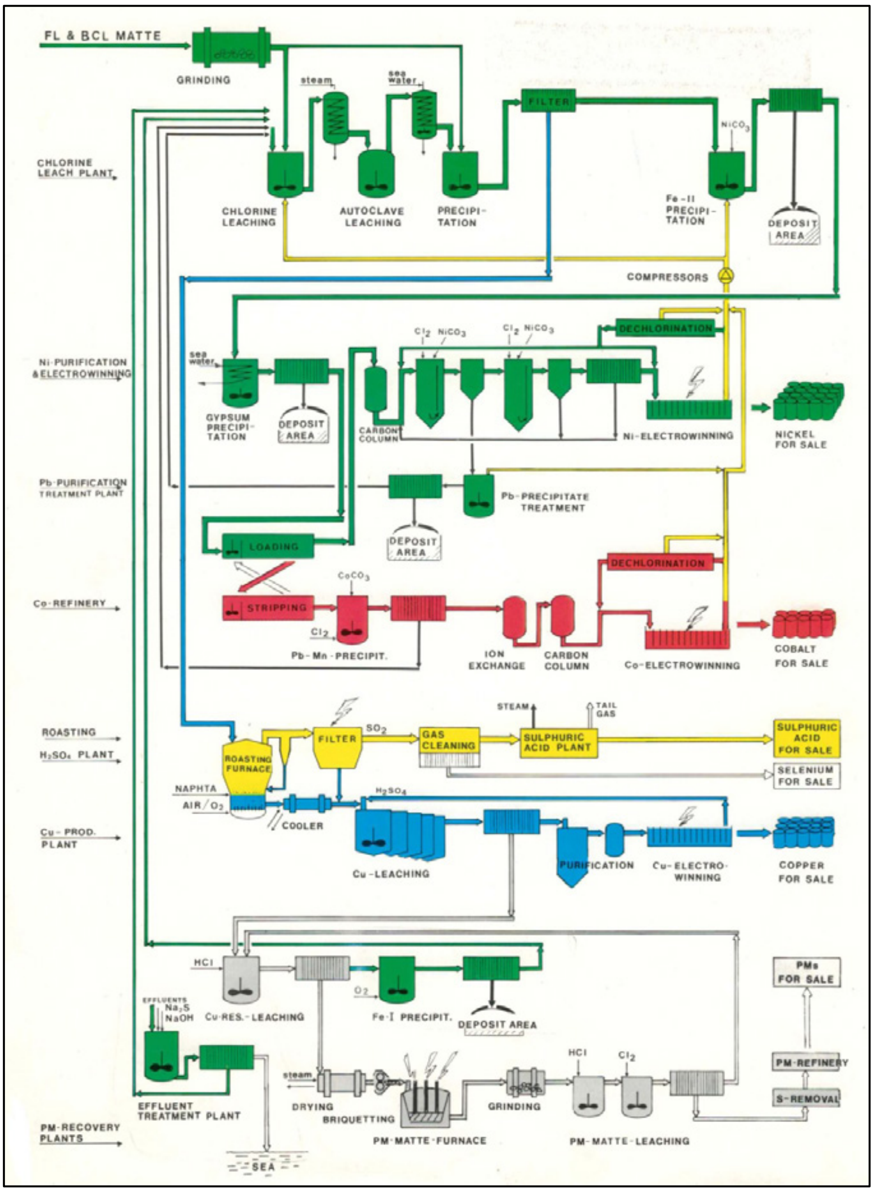


Figure 22. Glencore (Falconbridge) Chlorine Leach Process, Kristiansand[(139)]

Eramet Refinery, Le Havre-Sandouville, France

Eramet has traditionally processed matte from its laterite smelting operation at Doniambo in New Caledonia. Figure 23 shows the Doniambo matte smelting flowsheet, and Figure 24 shows the refinery flowsheet at Sandouville in northern France.

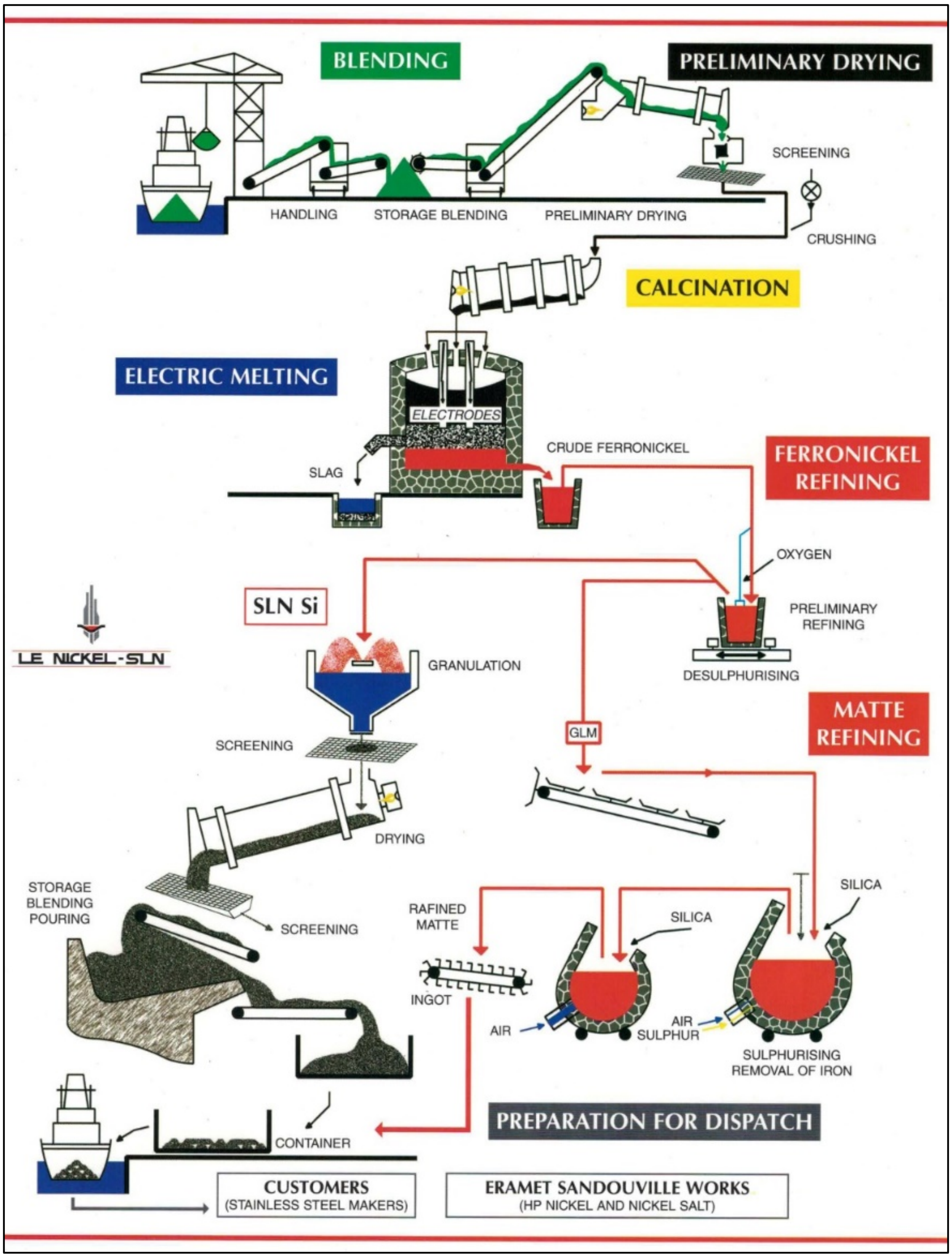


Figure 23. Eramet Doniambo, New Caledonia Flowsheet Making Matte(140)

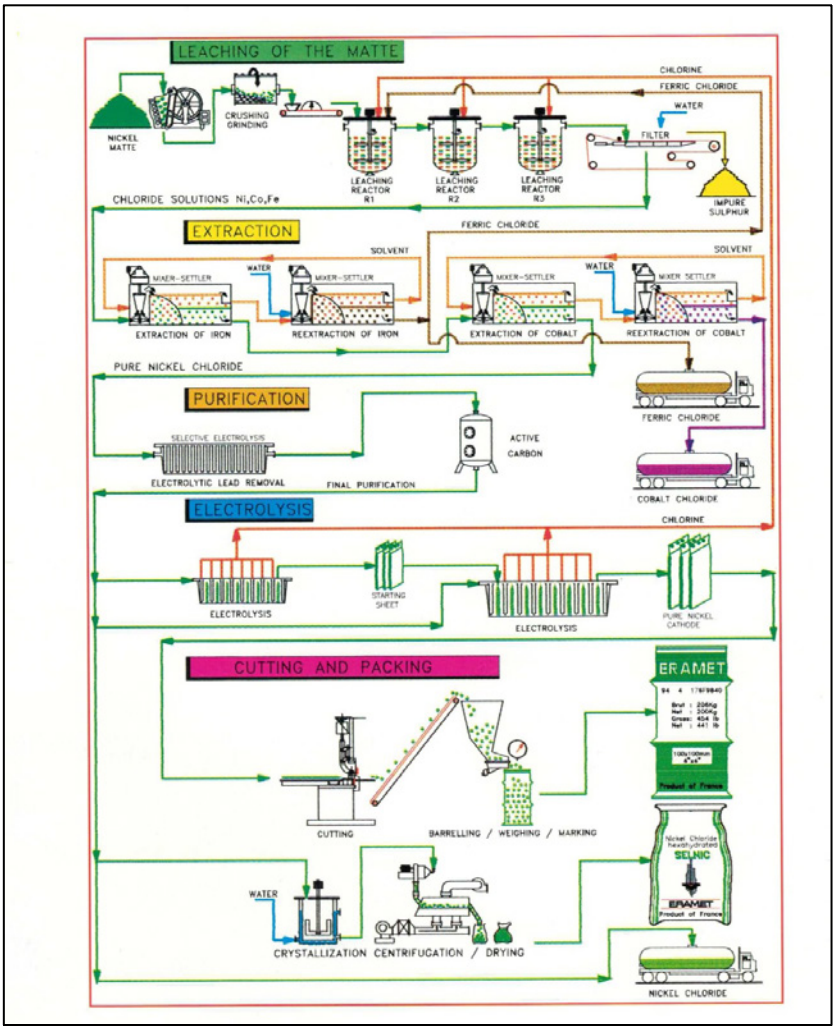


Figure 24. Eramet Le Havre-Sandouville Refinery(140)

Sumitomo

Sumitomo's refinery at Niihama in Japan is also chloride-based(141, 142), although the feed for the refinery generally comes from sulphate-based primary operations.

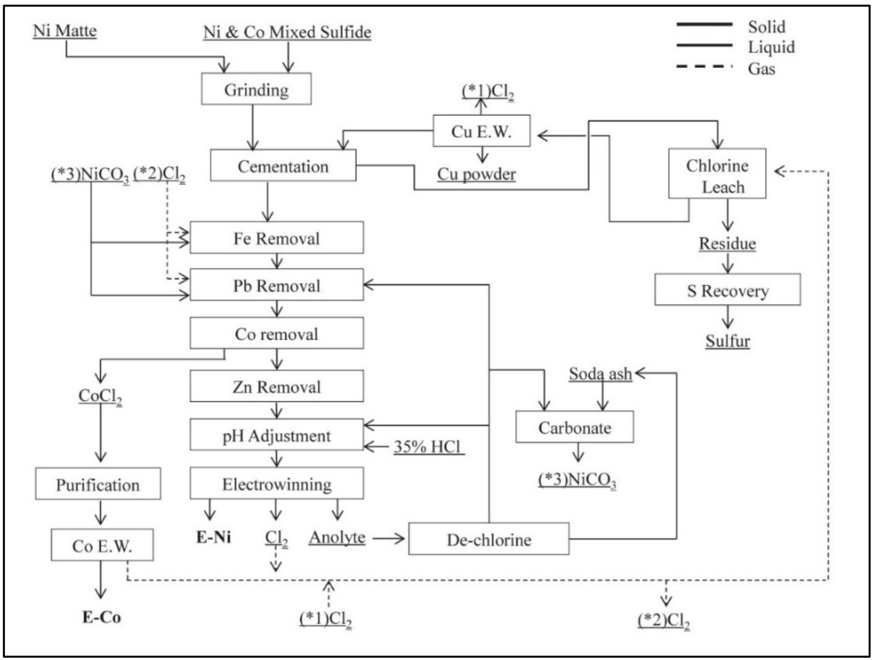


Figure 25. Flowsheet of Sumitomo Niihama Cobalt-Nickel Refinery, 2017(141)

Mixed Chloride-Sulphate

Jinchuan

The Jinchuan refinery(143) in northern China was originally modelled on that of Inco (Vale) in Thompson, Manitoba. The plant was commissioned in 1966, and in 1990 produced 24,000 tonnes of nickel, 180 tonnes of cobalt and 20 tonnes of cobalt oxide(143). Contrast this with 2018, when it produced 150,000 tonnes of nickel, 1.1 million tonnes of copper, 10,000 tonnes of cobalt and 3.5 tonnes of PGMs(144). In the mid-1990s, Jinchuan commissioned an Outokumpu copper flash smelter, subsequently followed by an oxygen top blown nickel smelter and a nickel flash smelter. It owns and operates several mines on the Central African Copperbelt, including the Ruashi, Chibuluma and Kinsenda mines.

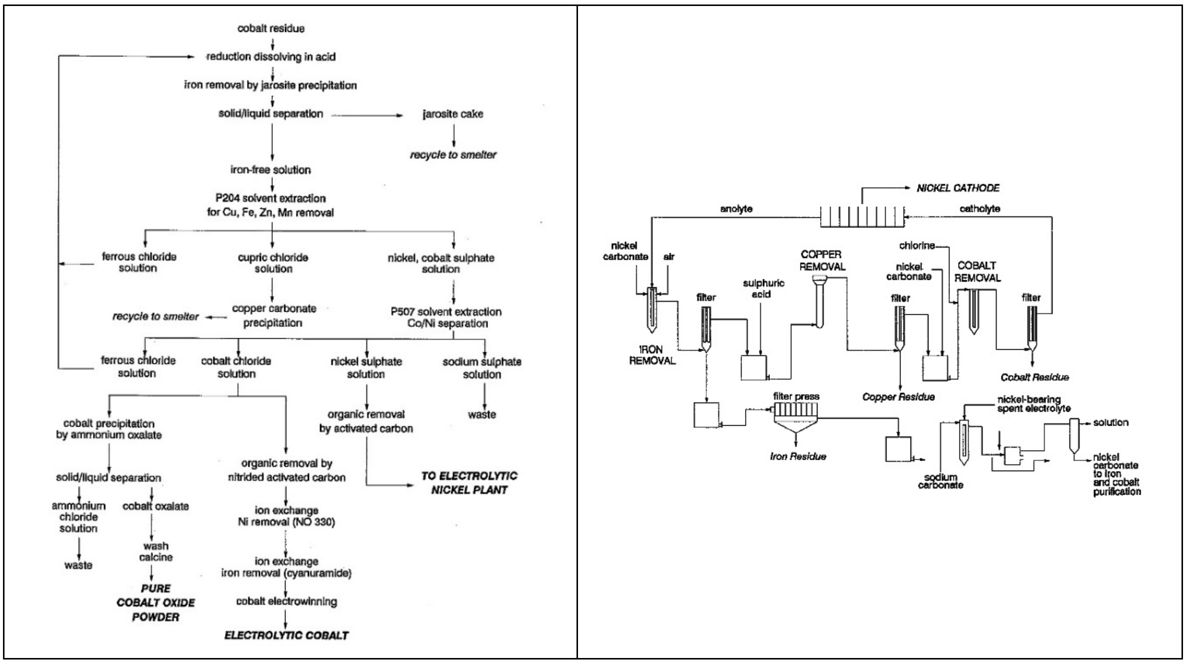


Figure 26. Jinchuan Refinery Flowsheets, 1990(143).

Vale (Inco) Thompson, Manitoba

The Thompson refinery closed in mid-2018 after operating for 57 years(145). The flowsheet was unusual in that matte anodes were electrorefined directly in a mixed chloride-sulphate electrolyte(146).

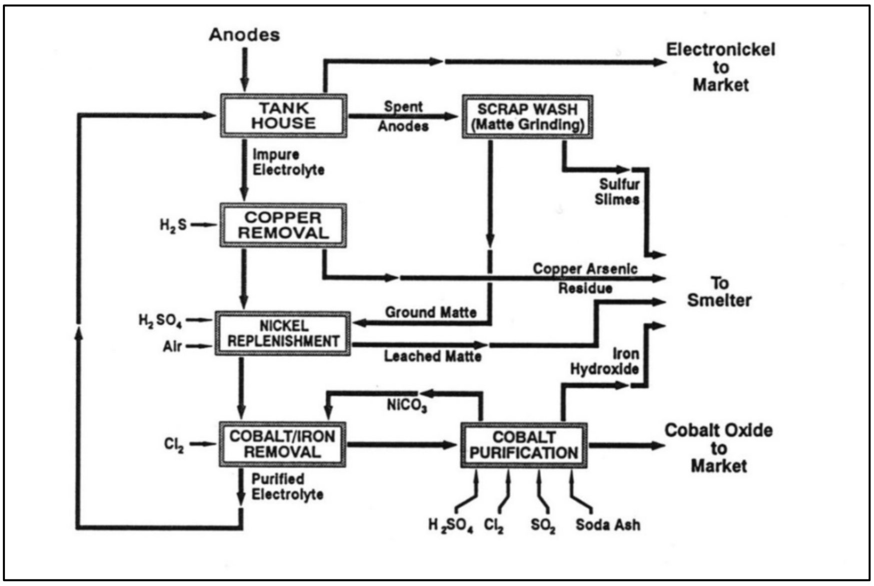


Figure 27. Thompson, Manitoba Refinery Flowsheet(146)

Voisey's Bay Nickel (Vale, Newfoundland)

The Voisey's Bay nickel-cobalt-copper deposit was discovered in 1994, and Vale (Inco) acquired 100% ownership in 1996. A chloride-assisted pressure leach was developed(147), after which a miniplant was operated at its research laboratories. A demonstration plant (Figure 28) was subsequently built and operated from October 2005 to June 2008 in Newfoundland. Figure 29 shows the flowsheet as it was at the conclusion of the demonstration plant in 2008(148).

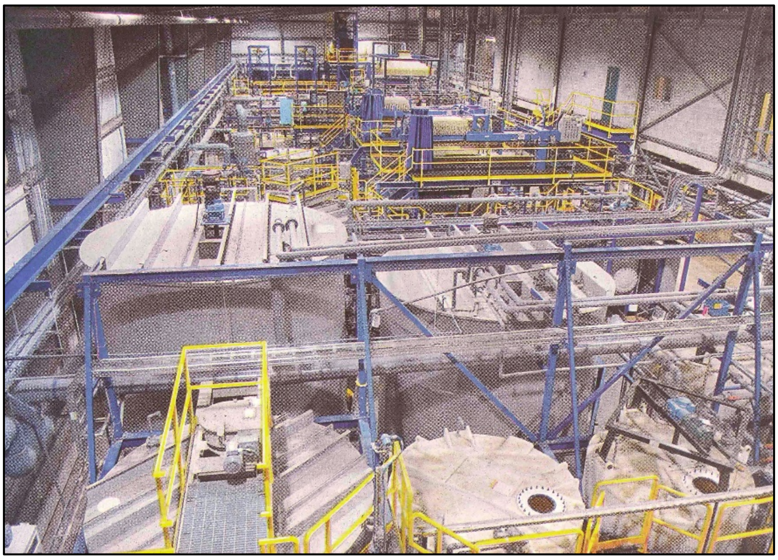


Figure 28. Vale (Inco) Demonstration Plant, Argentia, Newfoundland, 2006(149)

The novel aspects of the process are employing a chloride-assisted pressure leach, wherein most of the iron and sulphide sulphur are converted to hematite and elemental sulphur, respectively. The chlorine is in a closed loop process, being recycled from nickel electrowinning, which is based on the process that was used in the Thompson Refinery in Manitoba.

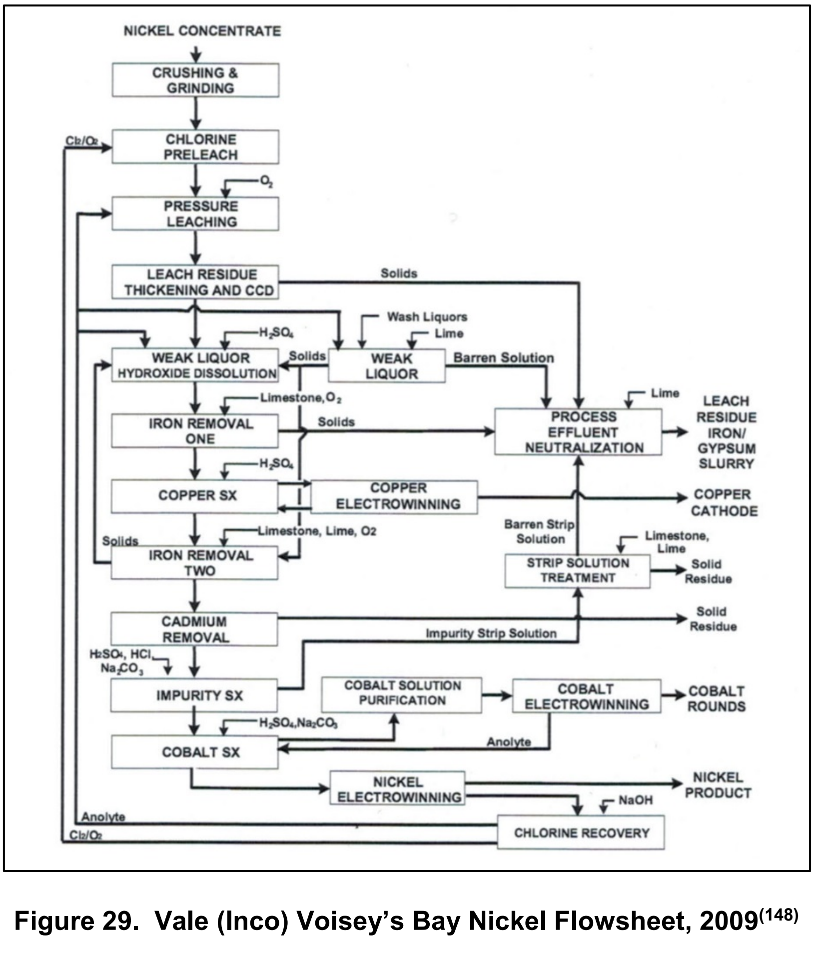


Figure 29. Vale (Inco) Voisey's Bay Nickel Flowsheet, 2009(148)

HPAL Laterite Sulphate-Based Circuits

As with hydrometallurgical processes in general, sulphate-based circuits are the most common, including the HPAL laterite plants, the Central African plants and Vale Port Colborne.

Moa Joint Venture, Cuba

The first of the HPAL plants, at Moa Bay in Cuba, has been in operation since 1960, although significant improvements have been made since Sherritt became part of the Joint Venture(117). Figure 30 shows the Moa Bay flowsheet. Pressure leaching is carried out in pachucas, unlike the horizontal autoclaves that are common in more modern plants.

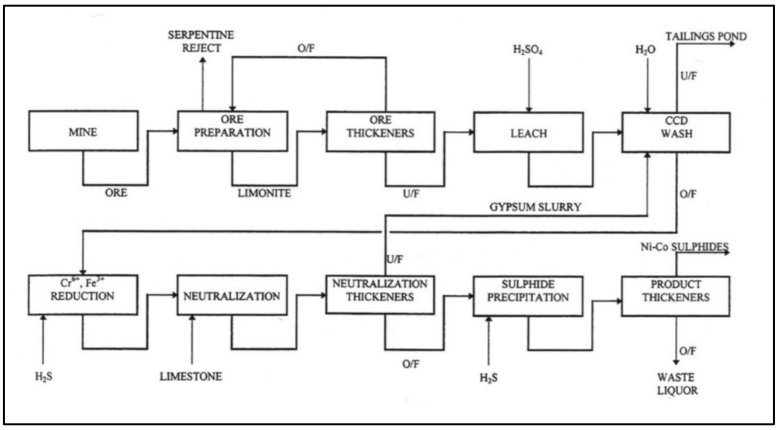


Figure 30. Moa Bay HPAL Leaching Circuit(117)

Ambatovy, Madagascar

The Ambatovy Project in Madagascar was originally a Joint Venture between Sherritt International Corporation (40% owner and mine and plant operator), Sumitomo Corporation (32.5% owner) and KORES (Korea Resources Corporation, 27.5% owner)(150, 151). In 2017, Sherritt reduced their holding to 12%, while remaining the operator(152). The plant was commissioned in 2012, and commercial production (defined as 70% of design capacity) was achieved in January 2014. The production level required to achieve financial completion (90% of design capacity for 90 days) was achieved in March 2015. Figure 31 shows the HPAL flowsheet and Figure 32 that of the refinery(150).

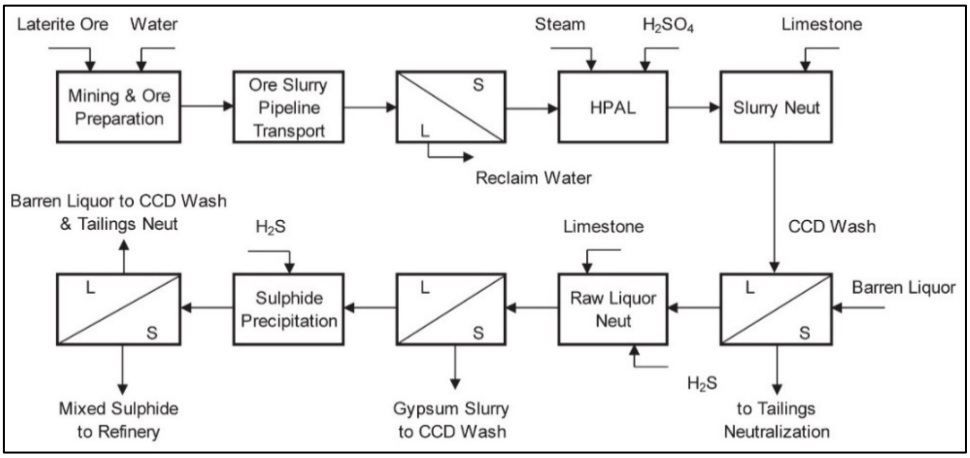


Figure 31. Ambatovy Pressure Leach Flowsheet, 2016(150)

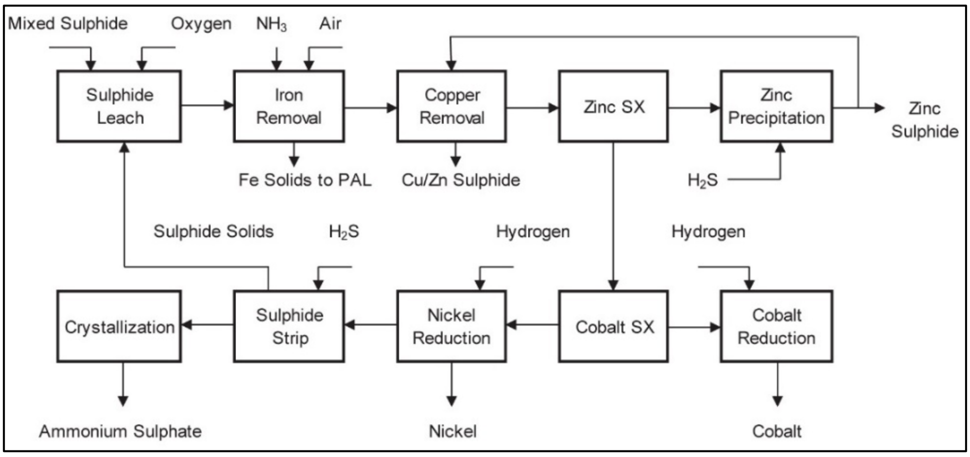


Figure 32. Ambatovy Refining Flowsheet, 2016(150)

Goro, Vale, New Caledonia

The Goro Project in New Caledonia has had, it would be fair to say, quite a chequered history. However, it is now operating, and as noted earlier, Vale has committed an additional US\$500 million to expand the operation, this despite the large operating losses it has incurred(34). Inco (Vale) presented a fairly detailed publication concerning the choice of solvent extraction reagents at ISEC 2002(153), and the history of the development of the process in 2005(154). Figure 33 shows the Goro Process as it was conceived prior to start-up(153,154).

The novel aspects of the Goro Process are the use of Cyanex® 301 for the bulk solvent extraction cobalt-nickel recovery from the HPAL leach solution, without the co-extraction of magnesium, manganese and calcium, and then switching from sulphate to chloride in the stripping circuit(155). Cyanex® 301 is a sulphur-based extractant which is prone to premature oxidation, so precautions have had to be implemented to prevent this, notably the use of Bateman pulsed columns. The other novel aspect of the Goro Process is the use of pyrohydrolysis to process the nickel chloride solution into nickel oxide, this being only the second application of this technology, it having been formerly practiced for several years at Kristiansand.

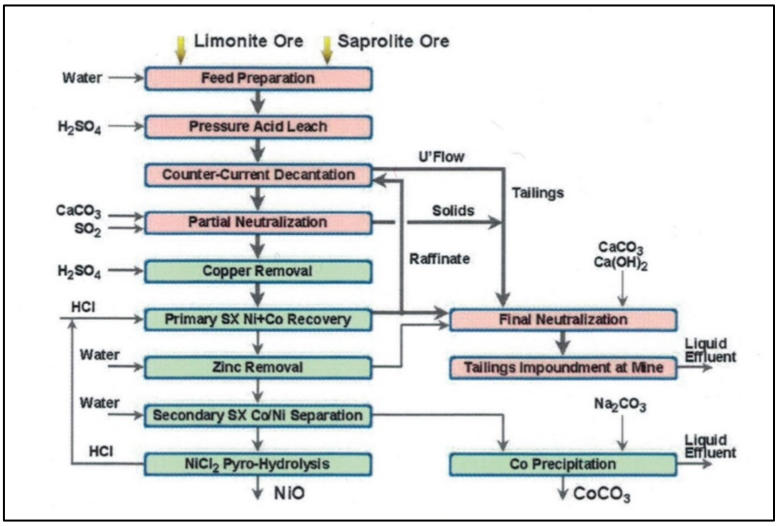


Figure 33. Vale (Inco) Goro Process, New Caledonia, 2002(153)

Ramu, Papua New Guinea

The Ramu Project in Papua New Guinea was a joint venture between Highlands Pacific (8.56%), the PNG Government and Landowners (6.44%), and MCC Ramu Nico Ltd (85%). MCC (Metallurgical Corporation of China) holds a 61% interest in MCC Ramu Nico Ltd, with the remaining 39% held by a number of other Chinese entities. In early 2019, Cobalt 27 entered into an arrangement to acquire Highlands Pacific, and with it, the company's interest in Ramu(156). Construction of the plant was largely completed by 2012, after which progressive commissioning achieved 72% of nameplate capacity by the end of 2014(157). The capital cost was US\$2.1 billion, which is very much on the low side for HPAL laterite projects, with an expected annual production of 31,150 tonnes of nickel and

3300 tonnes of cobalt over a mine life of more than 20 years. Production in 2018 was 35,355 tonnes of nickel and 3275 tonnes of cobalt(158).

Figure 34 shows a simplified version of the Ramu flowsheet(157). It is a conventional HPAL plant, making a MHP product for final refining in China. The project is notable for the 135 km-long slurry pipeline from the mountainous mine site down to the HPAL plant on the coast(157).

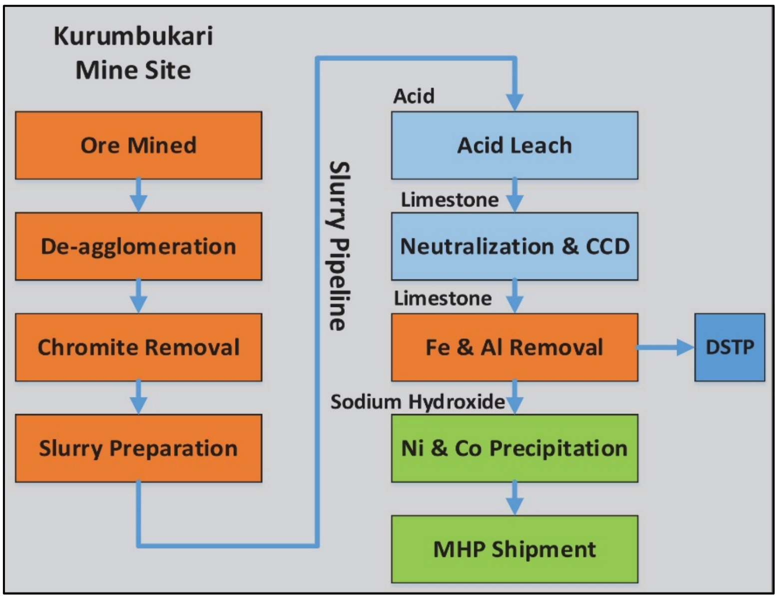


Figure 34. Simplified Ramu Flowsheet, 2015(157)

Ravensthorpe EPAL® Process

Ravensthorpe (RNO) was originally developed by BHP primarily to act as a feed for the QNI Yabulu refinery. It was officially opened in 2008, and shut down in January 2009(159). First Quantum (FQM) acquired the plant in December 2009 for approximately 10 cents on the dollar, and as of 2017, the plant has been on care and maintenance. The novelty of RNO was the so-called EPAL® Process, wherein the (limonitic) HPAL pressure leach slurry was neutralised with saprolite in order to enhance nickel recovery and reduce overall acid consumption. Figure 35 shows the flowsheet of this process(160).

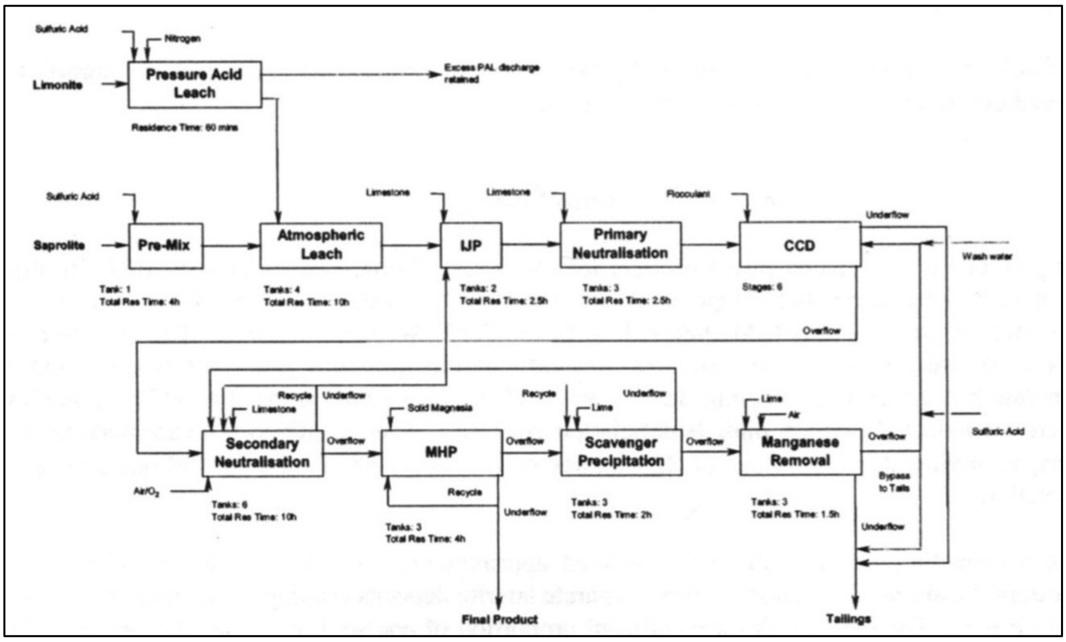


Figure 35. Ravensthorpe EPAL Flowsheet, 2004 (160)

Sumitomo – Coral Bay and Taganito

The Coral Bay Nickel Project (CBNC) in the Philippines commenced in 2002, and, according to Sumitomo, was the first HPAL plant to achieve name plate-capacity(161). Sumitomo therefore proved the operational reliability of HPAL with the CBNC project, and then first doubled the capacity, before embarking upon a second plant, Taganito, located on Mindanao Island, Philippines. Figure 36 shows the Coral Bay flowsheet, and Figure 37 that of Taganito(161).

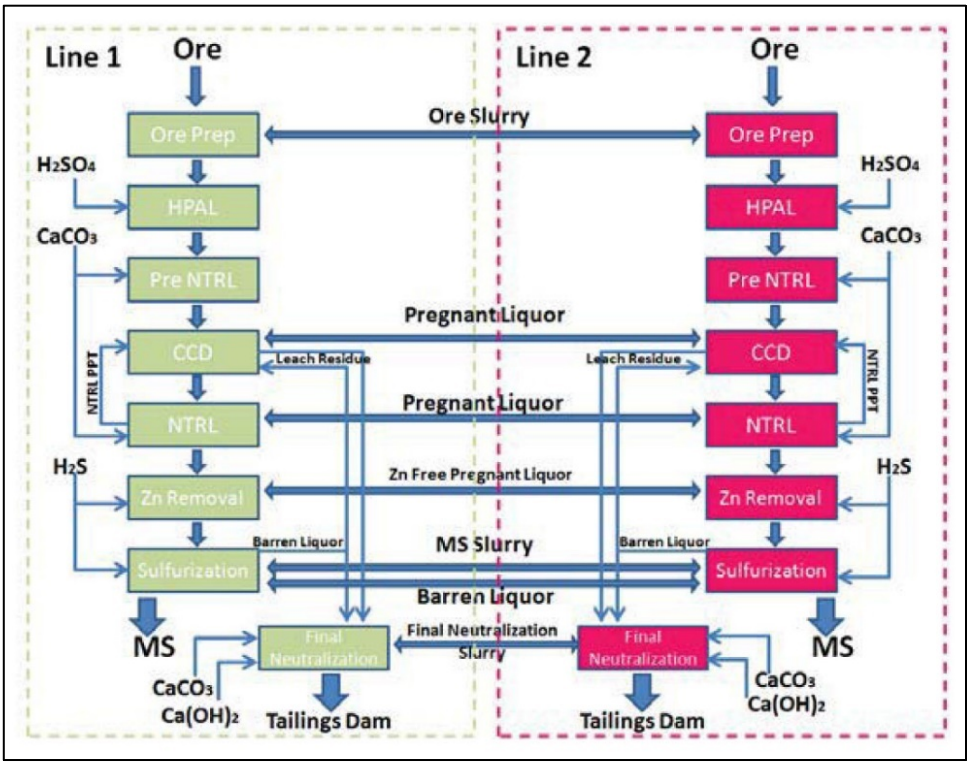


Figure 36. Sumitomo Coral Bay Flowsheet, 2015(161)

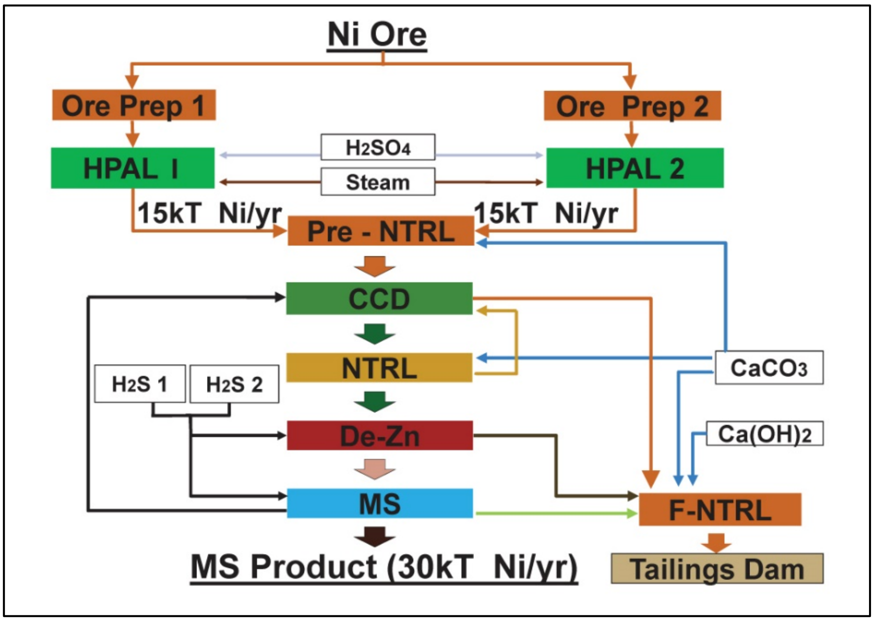


Figure 37. Sumitomo Taganito Flowsheet, 2015(161)

The Taganito (THPAL) plant is designed to produce 30,000 tonnes of nickel and 2,600 tonnes of cobalt as a mixed sulphide, which is shipped to the Niihama refinery(142). Construction commenced in 2010 and the plant was completed in June 2013, achieving name-plate capacity in May 2014.

Meta Gördes, Turkey

The Gördes Plant of Meta in Turkey is a so-called third-generation HPAL process, with construction and commissioning having been competed in 2014(162). The process is a relatively simple one for an HPAL plant, and the flowsheet is shown in Figure 38.

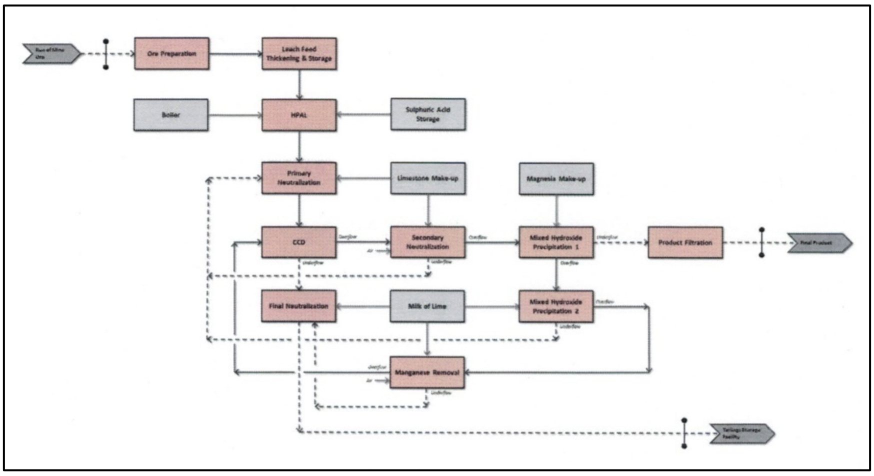
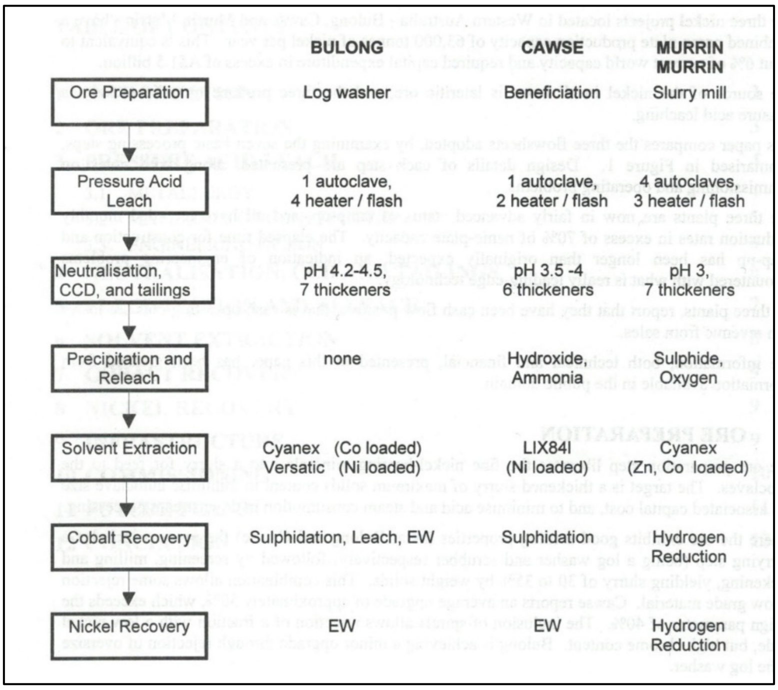


Figure 38. Meta Gördes Flowsheet, 2016(162)

The plant has suffered from several problems such that it was only in the middle of 2016 that it was able to run for extended periods of time. Ramp-up projects were continuing into 2017(162).

Western Australia Pioneering Laterites, Bulong, Cawse and Murrin Murrin, and Others

Kyle has presented generic flowsheets for the main laterite treatment processes, including smelting (ferronickel or matte), the Caron Process (reduction calcining, ammonia leaching), HPAL and EPAL® (HPAL plus neutralisation with saprolite as noted above)(163). HPAL is relevant to the three pioneering WA laterite flowsheets, which came on-stream in the mid-1990s, and have been summarised in one diagram(164). Of the three, only Murrin Murrin is still operating, and this only after a substantial write-off of the capital investment.



	BULONG	CAWSE	MURRIN MURRIN
Ore Preparation	Log washer	Beneficiation	Slurry mill
Pressure Acid Leach	1 autoclave, 4 heater / flash	1 autoclave, 2 heater / flash	4 autoclaves, 3 heater / flash
Neutralisation, CCD, and tailings	pH 4.2-4.5, 7 thickeners	pH 3.5 -4 6 thickeners	pH 3, 7 thickeners
Precipitation and Releach	none	Hydroxide, Ammonia	Sulphide, Oxygen
Solvent Extraction	Cyanex (Co loaded) Versatic (Ni loaded)	LIX84I (Ni loaded)	Cyanex (Zn, Co loaded)
Cobalt Recovery	Sulphidation, Leach, EW	Sulphidation	Hydrogen Reduction
Nickel Recovery	EW	EW	Hydrogen Reduction

Figure 39. Summary Comparison of the Three WA Laterite Processes, 2001(164)

There have been many attempted laterite processes, some successful, some not. Table 5 summarises the reported limonitic feed compositions for a number of these, together with their current status. Not a lot can be concluded from these data, there being quite a spread in the analyses of the various elements.

An interesting observation, perhaps, is that one of the more successful plants, Ramu, has one of the lowest feed nickel values, whereas one that has experienced a lot of problems, Goro, has one of the highest, as well as having high cobalt, relatively speaking. The Ramu flowsheet is quite simple and straightforward, with an intermediate product being generated for final refining at an existing refinery. Goro, on the other hand, is a very complex flowsheet, with finished products being made on site. Perhaps it can be concluded, therefore, that it is much better to keep the flowsheet as simple as possible, and to make an intermediate product suitable for final refining at an existing refinery.

One other aspect here is costs, which to the layman are something of a mystery. Again, taking Ramu as an example, the reported capital outlay was US$2.1 billion, for a production of 35,000 tonnes of nickel and 3,500 tonnes of cobalt annually(157,158). A modelling exercise carried out by Dry(209) suggested a generic variable cost of US$2.30/lb Ni for the HPAL process making an intermediate mixed hydroxide product. At current metal prices (US$5.80 for Ni and US$13/lb for Co), then at the production rate noted above, the net revenues by a very simplistic calculation are US$550 million less US$180 million for the variable cost, i.e. US$370 million. This is nearly six years for payback at best. The situation is actually worse than this, since the preceding simplistic calculation does not include fixed costs nor further refining costs. The question, therefore, is how have such projects been justifiable, especially if the capital costs soar to the levels incurred by Ambatovy, Goro and even Ravensthorpe, and more importantly, especially in the context of this paper, how will future projects, if they are to be based on HPAL, be justified?

As noted earlier, none of these plants is large, being at most 60,000 tonnes of nickel, and usually appreciably less. When compared to say, aluminium plants (up to 400,000 tonnes) or zinc or copper plants (up to 250,000 tonnes), there is no economy of scale, and the capital investment is considerable. If cobalt production is to be enhanced, up to a minimum of 100,000 tonnes, then it will require several of such plants to be built, which with the kind of investment required, might prove problematic.

As noted later in this section, there have been chloride-based processes developed for treating laterites. Given that the major refineries (i.e. those of Glencore, Eramet and Sumitomo) are chloride-based, and have been operating successfully for many years, it surely makes sense to extend this to primary processing. Materials of construction are clearly not an issue, and knowledge of chloride-based chemistry is inherent. Both capital and operating costs are potentially substantially reduced, and the advent of a viable hydrochloric acid recycling process suggests that if the vast laterite deposits, including both limonite and saprolite profiles, are to be exploited in order to meet the demands of the “Age of Lithium-Ion Batteries,” chloride-based processes need to be seriously considered.

Other Sulphate-Based Processes

Finland – Harjavalta and Kokkola

These refineries were established by Outokumpu Öy, transferred to OMG (Outokumpu Metals Group) and subsequently sold to Norilsk and Freeport McMoran(165), respectively. Harjavalta is currently fed by material from Russia(166), and Kokkola, at one time the world’s biggest cobalt refinery, is fed by material from Tenke Fungurume in the DRC(167). Flowsheets of the operations are not included here, but a very detailed description of the plants was given by Outokumpu in 1980(168). Harjavalta was notable for its use of electrolytically-generated nickelic hydroxide which was then used to precipitate cobaltic hydroxide from the main nickel stream. This process was not very efficient, and was abandoned once Cyanex® 272 became available.

Table 5. Reported Chemical Analyses of Various Limonitic Laterites, % Metal

Location	Ni	Co	Fe	Mg	Al	Mn	Reference	Development
Ambatovy 2005	1.29	0.114	46.2	1.03	3.11	0.83	(169)	Operating
Bulong 1999	1.11	0.08	20.8	4.62	2.75	0.36	(170)	Mothballed
Çaldağ 2006	1.13	0.07	21.7	1.93	1.01	0.32	(188)	Pilot, abandoned
Cawse 1999	1.00	0.07	18.0	1.58	1.71	0.17	(170)	Mothballed
Coral Bay 2006	1.26	0.09	42.3	2.21	1.83	0.70	(171)	Operating
Dominican 2011	1.72	0.03	15.6	9.37	0.72		(172)	Miniplant, abandoned
Gladstone 2005	0.79	0.05					(173)	Pilot, DFS, abandoned
Goro 2005	1.53	0.12					(154)	Operating
Guatemala (Fenix) 2007	1.28	0.19	48.3	1.0	2.73	1.13	(174)	Pilot, abandoned
Guatemala (Sechol) 2003	1.39	0.08		7.58			(175)	Pilot, abandoned (NPI)
Horizonte 2012	1.42	0.11	23.3	5.89	4.15		Unpublished	Miniplant, abandoned
Indonesia (Inco) 1997	1.2	0.15	48.0	0.57	2.0	1.10	(176)	Study
Ivory Coast 2011	1.42	0.042	24.6	2.53	1.98		(172)	Miniplant, abandoned
Ivory Coast 2011	1.20	0.037	18.2	3.50	1.98		(172)	Miniplant, abandoned
Jervois Young 2001	0.64-1.01	0.068-0.083	16.2-26.0	3.55-6.69	3.28-5.71		(177)	Miniplant, abandoned
Jervois Young 2011	0.63	0.082	17.9	10.2	4.22	0.3	(172)	Miniplant, abandoned
Moa Bay 1997	1.29-1.49	0.109-0.132					(117)	Operating
Mount Thirsty	0.56	0.12				0.88	(178)	PFS
Murrin Murrin 1999	1.24	0.09	22.0	4.0	2.50	0.40	(170)	Operating
Ramu 1995, 2018	0.96	0.11	37.0	1.43	3.58	0.72	(179)	Operating
Ravensthorpe 1999*	0.79-1.21	0.032-0.072	6.0-16.7	0.5-9.4	0.1-1.3		(180)	Mothballed
Sunrise ** (formerly Syerston) 2016	0.65	0.10					(70)	DFS
Syerston 1996	0.81	0.18	42.5	0.48	0.96	0.99	(181)	Pilot, abandoned
Taganito 2015	1.00			1.10			(161)	Operating
Vermelho 2005 (now Horizonte)***	0.77	0.04	21.0	5.79			(182)	Pilot, abandoned
Weda Bay 2012	1.62-1.67	0.079-0.086	22.0-23.5	10.2-11.0	1.41-1.59	0.48-0.52	(183)	Pilot, abandoned (NPI)

Note: * Ni can be upgraded physically – 33.7% mass pull gives 221% upgrade, 74.4% Ni recovery
** Regarded now more as a scandium project, 454 ppm Sc
*** Vermelho was abandoned when Vale acquired Inco. Horizonte Minerals acquired Vermelho in 2017

Chambishi, Zambia

The original Chambishi plant was commissioned in the late 1970s(62). In the 1990s, AngloVaal Mining (Avmin) acquired the plant and access to the Nkana (Kitwe) slag dump, and determined to expand the Chambishi operation by incorporating the process originally developed for the Nkana Cobalt Plant during the 1970s(57). Figure 40 shows the original circuit and the implementation of the new circuit, named Cosac (Cobalt from Slag And Copper).

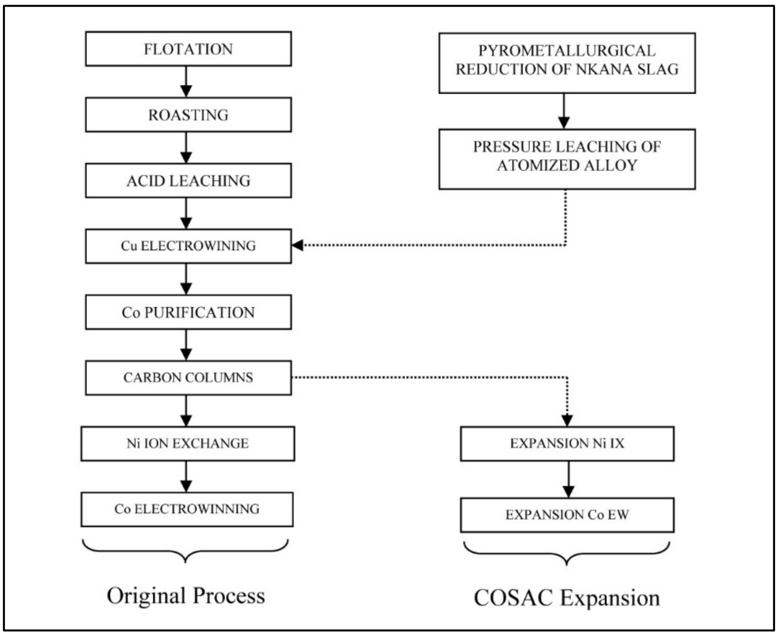


Figure 40. Chambishi Flowsheet, Original and After Expansion(58,65)

Eramet – Weda Bay

Eramet is the largest shareholder in the Weda Bay project, comprising a somewhat complicated joint venture structure(183). Figure 41 shows the process developed, which is an atmospheric sulphuric acid process operated at 100ºC for 18 hours, with the addition of SO_2 to ensure maximum cobalt dissolution (along with manganese). Nickel recovery is reported to be 94-96%, with cobalt at 91-93%(183). Iron is removed as sodium jarosite. Cobalt is separated from nickel via solvent extraction with Cyanex® 272, and precipitated as a sulphide for further processing. Nickel is recovered as a basic carbonate.

In February 2017, Eramet entered into an agreement with the Chinese steel producer group Tsingshan, which would entail producing a nickel ferroalloy from Weda Bay ore in Indonesia based on a pyrometallurgical process, for a nameplate capacity of 30,000 tons of nickel per year(184). The steel ferronickel smelter will not recover the cobalt. A more recent announcement, however, suggests that a plant is to be integrated with a lithium-ion electric vehicle battery manufacturing facility(185), and it is also reported that Tsingshan is going to build a HPAL plant as well, "faster and cheaper than anybody else has done"(186). That being the case, it is considered that this could not only have a distinctly negative effect on the long term price of nickel, but if Tsingshan is able to do that, then this would surely lead to further Chinese strengthening in the overall cobalt market, since most of the DRC cobalt is already under Chinese control.

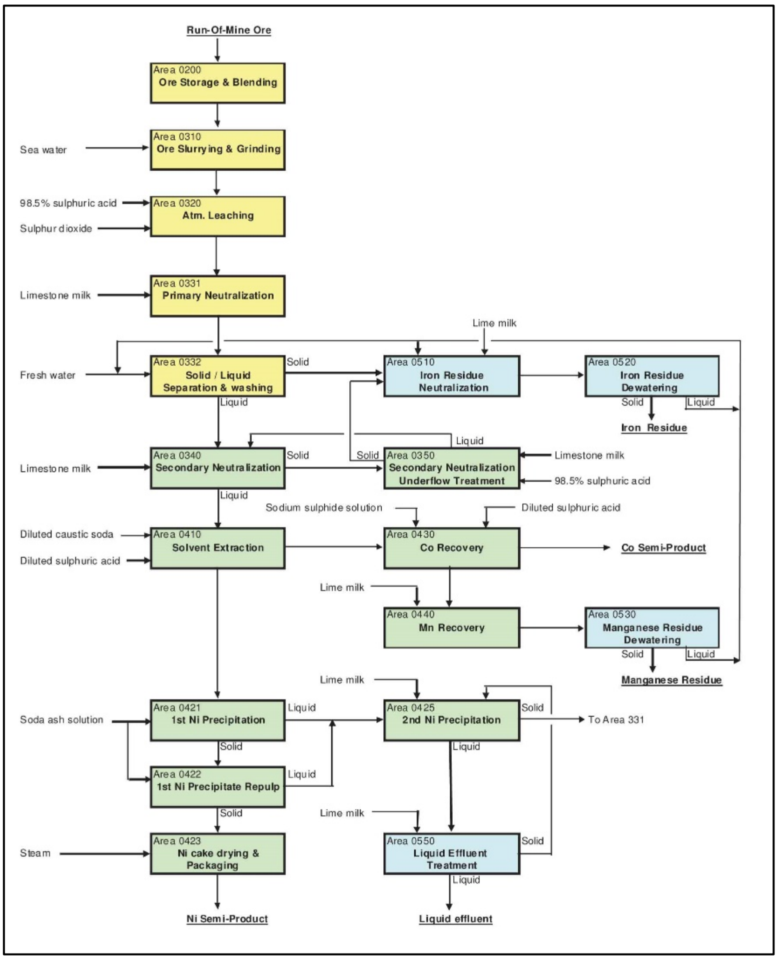


Figure 41. Eramet Weda Bay Atmospheric Leach Process(183)

Vale (Inco) Port Colborne

Electrorefining of Co from metal anodes began at Port Colborne in 1954. Cobalt was recovered from Ni electrolyte, partially purified, and cast into anodes and Co cathodes were deposited on stainless steel mandrels. A separate and new Co electrowinning facility was built in 1983 and is still in operation today, processing a mixed Ni-Co carbonate by leaching, separating Ni from Co, and electrowinning Co using insoluble anodes(187). Figure 42 shows the flowsheet used to carry out the bulk separation of cobalt from nickel (initial ratio Co:Ni 1:110)(187).

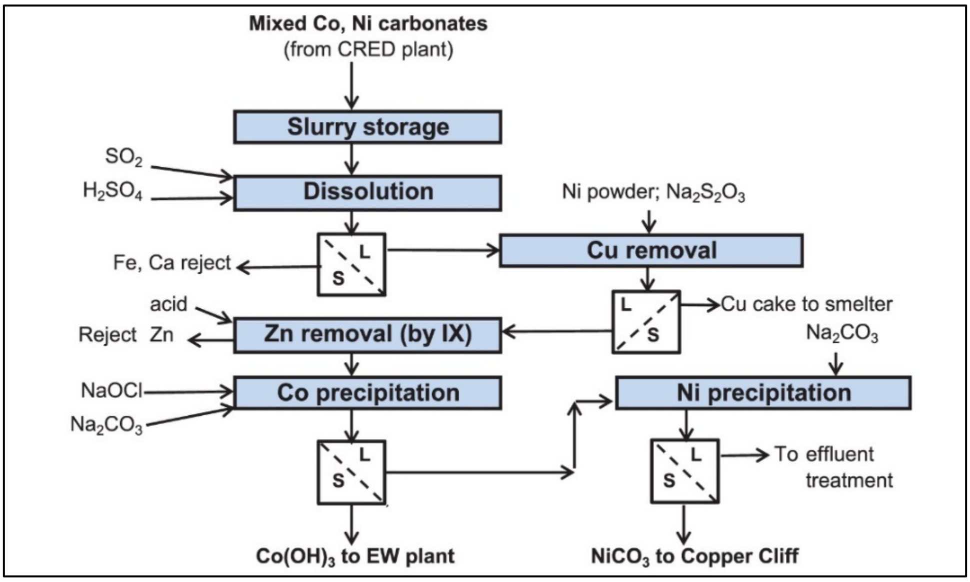


Figure 42. Vale (Inco) Port Colborne Co/Ni Separation Flowsheet(187)

Figure 43 shows the flowsheet of the final electrowinning recovery of cobalt "rounds"(187).

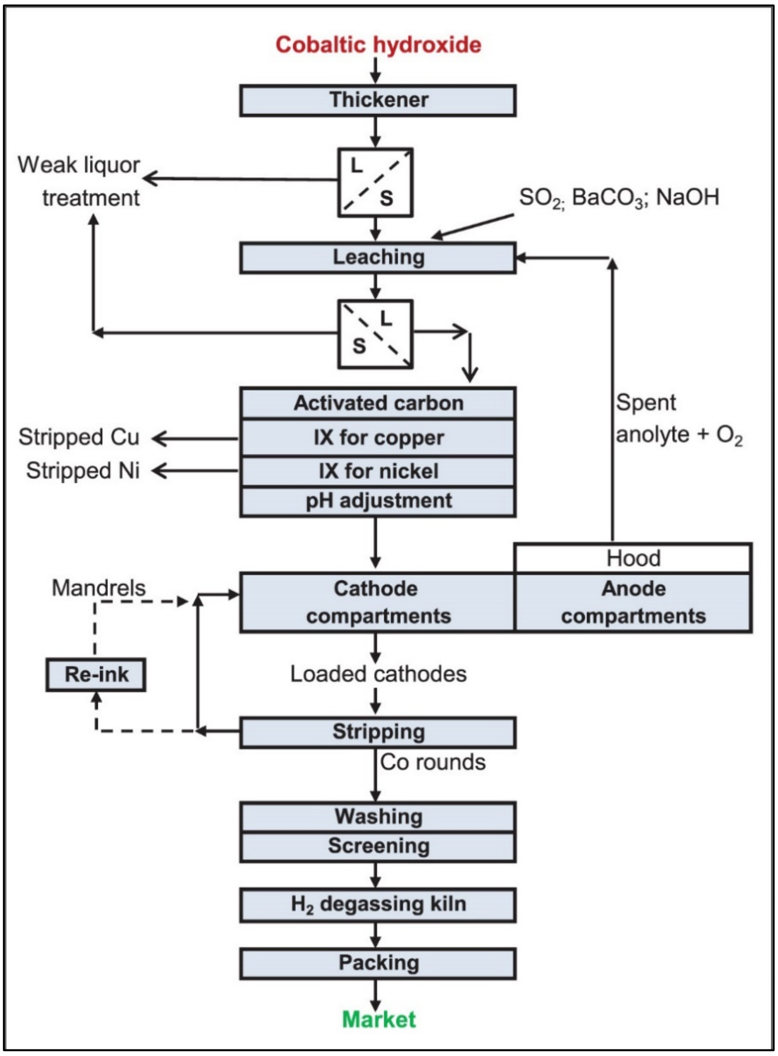


Figure 43. Vale (Inco) Port Colborne Cobalt Refinery(187)

Níquel Tocantins, São Paulo, Brazil

The Níquel Tocantins plant is part of the private, family-owned Votorantim Group, and as such, there are almost no publications about the group's operations. The company operates a conventional reduction roast and ammonia leach Caron Plant at Níquelandia in northern Brazil. The mixed basic nickel/cobalt carbonate generated at the mine site is transported over 1000 km to São Paulo because there is insufficient infrastructure and little electric power at Níquelandia. The following description of the refinery is based on a personal visit in 2001, since no published flowsheet can be located.

Basic Nickel Carbonate (BNC) from the mine site is dissolved with sulphuric acid in a series of reactors. The first leach reactor is operated at 70-80ºC (maintained by the exothermic heat of reaction), and a terminal pH of around 2. In the second tank, the pH is raised to 5.0-5.5 by the further addition of BNC. The filtrate proceeds to solvent extraction with Cyanex® 272 (C272). It is worth noting that this is the plant where Cyanamid (as Solvay then was) first discovered the requirement to add an antioxidant to C272 reagent mixture to prevent its oxidation by cobalt. The SX plant consists of 6 stages of extraction, 3 washing, 3 stripping and 1 regeneration. Interstage neutralisation in the extraction circuit is by caustic addition, and the pH is maintained at 5.2-5.5. There is virtually no zinc in the BNC, so this is not a problem. Residual amounts of Cu and Fe extract, and are removed in the Co circuit, as are Pb and Mn. Mg is controlled in the scrub section of the SX circuit, and the loaded organic is stripped with spent cobalt electrolyte (~30 g/L H_2SO_4). Stripping conditions are such that the resulting strip solution is at a pH of about 2.5-3.0, which, with the use of both anode and cathode bags, permits a closed circuit, analogous to that of Cu SX/EW, to be employed.

The raffinate, essentially pure nickel sulphate solution, is treated in carbon columns and proceeds to Ni electrowinning. The sulphate electrowinning of cobalt and nickel uses both anode and cathode bags. The cobalt concentration in the electrolyte is 60-65 g/L, with a bite of 18-20 g/L Co. The concentration of nickel in the electrolyte is 85-100 g/L, with a bite of 28-30 g/L. Both tankhouses operate at around a nominal temperature of 65ºC.

The quality of both metals is very high indeed (>99.95%), approaching that of the chloride products from Glencore (Falconbridge). Nickel is sheared into 10-cm squares (occasionally 2.5-cm squares for special orders), and cobalt is crushed into approximately 2.5-cm pieces.

From personal observation, this is an excellent operation, such that there is even a flower bed in the middle of the plant. It is claimed to be one of the lowest cost operations in the world, this despite the transport from northern Brazil to São Paulo.

European Nickel Çaldağ Heap Leach, Turkey

European Nickel was the first company to really attempt heap leaching of laterites. The company ran a 3-heap demonstration project, comprising 20,000 tonnes of laterite, commencing in 2004, which proved for the first time that not only could heaps be constructed from certain laterites, but that good recoveries (80%) of nickel and cobalt could be achieved. Acid consumption was high, however, at 579 kg/tonne. Figure 44 shows the metal recovery flowsheet from the heap leach process liquor(188). Despite a seemingly successful demonstration, the project never achieved commercialisation.

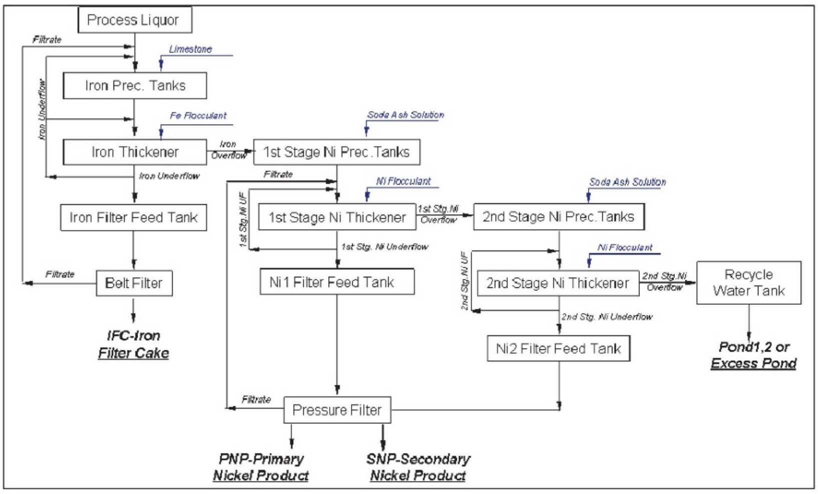


Figure 44. Metal recovery Flowsheet, Çaldağ Heap Leach(188)

Proposed Circuits

There have been many proposed circuits published in the scientific literature, most of which have never seen the light of day, and of which the most-developed is probably the CESL Process. CESL (originally Cominco Engineering Services Limited), a division of Teck, has developed a suite of processes(189,190,191,192,193,194), based on chloride-assisted sulphate pressure leaching, which was originally developed as Noranda's Antlerite Process in the 1970s(195). Despite many pilot operations and much effort, there still remains to be a commercial CESL plant.

Direct Nickel

Uniquely, Direct Nickel Technologies (DNI) is the only process currently attempting to utilise nitric acid as the lixiviant, which the company claims is the most cost-effective and efficient way of recovering cobalt and nickel from laterites(196,197). It is also claimed, erroneously, that the process is the only one able to treat both saprolite and limonite (see Neomet Process below). However, there is, as yet, no commercial operation in existence, despite several pilot campaigns. There have previously been attempts to develop nitrate-based circuits(198), notably the Nitrox or Redox Process(199,200), which was intended to be piloted at Bakyrchyk Gold in Kazakhstan(201), but was never successful(202). The use of nitrates for refractory gold has been summarised by Li(202), and it appears that the process may now be being operated in China. Certainly, nitrate processing has never been successfully applied to base metals, and no large-scale commercial plants have ever been built. Nitric acid, being a very powerful oxidant, is inherently unsafe, especially in the presence of reductants such as metal sulphides or organic carbon, and as such, is prone to "runaway" reactions. Controlling and dealing with such runaways is completely counter-intuitive, which is where the safety issues arise, and will be a major challenge for DNI to overcome in order to commercialise the process.

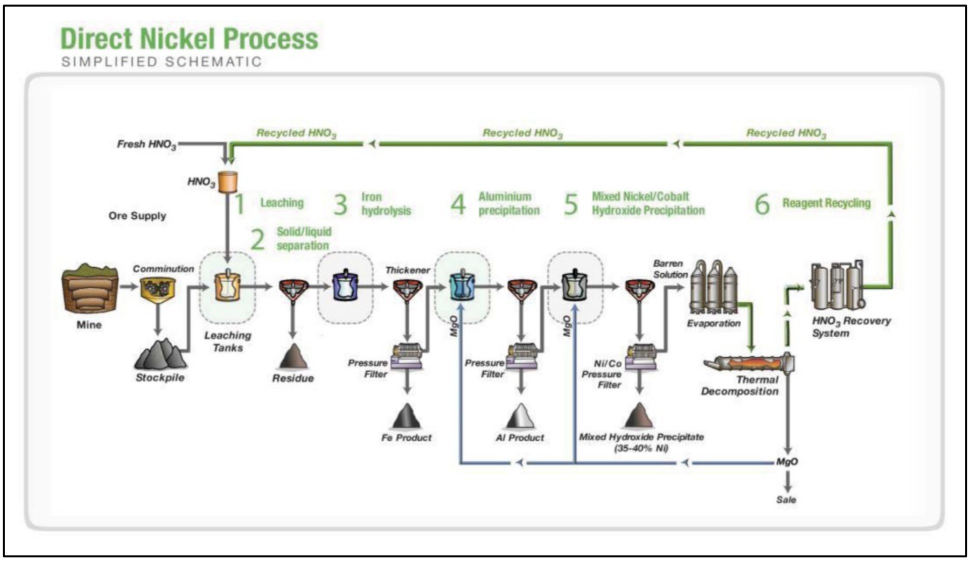


Figure 45. Direct Nickel Simplified Flowsheet(196,197)

NiWest

NiWest, not to be confused with the BHP Nickel West operation at Kwinana, is located adjacent to the Murrin Murrin property in WA(203,204). Figure 46 shows the flowsheet published on the company website in 2018(203), which is slightly different to the one given at ALTA 2015(204). In the 2015 flowsheet, the product was nickel metal, whereas the newer version shows nickel sulphate, in keeping with the general movement to make battery-grade salts. The company completed a PFS in mid-2018, showing very favourable economics, but at the time of writing this paper (February, 2019), there has been no announcement as to whether the project will go ahead.

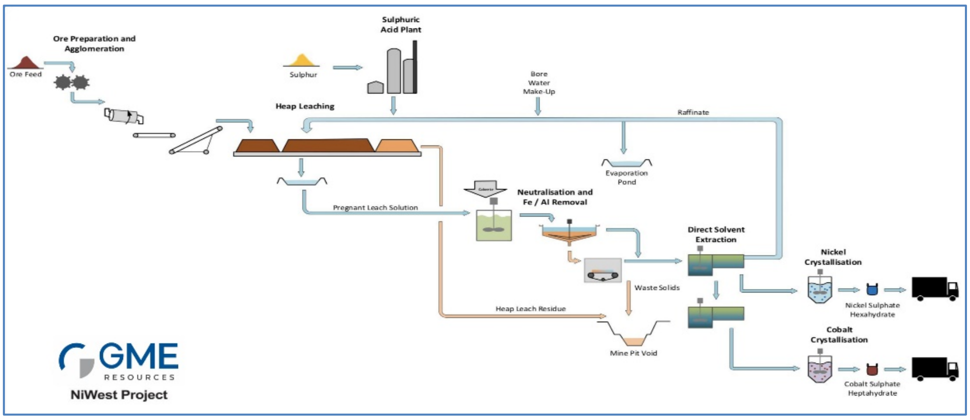


Figure 46. NiWest Project Flowsheet 2018(203)

Noranda (Glencore) Blackbird

During the 1980s, Noranda sensed an opportunity as the price of cobalt sky-rocketed, and acquired the Blackbird mine in Idaho. As noted earlier, this mine had operated in the 1950s, cobalt having been deemed a strategic metal by the US government. An oxidative pressure leaching (POX) process was developed, and arsenic was controlled by precipitation as sulphide(77). The process was one of the first to use the bis-picolylamine ion exchange resin for the separation of small amounts of nickel from cobalt sulphate process liquors, and pioneered the concept of the split elution technique, subsequently adopted in Chambishi(205). Despite favourable economics for the process flowsheet, the project was abandoned since the mining costs were too high and the price of cobalt retreated to more traditional levels. It has to be said that if the project were carried out today, a chloride-based process would be favoured, since there are now very efficient ways of recycling hydrochloric acid, and arsenic fixation is very much easier to achieve in a chloride medium. The mine remains on care and maintenance to this day.

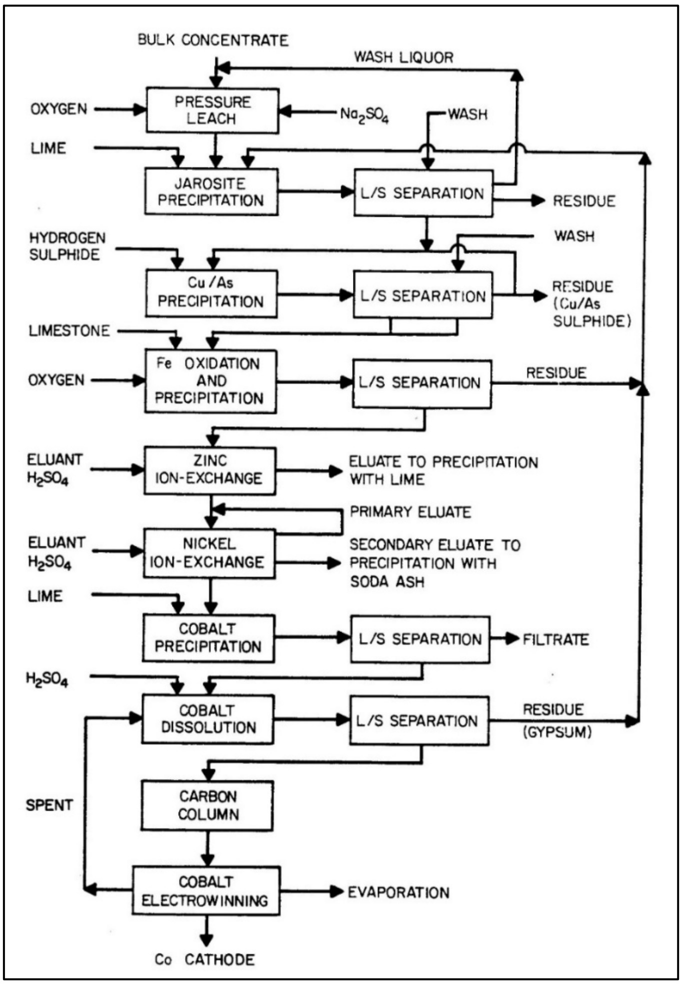


Figure 47. Proposed Blackbird Refinery Flowsheet(77)

Neomet Chloride Process

The Neomet Process was developed to take advantage of the unique features of chloride chemistry, whilst at the same time being energy-efficient, environmentally-friendly and, contrary to many traditional approaches, to recover useful iron, aluminium and magnesium products rather than sending them for disposal. As with the DNI Process referenced above, either limonite, saprolite or combinations thereof can be processed. The key unit operation is the moderately low-temperature hydrochloric acid regeneration process(206), which has overcome the problems that SMS Siemag had with a similar process(207). Figure 48 shows a generic Neomet Process flowsheet(208).

An evaluation, based on modelling of the flowsheets, has indicated the two developing processes, Neomet and Direct Nickel, both appear to be potentially competitive with the established HPAL processes, and distinctly superior if their by-products prove to be marketable(209). A particular advantage of the Neomet approach is that there are virtually no solids to be disposed of, thus avoiding the vast tailings dams associated with HPAL processing. The latter typically generates 1-1.5 tonnes of residue for every tonne of laterite mined, which must disposed of. The Neomet Process, at worst, generates 200 kg of a low volume, benign alumino-silicate residue.

SALT (Starved Acid Leaching Technology) Process

This is a relatively recent development, the Starved Acid Leach Technology (SALT) being developed by InCor Technologies and the University of British Columbia to recover nickel and cobalt from nickel saprolites and Caron plant residues without incurring the high acid consumption due to magnesium, as would normally be the case(210). Relatively small amounts of acid are applied to ground saprolites or Caron residues in order to selectively leach nickel and cobalt under atmospheric low free-acid conditions. Nickel and cobalt may be recovered from the leachate as a mixed hydroxide. Initial results indicated extraction levels at 57.9% (Ni), 65% (Co), 10% (Fe) and 46.5% (Mg) at an acid addition rate of 350 kg/t of dry ore. Figure 49 shows the process as-conceived.

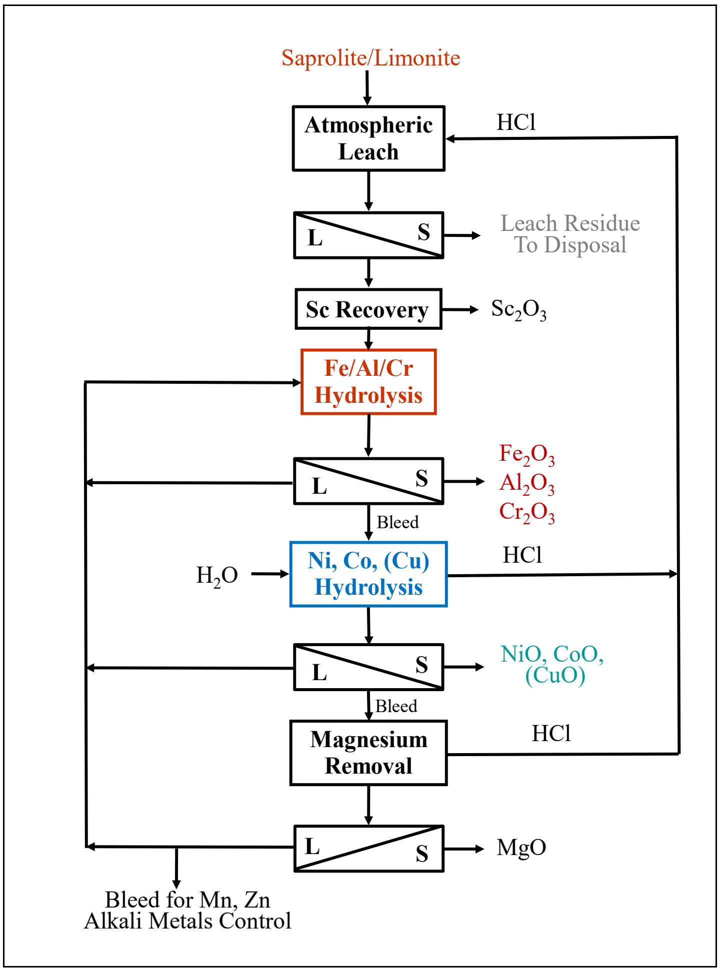


Figure 48. Neomet Process Laterite Processing Flowsheet, 2013(144)

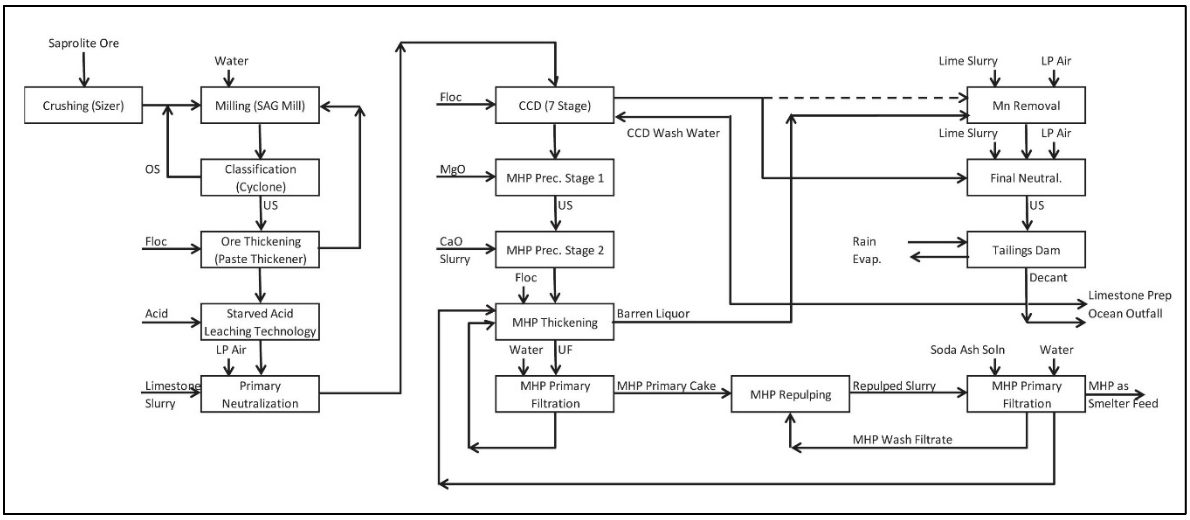


Figure 49. SALT Process Plant Block Flow Diagram(210)

BATTERY RECYCLING

Background

As discussed previously, battery recycling seems, on the face of it, not only an obvious activity to undertake, but also one that is very necessary. Environmental legislation, not to mention the sustainability of the metals extraction industry, especially with respect to cobalt, and, to a lesser extent, nickel is mandating that this be put in effect. End-of-life requirements are already a major issue for OEMs (Original Equipment Manufacturers), and are having to be put in place before permits are granted for manufacturing. We can expect, therefore, a significant increase in the amounts of batteries that have to be recycled. Not only that, but the preceding discussion has indicated that it is unlikely that primary sources of cobalt will be adequate to cope with the anticipated demand for the metal, especially in the short term if the EV revolution really takes hold.

There are very mixed signals about the amount of lithium-ion batteries (LIBs) that are recycled, just as there are for cobalt demand, already discussed. One estimate is that, currently, 100,000 tonnes of lithium-ion batteries were recycled globally in 2018, with an expectation that this could reach 290,000 tonnes by 2025(211). This represents somewhere between 10-40,000 tonnes of cobalt, which is still significantly less than the projected shortfall in the near term, but would be, nevertheless, an appreciable contribution to the cobalt supply. CSIRO estimates that in Australia, just 2% of LIBs are recycled, compared to 98% for lead-acid batteries(212). In the US, there are concerns that innovations in battery technology are actually reducing the need to recycle(213). It was noted that a study by EPRI (Electric Power Research Institute) concluded that “Overall, the potential environmental benefits attributable to LIB-based grid-scale ESSs remain unclear”(213).

Due to the perceived lack of currently profitable recycling options, it is variously claimed that the majority of LIBs are sent to landfills for toxic waste, with only a smaller amount being refurbished for re-use (mostly in China). As noted earlier, refurbishment is likely not a long-term practical option, since the cobalt-based cathode structure will have degraded in the battery’s first life. In contrast, currently ~99% of lead acid batteries are recycled globally because there are plentiful profitable recycling options for these types of batteries. However, this perception is not necessarily true. Table 6 gives just one estimate of the amount of lithium-ion batteries recycled in some jurisdictions(214).

Table 6. Estimated Return Percentages of LIBs for Selected Countries to 2012(214)

Country	Return percentage	
	2002	**2012**
Switzerland	61%	73%
Belgium	59%	63%
Sweden	55%	60%
Germany	39%	44%
Austria	44%	-
Netherlands	32%	-
United Kingdom	-	32%
France	16%	-
Finland	15%	40%
Canada	3%	5.6%

It is clear that there is some degree of battery recycling going on, and equally clear that more needs to be done. The numbers for Canada, which are likely mirrored in the US, suggest that much more needs to be achieved in North America.

Battery Recycling Practicalities

Despite the obviousness of doing so, the re-processing of batteries is, in reality, not a trivial activity, and in some ways contributes to the low recycle rates, especially in North America(213). Some of the reasons for this are as follows:

1. Batteries are dangerous, as witnessed by the incidents of them catching fire on planes(215), and the more serious train explosion in 2017 in Texas(216). Extreme caution, therefore, is required when handling them, especially in terms feed preparation. To date, it is fair to say that managing spent LIBs has been somewhat haphazard.
2. Not all batteries are fully discharged, so there is frequently some “energy” left, and generally any batch of recycled batteries contains some that are fully charged, some fully discharged, and everything in-between.

3. Cobalt, nickel and manganese can exist in several oxidation states, and generally the higher states are found in batteries. Cobalt, for example, may even be in its rare +4 valence state, which can be highly unstable. In their higher oxidation states, all of these metals are very powerful oxidants, so that when designing a processing scheme, this has to be taken into consideration.
4. If recycling is operated in conjunction with end-of-life processing, then the battery OEMs, with current technology, require a highly pure metal sulphate salt to be returned. Whilst it might seem logical to simply return the original metal mixture as an oxide, for instance, the current methodology of battery manufacture, designed to create the layered structure necessary for intercalation discussed earlier, generally precludes this.

As is often the case with a fledgling industry, which battery recycling is, especially one connected to the mining and metals extraction industry, it attracts many would-be practitioners who envisage an opportunity to make a quick buck, so to speak, and a proliferation of “proprietary treatment processes.” There are many articles and processes described and proposed for the recycling of batteries, mostly from Research Institutes rather than genuine operators. Tanong et al. have summarised some of the more relevant processes, and it is apparent that there is not one current process which can recover all of the components comprising lithium-ion batteries(217). Another fairly in-depth study has been undertaken by Saloojie and Lloyd(218), which covers some additional processes not covered by Tanong et al. They note that there are four commercial battery recycling processes in operation, namely those of Recupyl(219,220), Umicore(221,222), Toxco (now known as Retriev)(223) and Akkuser(218), as well as Inmetco (a subsidiary of American Zinc Recycling, formerly Horsehead), which does not recycle LIBs at the present time(224). A recent article by the Argonne National Laboratory in the US, reviewing the existing state of commercial recycling, concluded “*There is no simple route to recycling of Li-ion batteries. These are varied and complicated products, whose design continues to evolve. Their recycling would have environmental and hopefully economic benefits, but none of the several methods for their recycling is ideal; each has its own drawbacks and advantages*”(225). Table 7 summarises the principal commercial operations.

Table 7. Principal Commercial Recycling Operations

Company	Process (End-to-End)	Patents	Products	Issues	Sustainable Economic Eco-friendly*
Umicore	No	No	Ni, Co only	Smelting – massive C footprint, Li lost to slag	No
Akkuser	No	No	Intermediates	Physical separation, products sent elsewhere	No
Retriev	No	2	Intermediates	Metals refined off site	No
Recupyl	No	1	Plastics, casings, Co, Li & Mn	Organics, graphite not recovered, chemistry is inconsistent	Yes
MCT-BRME	No	1	Metals	High temperature melting	No
Sitrasa	No	No	Unknown	Unknown	Unknown

* Defined as causing no environmental harm

None of these is the answer, though. Those companies making intermediates generally end up sending the product to Umicore, which is the largest recycler. However, smelting is not really a process for the modern age, having a high energy consumption (despite gaining some energy from the incineration of the plastics), is environmentally unsound, and is inefficient in terms of product recovery, especially with lithium being lost to the slag. End-to-end here is defined as the following:

- It has to separate and recover all components of the batteries, and return to OEMs in a useful form for re-use;
- Plastic and metallic casings;
- Anode material (graphite);

- Cathode material (Co, Ni, Mn, Li), as high-purity sulphate salts (Co, Ni, Mn) and LiOH/Li_2CO_3;
- Connectors (e.g. Cu);
- Electrolyte (including volatile organics, such as ethylene carbonate).

Recupyl, which would appear to have the most complete process, nevertheless has inconsistent chemistry in its publications(219). It claims to stabilise the lithium hexafluorophosphate by the addition of chloride, and recover it at the end of the processes. However, adding chloride to spent LIBs results in chlorine evolution, and hence loss, so that the aqueous environment would be expected to hydrolyse the hexaflurophophate, as noted below.

Batteries are complex structures, containing steel and/or plastic casings, anode material (usually graphite), but now comprising newer anode materials such as lithium titanates, cathode material (variously mixtures of high-valent metal oxides of cobalt, nickel and manganese, combined with lithium), metallic copper and aluminium, and an electrolyte comprising a volatile organic solvent, such as ethylene carbonate, with a complex lithium salt. Fully charged, these batteries have a potential of several volts, nominally from 1.5 to 3.6, but can be as high as 4.2V. Thus, recycling and re-processing of these batteries is equally complex. Notwithstanding the efforts being made to replace the graphite anode material with, for example, lithium titanate, it is the cathode material that is of the greatest interest at the present time, for this is where the cobalt (and nickel) is contained, and consequently where the greatest value is.

The cathode material of the battery is also quite hygroscopic. Where lithium hexafluorophosphate is the electrolyte, which is the most common, it readily reacts with water, as shown in the following series of equations:

$$LiPF_6 + H_2O \rightarrow LiOH + PF_5 + HF \quad (1)$$
$$PF_5 + H_2O \rightarrow POF_3 + 2HF \quad (2)$$
$$POF_3 + H_2O \rightarrow HPO_2F_2 + HF \quad (3)$$
$$HPO_2F_2 + H_2O \rightarrow H_2PO_3F + HF \quad (4)$$
$$H_2PO_3F + H_2O \rightarrow H_3PO_4 + HF \quad (5)$$

The presence of moisture, therefore, results in the potential formation of dangerous and toxic gases, especially hydrogen fluoride, HF. Additional moisture results in further hydrolysis forming more hydrogen fluoride and ultimately phosphoric acid. Care, therefore, has to be taken in the initial feed preparation process to counteract against toxic gas formation and the high reactivity of the cathode material.

There are, as would be anticipated, a number of opportunistic processes being proposed, most of which are hype without any substantial backing to the, often extravagant, claims being made. Table 8 summarises the main processes. Of these processes, only the Urban Joint Venture can recover all of the components, as defined by “end-to-end” above. American Manganese claims a process patent, but in reality, it is based on the crystallisation of sodium sulphate and efforts to sustain a water balance – no other details are given, but it is being hyped a great deal. Li-Cycle is mainly a blog, saying all the right things, but giving no process details whatsoever. There are no details from Envirostream, which is mainly a collector, sending the cathode material to Korea for final processing, nor from Neometals, although it is known that the latter has a process using solvent extraction (SX).

Whilst SX is a great process in the right circumstances, for recovering and concentrating metals from dilute streams, it was not designed for primary recovery from concentrated feed solutions, and in the case of Co/Ni separation, predominantly for removing small amounts of cobalt from nickel process streams. It is also very pH dependent, so that for high cobalt concentrations, correspondingly high sodium (or other alkali metal) sulphate concentrations can be anticipated. Furthermore, the concept of using multiple reagents to achieve various separations imposes strict process conditions wherein great care has to be taken to ensure that no cross-contamination occurs. It is considered that SX, and especially multiple SX circuits, is not suitable for the small-scale plants required for reprocessing of LIB cathode materials.

Table 8. Some Proposed New Recycling Processes

Company	Process (End-to-End)	Relevant Patents	Products	Issues	Sustainable Economic Eco-friendly*
American Manganese	No	1	Co carbonate, sodium sulphate (anhydrous)	Not a recycling process, water removal	No
Li-Cycle	No	No	Unknown	Mostly a blog, no process details	No
Envirostream	No	No	Unknown	Claims, but no details	No
Enviroleach	No	2	Unknown	Exotic chemicals used	No
Neometals	No	1	Unknown	SX not suitable for concentrated solutions, especially Co, water balance	No
Urban JV	Yes	5	All components	None apparent	Yes

Some Preliminary Diagnostic Feed Preparation Studies

Whilst there are numerous articles on battery reprocessing, very few of these have made any studies on the initial crushing and screening of batteries in any great detail. Very recently (March, 2019) a paper was published in which an effort was made to characterize the cathode material through the analysis of various screen fractions(226). Nevertheless, whilst interesting, the initial crushing and screening was not addressed.

Thus, in order to investigate some of these potential feed preparation issues, a number of diagnostic tests were carried out. Single cells, both LCO and NMC, were connected to a potentiostat and the output potential of the cell recorded. Each cell was then immersed in liquid nitrogen, which seems to be a standard method applied to discharge cells, even appearing on YouTube, and the output potential recorded as a function of time, as shown in Figure 50. It can be seen that in most cases, electrical activity had ceased after about 12 minutes, but thereafter it could reappear. After 20 minutes, electrical activity was essentially zero in all cases. It was also noted that electrical activity could be re-established if the cells were allowed to re-equilibrate at room temperature, but this did not happen in all cases. For this reason, therefore, it was deemed necessary that the frozen cells should be shredded as soon as possible after immersion in the cryogenic fluid was finished. It should, however, be noted, that whilst most were discharged, not all cells tested were amenable to this cryogenic discharging process.

Subsequently, a batch of mixed LCO/NMC batteries were frozen in liquid nitrogen for 20 minutes to discharge them as much as possible, and were then immediately shredded, after which the shredded material was screened, much the same as in the article referenced above(226). The results obtained are shown in Figure 51, and Figure 52 shows the visual appearance of the three main size fractions apparent in Figure 51.

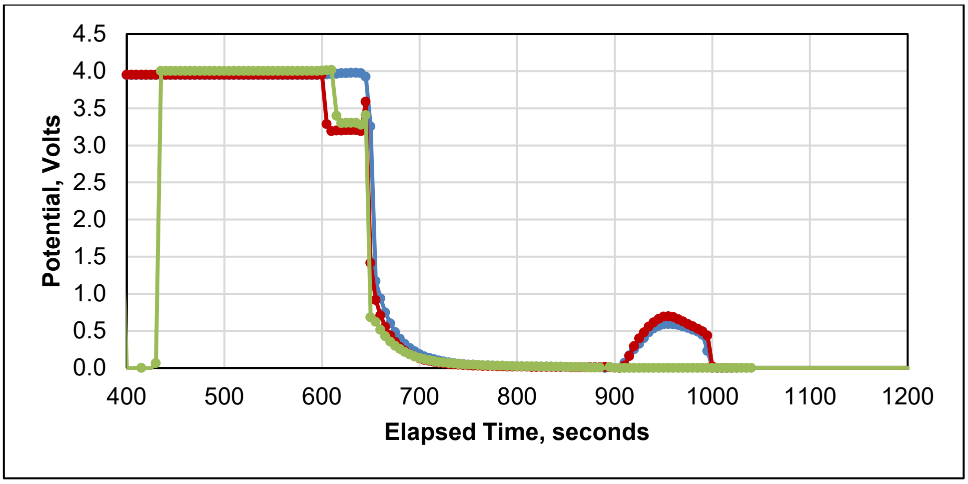


Figure 50. Potential-Time Curves for Various Batteries Immersed in Liquid Nitrogen

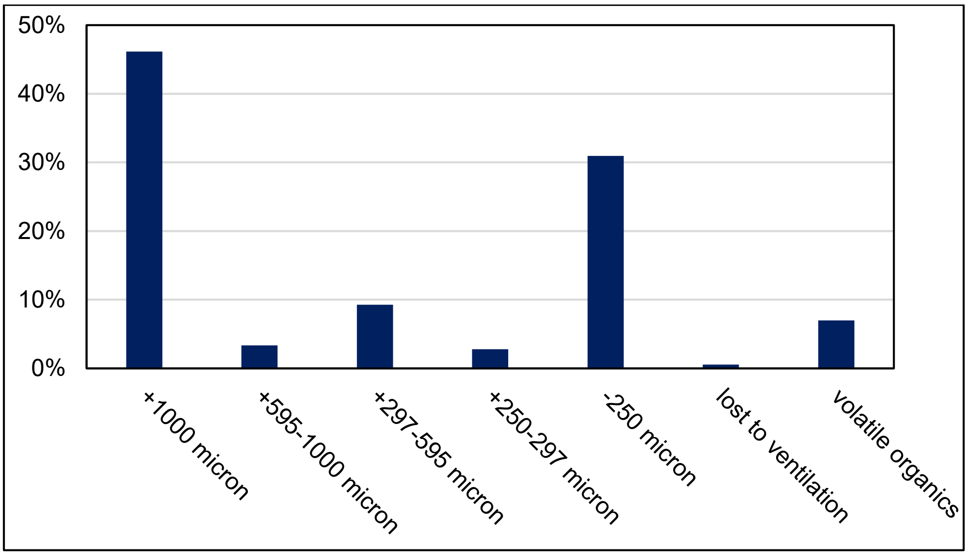


Figure 51. Distribution of Screen Fractions of Frozen and Shredded Batteries

The +1000 micron fraction, comprising nearly half of the original mass, was predominantly plastics from the casings, and the -250 micron fraction the active cathode material containing the valuable metals. Similar size fractions are apparent in the work of Porvali, et al.(226). In the batch tested, and as shown in Figure 51, much of the volatile organic component of the cathode material was volatilized, being 7% in the example, although it can comprise as much as 10%. The amount present will depend on the state of the batteries and for how long they have been stored.

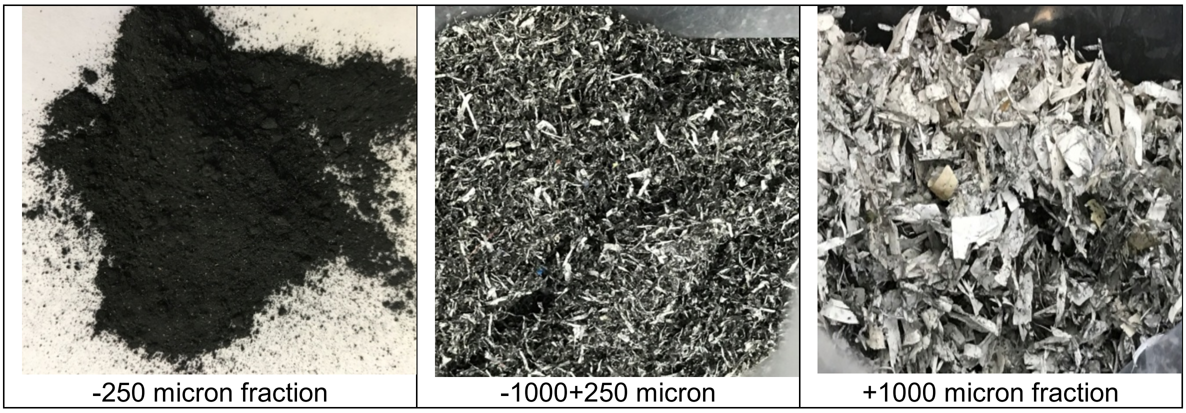

-250 micron fraction
-1000+250 micron
+1000 micron fraction

Figure 52. Screen Fractions of Frozen and Shredded Batteries

The density, both the true density, and the bulk (free-flow) density of the five screen fractions from Figure 51 was determined by a standard water displacement method. The results are shown in Table 9.

Table 9. Density of the Various Screen Fractions from Frozen and Shredded Batteries

Screen Fraction	True density (g/mL)	Free flow density (g/mL)
+1000 microns	1.1	0.2
+595-1000 microns	2.5	0.4
+297-595 microns	2.6	0.6
+250-297 microns	2.7	0.9
-250 microns	3.5	1.1

The density measurements clearly show the light plastics fraction, and indicate that dense medium methods may also be applicable to recover this fraction, as suggested by Porvali, et al.(226). All four oversize fractions were then separately treated in a single hammer mill pass to further reduce the particle size to the targeted fraction. The milled material was then re-screened, and an additional 24% of minus 250 micron material was recovered in this manner, resulting in a total of 55% recovery from the original batteries. The secondary milling process collected substantial additional material that was likely adhering to the metallic fractions after shredding, and would account for the results obtained by Porvali et al., as suggested in their paper(226).

The two coarser screen fractions comprise predominantly metals and plastics used in the casings. From a recycling point of view, these can be returned as-is to the OEMs, and only the cathode material, comprising 55% of the original mass requires further metallurgical processing.

Just as shredding and screening is not straightforward, neither is the processing of the cathode material to recover the separate metallic components. The ratios of Co:Ni:Mn in batteries are not found in primary operations, plus Li is also present. Commonly in commercial operations, there is a small amount of cobalt in nickel process solutions, and vice versa, and manganese is a nuisance element in both, generally removed by oxidative precipitation. With batteries, the ratios can be unity, depending on the type of battery, so that the separation schemes are much more challenging.

Flett, in 2004, reviewed all of the processes that have been used to effect separation of small amounts of cobalt from nickel and vice versa(227). He concluded that solvent extraction processes were superseding precipitation processes for separating cobalt from nickel, and that ion exchange was the only method to effectively remove nickel from cobalt in a sulphate medium. Oxidative precipitation processes for cobalt separation from nickel solutions were also reviewed. Much like is the case for the equivalent solvent extraction and ion exchange processes, it was noted that the issue with all of them was pH control, especially if significant amounts of cobalt were present. It was further noted that even strong oxidants such as Caro's Acid (H_2SO_5, peroxy monosulphuric acid), sometimes referred to as a superoxidant, were generally inadequate for effective and efficient cobalt removal. Additionally, it was noted that all such reagents generate acid, requiring substantial amounts of base to be added at the same time.

More recently in 2018, Sole has summarised all of the various reagents that have been used for the recovery and separation of nickel and cobalt(228). No scheme for the recovery of the four metals present in lithium-ion batteries, namely copper, manganese, cobalt and nickel was described. Dunn et al. described the use of Caro's Acid and ozone as methods of oxidative precipitation(229). As with the article by Flett referenced above, it was noted that pH control is important, and also that the cobalt products contained significant amounts of nickel, requiring their re-processing. The large amounts of nickel co-precipitated were undoubtedly due to the long residence times employed. Both Outokumpu, at Harjavalta, and Bindura in Zimbabwe used this principle commercially, by removing cobalt using electrolytically generated nickelic hydroxide, which subsequently oxidized and precipitated the cobalt. The process was abandoned in both cases, with the cobalt precipitate containing too much nickel. The University of Queensland has upgraded a modification of the "superoxidant" process applied to reprocessing of MHP(230,231). The data seem to indicate that a relatively pure nickel sulphate can be obtained, but that the cobalt precipitate still requires significant further processing to obtain a pure product.

This brief review of the literature on cobalt-nickel-manganese separation with reference to battery recycling indicates that there remain substantial challenges, and that more sophisticated and novel methods will be required to achieve this in order to return cobalt, in particular, back into use. It is beyond the scope of this paper to explore what these methods might be.

DISCUSSION AND CONCLUSIONS

In this paper, an attempt has been made to clarify and quantify the impact that the "Age of Lithium-Ion Batteries" will have upon the extractive processing of nickel, cobalt and copper. It is generally taken as a "given" that electric vehicles, powered by these lithium-ion batteries, will occupy an increasing proportion of all vehicles manufactured, with a target of approximately 30% by the year 2030. Such a target seems to have been determined as a result of reducing GHG emissions from cars, and not from the availability of resources required to effect this change. As far as can be ascertained, it has been assumed that "technology", whatever it might be, will be able to meet the requirements. However, it is clear that the repercussions of implementing this have not really been assessed in any meaningful manner, other than to state that there will likely be a shortfall of cobalt.

The proponents of electric vehicles would like to see a repeat of the dramatic change that occurred in the early years of the twentieth century when motor cars replaced the horse-drawn buggy, which, let it be said, is an admirable objective. The main reasons for doing so are similar in that environmental concerns, albeit somewhat different, are the driving factor. For example, in 1900, in New York City alone, horses deposited over 1000 tonnes of manure each and every day(232). Further to this, a little-known and somewhat surprising fact is that in the early 1900s, approximately 40% of motor vehicles were electric. Unfortunately, they were heavy and inefficient (they could do at most 90 miles in a day on a single charge), and with the advent of both the Model T Ford, which was one-third the price, and the Oil Bonanza, especially in Texas, they disappeared(232).

For EVs to reproduce a similar rapid change, with present and near-term battery technology, there needs to be an equivalent "Cobalt Bonanza." Such seems highly unlikely however. Even without any increase in production levels (presently 110,000 tonnes/annum), the current known identified terrestrial reserves of cobalt will be exhausted within 70 years. Neither can cobalt production be divorced from that of nickel and/or copper. Whilst all the focus has been on cobalt, simply because it is both the predominant component in batteries, but also has the lowest production rate (in terms of tonnage), the situation regarding nickel and copper is even worse. At current production levels, the known land-based reserves of both these metals will actually last 35-40 years, compared to 70 years for cobalt. However, crystal-ball gazing suggests that, at the very minimum, cobalt demand will double over the next decade, with some estimates even suggesting that it could quadruple. If the latter is correct, then known cobalt reserves will disappear within twenty years. And, because cobalt is so intimately associated with nickel and copper, then both of these metals are also under threat.

For copper, as noted earlier, there is a need for at least thirteen new Collahuasi mines. For nickel, the majority of the reserves are associated with laterites. The currently preferred processing technology is HPAL, which has had more failures than successes, which is incredibly capital-intensive, which requires very long ramp-up times, and for which the economics really appear to be marginal at best. The decision to invest billions of dollars into such projects is not going to be an easy one to make. China already controls the bulk of the world's cobalt reserves, and if, as indicated, it is going to be able to build HPAL plants faster and cheaper than has hitherto been possible, then such an ability will only lead to further Chinese control. In this respect, consideration really needs to be given to alternative laterite processing technologies, which are both significantly less capital-intensive, and, at the same time, can process all horizons of a laterite orebody. The leading contender in this respect is chloride-based processing technology.

Assuming, then, that the "Electric Future" is here to stay, this presents quite a dilemma and also a challenge to the extractive base metals industry, and in particular to cobalt and nickel processing. How can this quandary be addressed? There are potentially two solutions, one short term which must be addressed with more urgency than is currently the situation, and one much more long term, but one which has both political and practical issues. The longer-term solution lies on the sea bed, being the so-called deep-sea manganese nodules and cobalt crusts. The cobalt in this resource is approximately ten times that of land-based reserves, and there is also substantial nickel, but proportionately nowhere near that of cobalt. Unfortunately, nodules contain relatively little copper. Because these nodules are on the ocean floor, they are "international" in the sense that, in most cases, they have no sovereign jurisdiction, which, at the moment, is a political can of worms. Despite the creation of the International Sea Bed Authority, it is something that will have to be addressed if climate change is to be tackled and an "Electric Future" realised.

The short term solution is to implement a very much more rigorous recycling strategy. At present, there is no firm estimate of how many batteries are recycled, but whatever it is, it simply has to be increased. Just 100 tonnes/day of batteries recycled would yield over 5000 tonnes of cobalt per annum. To do so requires a very small processing plant compared to a typical nickel laterite, which would require in the order of 15,000 tonnes/day to produce the same amount of cobalt. Recycling is not going to solve the supply-side problem entirely, but it is an admirable short-term strategy to alleviate it.

POSTSCRIPT – THE "ELECTRIC FUTURE"

The premise of the preceding discussion in this paper has been that EVs will significantly replace petrol (gasoline)-driven vehicles in order to mitigate against the increasing atmospheric CO_2 levels and resulting climate change. Certainly, the record temperatures in Australia, and the Polar Vortex in North America, experienced in January of this year (2019) attest to this, and it is widely believed that reducing emissions from petrol (gasoline)-driven automobiles and replacing them with electric vehicles will help in this regard. This scenario is by no means a certainty, however, and there are an increasing number of voices arguing just this(233). The current target, as noted previously, is that approximately 30% of new vehicles should be electric by 2030, which, given the above discussion, seems somewhat optimistic. There are several possible reasons why EVs will likely not catch on, at least not to the extent envisaged, over and above the problems with cobalt supply already discussed, with the current, or even anticipated, technology of batteries. There is, however, every reason to suppose they will occupy at the very least a niche market.

If the power needed to recharge EVs is derived from fossil-fuel generated electricity, then we are surely no further ahead, so it should, logically, be mandatory that charging can only be from renewable (or nuclear) sources. How this could be enforced is entirely another matter, though. There is also the issue of practicality. In cold climates, cars need to be heated, which will significantly reduce the range of the batteries, and conversely, in very hot climates, air conditioning is required. Also, at the time of writing, it takes, typically, at best around 75 minutes to fully recharge an EV battery pack, versus less than 5 minutes to fill up the tank for a conventional petrol (gasoline)-driven vehicle. There are, of course, attempts to achieve a 75% charge within 5 minutes, but doing this does lead to significant heat management issues(234). None of this is to say that there will not be an "electric future," but it is not an inevitability, and it is highly unlikely that there will be the dramatic changeover seen from horse-drawn vehicles to the motor car which was witnessed in the first decade of the twentieth century. It is not, therefore, unreasonable to postulate that there might be an equal amount of effort devoted to making hydrogen-based fuel cells more of a practical reality.

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DISCLAIMER

In a paper of this nature, which is sourced from a multitude of references, every effort has been made to be as current and accurate as possible at the time of writing (from August 2018 through May 2019). Beyond that, the opinions expressed here are solely those of the author, and do not necessarily represent those of either ALTA or NMR360 Inc. Should there be differing opinions, the author more than welcomes constructive dialogue on such.

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