

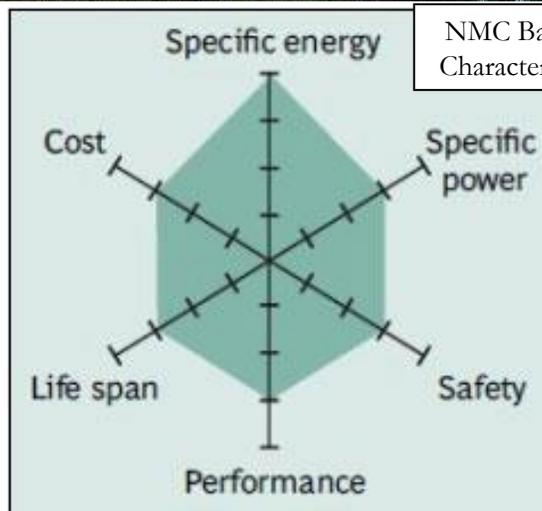
Nickel Sulfide Processing

Another Reason it is “the Devil’s Metal”

4 Paper Set



Talus Dome,
Edmonton, Alberta
316L Construction



NMC Battery
Characteristics

Trytten Consulting Services

Jan 2024

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Nickel Sulfide Processing – Another Reason It Is the Devil’s Metal

Part 1: Introduction and Beneficiation

Lyle Trytten - President, Trytten Consulting

Dec 2023

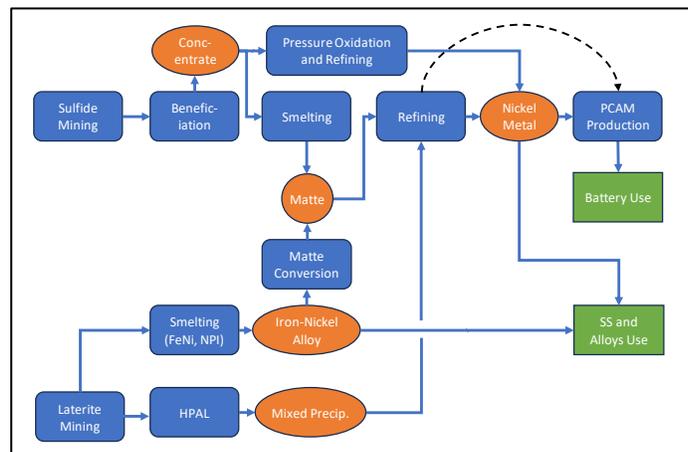
Introduction

Terrestrial nickel exists in two major forms, sulfide ores and laterite (oxide) ores, as well as minor occurrences as awaruite, a nickel-iron alloy. There are also nickel deposits in the ocean, in the form of polymetallic nodules (manganese-based) on the ocean floor and sulfide deposits at active and historic vents and risers. This white paper addresses the complexity of nickel sulfide processing, demonstrating why nickel is a much tougher nut to crack – the term *kupfernickel* (devil’s copper) coined by Saxon miners in the mid-1700sⁱ turns out to be prescient. More detail of operational and potential processes is available in several publications, including Crundwell et alⁱⁱ, Warner et alⁱⁱⁱ, Moskalyk and Alfantazi^{iv}, Faris et al^v; and Kerfoot^{vi}. The [author](#) has previously published white papers on a number of nickel topics (see LinkedIn profile). A video introduction to the nickel industry is available from the Metallurgical Society of the Canadian Institute of Mining^{vii}.

This set of 4 white papers will attempt to summarize the nickel sulfide processing industry and provide some thoughts on potential developments. Summary information in this white paper is derived from the above and many more sources as well as the author’s personal experience.

For those unfamiliar with the other side of nickel (laterites), there is a short appendix in this document; detailed discussion is beyond the intended scope for these papers.

A high-level overview of the nickel production chain is shown right. Aspects of this will be explained in this and following white papers. A glossary is appended; elemental abbreviations are widely used in this white paper.



Nickel Sulfide Ores

Sulfide ores have two major advantages over laterite ores: they are normally easily concentrated using mineral processing techniques (laterites typically require intensive treatment of the whole ore), and the resulting concentrates contain energy which can be used when the sulfide ions are oxidized. Nickel sulfide deposits occur across a broad range from low- to high-grade with a wide range of byproduct value, but are often thought of as being in two broad categories (with some exceptions):

- High-grade Ni-Cu-Co-PGE ores, usually underground deposits (surface deposits having been discovered and developed in past decades) with high byproduct value. Examples include Norilsk, Sudbury, Thompson, and Kambalda (i.e. the “traditional” nickel mines). These can be nickel-dominant or copper-dominant ores.
- Low- to mid-grade Ni-Co-Cu-PGE ores with a range of commercial byproduct values in surface deposits (since the ore value does not justify the cost of underground mining). Some of these are nickel-dominant (i.e. Mt Keith, Turnagain, Dumont) while others are copper-dominant polymetallic ores (i.e. Duluth complex – Mesaba, Northmet, Twin Metals deposits), and some are copper-nickel balanced (i.e. Kevitsa).
- Some areas (i.e. BHP Leinster, Vale Ontario Operations) will have both lower-grade disseminated sulphide resources (large tonnage, <1% Ni) and higher-grade massive sulphide resources (small tonnage, up to 6% Ni).

Almost all sulfide ores are amenable to beneficiation. The complexity of the required processing and its ultimate success depend on the mineralogy of the deposit. The one nickel sulfide whole ore treatment facility in the world – Talvivaara – is based on an unusual nickel-zinc ore that is resistant to effective beneficiation.

Mineralogy is variable, with pentlandite (NiFeS₂) as the predominant nickel mineral, although heazlewoodite (Ni₃S₂) and millerite (NiS) can also occur, generally in much lesser quantities unless the deposit is sulfur-deficient. Nickel can also be present in arsenide and sulfarsenide minerals, although these are quite rare (notably in Tasmania where high arsenic levels have caused problems for the Auebury mine^{viii}, but they have also been noted in major nickel regions such as Sudbury and Western Australia). Many higher-grade deposits have a substantial portion of the nickel present in relatively low concentrations (i.e. 0.5 to 1%) in the iron sulfide pyrrhotite^{ix}, which can lead to distinct challenges in achieving both high recovery and high concentrate

grade and the rejection of substantial quantities of nickel to tailings, especially where nickeliferous pyrrhotite is the dominant sulfide mineral or pyrrhotite and pentlandite mineral grains are inter-grown. Some lower-grade ores have a substantial portion of the nickel in silicate minerals, from which it is unrecoverable by beneficiation. In either case, total nickel assays need to be considered in light of the recovery to a commercially viable product.

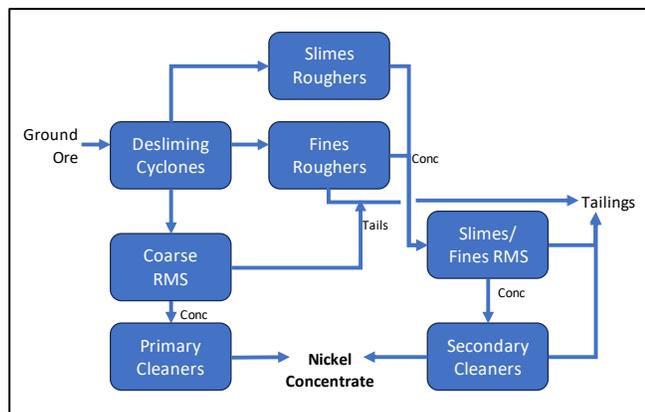
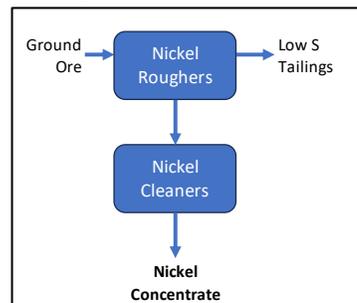
A factor that has come into greater understanding in recent years is the reactivity of ultramafic (high magnesium) ores with carbon dioxide. Many of these minerals, such as brucite, serpentine, and olivine, are reactive and can sequester CO₂ in a geological process, making new carbonate minerals; the reactivity is well-demonstrated in this [video](#) from CarbMin Lab at the University of British Columbia. This has been well documented for a number of mines and mineral projects, including notably Mt Keith in Australia^x and a number of the low-grade ultramafic ore bodies in Canada. Brucite is quite reactive at atmospheric conditions, with ground tailings directly sequestering CO₂ from the atmosphere upon exposure. Other minerals react strongly under elevated conditions (CO₂ concentration, temperature, pressure) with the potential to store hundreds of kg of CO₂ per tonne of tailings^{xi}.

Beneficiation



The dominant method of beneficiation in the nickel sulfide industry is froth flotation, a process where air is injected into a slurry containing the ground ore and a range of chemical additives that influence mineral behaviour (i.e. collectors, frothers, dispersants, pH modifiers, etc). The sulfide minerals tend to stick to the finely-dispersed air bubbles and float to the top where they can be collected, while the gangue minerals are rejected out the bottom to tailings. A typical flotation device (Metso TankCell®^{xiii}) is shown at left. Many manufacturers exist, and a range of design configurations, including higher-intensity and lower-intensity flotation devices and devices focused on recovery of larger particles. Paris has a good general discussion of nickel sulfide ore flotation practices.

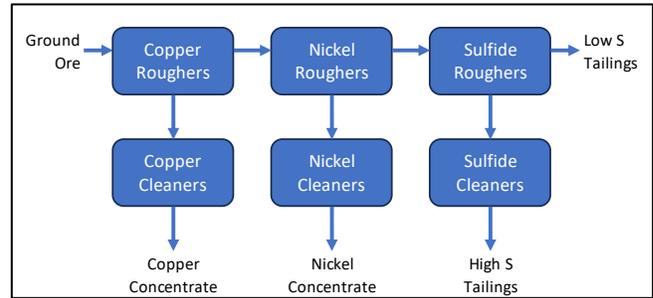
In some simple ores, such as ores with only one significant pay mineral present, the beneficiation can be quite simple, as shown at right for the Turnagain project in Canada. If the ore is low grade, the simplicity of the process masks the underlying reality of processing low-grade ores: large equipment and high power consumption per unit of nickel recovered.



Other conceptually similar ores may contain numerous problematic minerals such as talc, hydrophobic magnesium silicates, and fibrous minerals which can cause significant flotation challenges and result in more complex flowsheets. The flowsheet left is of the Mt Keith concentrator (derived by the author from an Eriez paper^{xiii}). Mt Keith encountered numerous problems on startup, and it took a dedicated long-term effort to achieve good process results.

Pyrrhotite is a particular problem for many deposits – whether nickeliferous or not. Pyrrhotite can occur in a variety of mineral forms with different mineral processing properties. Pyrrhotite:pentlandite ratios of 10:1 are not uncommon. Flotation behaviour is quite variable, and rejection of pyrrhotite from pentlandite can be challenging. Substantial work has been done in this area over many decades, but it remains a significant challenge. It can be misleading to draw parallels from deposit to deposit.

When co-existing with nickel, copper is usually present as chalcopyrite, a sulfide mineral which can often be recovered using differential flotation to produce separate copper and nickel concentrates. The payability for nickel in copper concentrate is usually zero, and the payability for copper in nickel concentrate may be low, but with effective separation the total payability is usually better than for a bulk copper-nickel concentrate, and market options are increased. A simplified flowsheet for separate copper and nickel concentrate production is shown right (derived by the author based on Kevitsa^{xiv} operation). This flowsheet uses a copper recovery and purification circuit, a nickel recovery and purification circuit, and a third flotation step to remove high-sulfur materials from nickel tailings for separate tailings management to address potential acid generation issues that may not be a problem with low-sulfur ores. This practice is expected to become more common for higher sulfur ores due to increased stringency of environmental regulations.



The relative recovery and concentration of this differential copper-nickel separation effect is illustrated by results reported for the Shakespeare^{xv} project in Ontario Canada (table right): the deposit has about 0.3% each Cu and Ni in the ore but produces far more nickel concentrate (with significant copper content) than it does copper concentrate (relatively clean). Consequently, downstream recovery of copper from the nickel concentrate is far more important than recovery of nickel from the copper concentrate. Similar trending results are reported from flowsheet development for Voisey’s Bay^{xvi}.

Nickel Concentrate				Copper Concentrate			
Grade		Distribution		Grade		Distribution	
Ni	Cu	Ni	Cu	Ni	Cu	Ni	Cu
9%	3.8%	97%	31%	0.9%	29%	3%	69%

In general, nickel minerals are slow floating compared to the more commonly recovered valuable sulfide minerals of copper and zinc, and require longer flotation times and consequently larger equipment. Many operations will include a regrind circuit to grind rougher concentrate finer and allow better gangue rejection and higher concentrate grades, while some ores require a fine initial grind of the whole ore in order to obtain the desired recoveries. This fine grind of the whole ore is more costly, so grind size and valuable metals recovery is a trade-off calculation.

Where it occurs as a nickel mineral of value, awaruite (Ni₃Fe) can be recovered using magnetic separation in addition to flotation, giving some increased value but at the cost of increased process complexity. No commercial awaruite recovery facilities are known to the author today, but they are an intriguing deposit type. Where awaruite exists as a small fraction of a larger sulfide deposit, awaruite presence in the nickel sulfide concentrate is not considered a problem, but an awaruite-dominant product will require a different method of downstream processing than is commercially available today unless its impurities are low enough that it can be sold as a final product, i.e. into the stainless steel industry competing with ferronickel (FeNi) and nickel pig iron (NPI).

Cobalt usually departs with nickel (with a typically lower recovery given its grade is usually 20 to 40 times lower than nickel in sulfide ores). Cobalt generally occurs substituted for nickel in pentlandite but can also occur in different sulfide or sulfarsenide minerals which may have different flotation kinetics.

Palladium, like cobalt, is usually associated with pentlandite and recovers to the nickel concentrate. Platinum is usually present as discrete minerals or sometimes inside pyrrhotite (which would typically make it uneconomic for recovery); the recovered metal is dominantly in the nickel concentrate as well. Gold is usually present as free gold and can concentrate to either nickel or copper concentrates (see table right).

Distribution to Nickel Concentrate			
Shakespeare		Tamarack	
PGE	Gold	PGE	Gold
95%	89%	89%	27%

Nickel Concentrates

Nickel concentrates have a wide range of compositions, which complicates the downstream processing. Along with variations in the nickel content, the quantity of byproducts and quantity/type of gangue material also impact downstream processing options.

The table overleaf (Crundwell, from Warner) illustrates the range of base metals compositions in commercial practice (as of 2007). This table does not include the PGE contents of the concentrates, which tend to be significant for many large operations such as Norilsk and Vale Sudbury, and for the South African PGE operations not listed. The latter tend to operate with low base metals contents, generally 2 to 6% Ni+Cu+Co (Warner).

Vale's Voisey's Bay mine has produced concentrates up to 29% nickel but is reported to be operating close to 20% today, with good copper and cobalt credits but little PGE value in the concentrate.

Some lower-grade nickel sulfide operations and projects, like Mt Keith, Turnagain, or Dumont, can produce high-grade pentlandite concentrates due to the mineralogy resulting from their unique genesis. The alteration of the ultramafic ore and re-mobilization of elements results in some nickel remaining in the silicate matrix (unrecoverable), but a substantial proportion converted into recoverable minerals, principally pentlandite or other sulfide minerals but also potentially awaruite. Even when sulfur levels are very low, much of the total nickel may still be recoverable to a high-grade concentrate since there is little pyrrhotite (and other sulfide minerals) to reject. Grades of 15% Ni+ are possible for pentlandite-dominant ores, and over 20% for heazlewoodite or millerite-dominant ores.

Observations

Nickel sulfide ores have a number of inherent advantages over laterite ores: easy to upgrade, inherent energy content, multiple valuable byproducts. Laterite ores require all the energy for extraction and conversion to be added – either thermal energy (smelting) or chemical energy (acid extraction). Laterite ores are more widespread and are easily developed surface deposits with generally higher grades. Because of their surface expression, laterite orebody discovery has been easier than for sulfides.

Nickel sulfide ores are predominantly pentlandite based, although ores may have a significant quantity of nickel tied up in pyrrhotite, silicates, and other minerals which may not be recoverable or desired in the concentrate. Some new projects contain additional nickel minerals with higher nickel and lower sulfur content, allowing higher grades but which may not be compatible with existing downstream processing operations. Within a single deposit there can be a range of value mineral types, concentrations, and grain sizes, and gangue mineral types, complicating beneficiation and downstream processing.

Over time, the industry paradigm of what a “good” ore looks like has changed as the best deposits are developed and depleted. The industry has moved from focusing on high-grade Ni-Cu or Cu-Ni ores with Co-PGE credits to lower-grade (<1%) ores to now <0.5% nickel ores. This mirrors a larger industry trend of declining ore grades – a trend well noted in the copper industry. The new large nickel projects with ore grades well below 0.5% bear marked similarities to the large copper porphyry deposits currently being mined throughout the Americas – but with distinct differences related to the mineral types and grain sizes.

Nickel sulfide ores are amenable to upgrading by factors of 10 to 100, allowing the mining of low-grade materials but shipping and processing of high-grade products. This is similar to the larger copper and zinc industries, where nominal product grades are in the range of 25-30% (copper) and 50-60% (zinc), almost regardless of ore composition. The vast quantity of waste material is thus produced at the mine site where the beneficiation occurs, with relatively minor masses of waste occurring elsewhere. The tailings are representative of the host rocks, less the removed sulfides in concentrate. High-sulfur ores will generally have high-sulfur tailings, while low-sulfur ores may be quite barren of sulfur after nickel recovery, leading to reduced tailings acid generation risks.

Beneficiation – principally grinding and flotation – is not a standardized process and must be adapted to the specifics of the ore: mineral type, grain size, byproduct types, and gangue types. In some cases, a coarse grind followed by rougher flotation and regrinding of the concentrate works, but in other cases a fine initial grind is required to obtain sufficient recovery. Despite many similarities, each case is unique, requiring substantial testwork to derive an “optimal” flowsheet and demonstrate that it is appropriate for the range of ores to be mined in a deposit. An ore deposit with zones of markedly different composition or behaviour can be challenging to treat with a single processing flowsheet. Geometallurgical testing covering all ore types from the deposit is a must for ensuring that processing risk is reduced.

Nickel concentrates have a very wide range of characteristics, in the nickel content, the Cu-Co-PGE content, and the gangue types. This complicates developing standardized downstream processing techniques. Some concentrates can contain impurities, like arsenic, which may render them difficult to transport and market.

Carbon sequestration is an exciting area that is pointing the way towards not just low-carbon, but potentially naturally net-zero operations. However, caution is required around the claims for such sequestration. Ample research demonstrates that natural capture from the atmosphere into tailings is real but highly dependent on temperature, moisture, fresh material exposure, and a

TABLE 15.1 Nickel, Copper and Cobalt Contents in Concentrate Feeds at Smelters Around the World*

Company	Smelter location	Concentrate, %		
		Ni	Cu	Co
BHP Billiton	Kalgoorlie, Australia	15	0.3	0.4
BCL	Selebi Phikwe, Botswana	5	3	0.2
Votorantim	Fortaleza, Brazil	7	1	0.1
Xstrata	Falconbridge, Canada	12	4.5	0.5
Vale	Sudbury, Canada	10	12	0.3
Vale	Thompson, Canada	14	0.3	0.3
Jinchuan Group	Jinchang, Gansu, China	9	4	0.2
Boliden	Harjavalta, Finland	14	0.8	0.4
Norilsk	Nadezda, Russia	12	5	0.4
Norilsk	Norilsk, Russia	5	2.5	0.2
Norilsk	Pechenga, Russia	9	4	0.3

The feeds are sometimes combinations of several concentrates but they give an indication of the compositions of nickel concentrate around the world.
*Warner et al., 2007

range of other factors, while more intensive capture generally necessitates additional capital expenditure and availability of high-concentration CO₂ streams, for which the cost effectiveness and carbon accounting must be carefully considered.

In the absence of a spate of discoveries of large, easily-accessed, high-grade nickel sulfide deposits (unpredictable, but the last major discovery – high-grade, long-life, high capacity - is Voisey’s Bay in 1994), most development in the next two decades looks to be large low-grade surface deposits operating at high throughputs with a few small higher-grade underground mines likely to come onstream or return from care and maintenance. High-grade sulfide deposits cannot be expected to provide much of the growth required in the nickel industry over the next 20 years. The required growth for global decarbonization is huge, on the order of doubling today’s total production.

Acknowledgments

Thank you to [Chris Martin](#), [Johnna Muinonen](#), and [John Marsh](#) for helpful comments on drafts of this section. Discussions with [Eric Young](#) have helped set some of the thinking on the overall nickel industry setup and imaging and how it is evolving for the rapidly growing battery industry. I have learned – and continue to learn - from many highly knowledgeable colleagues. The bulk of the information provided here is summarized from decades of work by many skilled people.

Glossary

Concentrate	an intermediate produced by beneficiation of a nickel ore to reject most of the impurities
FeNi	ferronickel, an iron-nickel alloy typically in the range of 20-35% nickel, suitable for direct addition to stainless steel mills
Matte	a high-grade metallized intermediate material derived from smelting a sulfide concentrate or converting NPI/FeNi with sulfur addition
NPI	nickel pig iron, an iron-nickel alloy typically in the range of 8-15% nickel, suitable for direct addition to stainless steel mills
NSG	non-sulfide gangue, a mix of minerals typically in the silicate or carbonate families
PGE	platinum-group elements (platinum, palladium, rhodium, ruthenium, iridium, osmium), all of which have high economic value
RMS	Rougher-Middlings-Scavenger flotation

Disclaimer and Disclosure

This analysis is the author’s current review and is intended to be indicative of the general state of the industry and potential future paths. Some suggested process routes have been left out of this discussion for the sake of brevity. All material is copyright Trytten Consulting Services. This material may be used and disseminated with credit to the author.

The author has previously worked for Sherritt International Corporation, a producer of nickel and cobalt from laterite resources and a developer of base metals processing technologies. The author’s current business includes an ongoing consulting arrangement with Giga Metals which is developing the Turnagain nickel sulfide project, life-cycle analyses in the metals industry, and contribution to technology and project due diligence studies.

Nickel Laterites - in Brief

Nickel laterites are weathered deposits that generally originated as peridotite or dunite parent rocks. Millenia of alteration through weathering (typically rainy tropical environments) results in layered deposits due to the dissolution and vertical migration of different elements. The end product is an ore body typically with an iron oxide crust (caprock), a moderate grade nickel-bearing layer of primarily iron minerals (limonite), and a high-grade nickel-bearing layer of primarily magnesium silicate minerals (saprolite) overlaying the parent bedrock. Typically laterite deposits are on the order of 10 to 30 meters deep. “Dry” laterites are formed by similar weathering processes usually mediated by rising and falling groundwater, resulting in more clay formation (i.e. smectites). A typical schematic of a tropical laterite is shown at right (Kerfoot).

The treatment of nickel laterites is well-known and has been expanding rapidly in the last 20 years. There are three basic

Idealized laterite	Approximate analysis, %					Extractive procedure
	Ni	Co	Fe	Cr ₂ O ₃	MgO	
Hematitic cap	<0.8	<0.1	>50	>1	<0.5	Overburden to stockpile
Nickeliferous limonite	0.8 to 1.5	0.1 to 0.2	40 to 50	2 to 5	0.5 to 5	Hydrometallurgy
	1.5 to 1.8	0.02	25 to 40	1 to 2	5 to 15	
Altered peridotite	1.8 to 3	0.1	10 to 25	2	15 to 35	Pyrometallurgy
Unaltered peridotite	0.25 to	0.01 to 0.02	5	0.2 to 1	35 to 45	Left in situ

commercial methods of treating laterites, listed in order of production below:

- smelting of higher-nickel laterites (saprolites and high-nickel limonites) to form iron-nickel alloys (FeNi, NPI), which are generally used in stainless steel production where the iron is of benefit,
- sulfuric acid leaching (hydrometallurgy) of limonites to form nickel-cobalt solutions which can be recovered in a variety of ways, usually by precipitation to mixed sulfide or mixed hydroxide precipitates for further refining to high-purity nickel products such as Class 1 nickel or battery chemicals, and
- Caron processing (reduction-roast) of limonites and transition material with ammoniacal leaching and recovery as nickel oxide, for which only one commercial plant remains active (Cuba). This is a pyro-hydrometallurgy approach.

The smelting processes used are generally very similar, using rotary kiln-electric furnace technology that is now quite well-proven, although some incidents have occurred with inability to achieve design production and/or poor furnace life due in part to engineering choices on power input, furnace sizing, etc. Because the nickel in laterite ores is in an oxidized state, reductive smelting is required, usually by carbon-based reductants. Moist laterite ore is dried, then treated below the ore melting point with reductants such as anthracite or petroleum coke in a rotary kiln to partially reduce (metallize) the nickel. The reduction is continued in the electric furnace where the ore is melted and metallic and slag portions tapped out separately. Ultimately the quantity of carbon reductants is similar to the quantity of coal burned for heat in the dryer and kiln – and many facilities also use coal-based electricity for the furnace. The result of carbon-based reduction, heat, and power is a high GHG footprint. FeNi has in the past been converted to nickel matte by sulfur injection and iron oxidation; this was commercially discontinued. The matte process has been revived and will allow the conversion of these iron-nickel alloys to higher-purity end products.

The sulfuric acid leaching is done primarily using high-pressure acid leaching (HPAL), but some small heap leaches have been trialed and this may become a growing approach for certain ore types. HPAL was first used in 1959 at Moa, Cuba, with later generations of facilities starting up in the late 1990s (Anaconda Nickel, Cawse, Bulong), 2000s (Coral Bay, Ravensthorpe) and 2010s (Goro, Ambatovy, Ramu, Taganito) and 2020s (Indonesian projects). Many of these facilities had extended ramp-up times and failed to achieve design capacity while others eventually achieved design rates after some years. It appears that the learnings from the Chinese-operated Ramu facility in Papua New Guinea have been leveraged to more success in the more recent projects in Indonesia, although long-term success has not yet been demonstrated.

Both matte and HPAL mixed intermediates can be processed to nickel metal for multiple uses, or processed to nickel sulphate for use in PCAM, or potentially to PCAM directly (Refining to PCAM in overall nickel industry diagram). The downstream processing end is changing quickly.

Other leaching methods have been proposed, including both nitric and hydrochloric, and there is no doubt they are technically feasible – the nickel will extract and it can be recovered. To date none of these methods have seen commercial acceptance, probably because with any new process the benefits need to be believed to outweigh the risks, which can be hard to quantify. With a history in the laterite business of new process facilities failing to achieve their design, all new processes tend to be viewed skeptically. The mining industry is conservative, and new process development and adoption is a long, difficult, and often unsuccessful journey.

ⁱ Old Nick's cursed metal; Spidle, K; CIM Magazine (2015)

ⁱⁱ Extractive Metallurgy of Nickel, Cobalt and Platinum-Group Metals, Crundwell et al; (2011) [610 pg]

ⁱⁱⁱ JOM World Nonferrous Smelter Survey Part III: Nickel: Laterite and Part IV: Nickel Sulfide; Warner et al; JOM (2006, 2007) [10 pg, 15 pg]

^{iv} Nickel Sulfide Smelting and Electrorefining Practice; Moskalyk and Alfantazi; Mineral Processing and Extractive Metallurgy Review, 23, (2002) [42 pg]

^v The Direct Leaching of Nickel Sulfide Flotation Concentrates – A Historic and State-of-the-Art Review Parts 1-3; Faris et al; Mineral Processing and Extractive Metallurgy Review, 43 (2022) [total 75 pg]

^{vi} Ullman's Encyclopedia of Industrial Chemistry – Nickel; Kerfoot; (2012) [66 pg]

^{vii} From Mine to Money-What Investors Need to Know About Nickel; MetSoc; 2021 (<https://metsoc.org/events-posts/value-chain-series-nickel/>)

^{viii} Mining Legacies website of the Mineral Policy Institute; <https://www.mininglegacies.org/mines/tas/avebury/>; see also Mallee Resources Avebury Mineral Resource Update, Jun 2023.

^{ix} Mineralogical Characterization of Sudbury Pyrrhotite Tailings: Evaluating the Bioleaching Potential; Duffy et al; COM 2015.

^x Strategizing Carbon-Neutral Mines: A Case for Pilot Projects; Power et al; Minerals 4, 399-436 (2014)

^{xi} CO₂ mineralization and concurrent utilization for nickel conversion from nickel silicates to nickel sulfides; Wang et al; Chem Eng Journal 406 (2021)

^{xii} <https://www.metso.com/portfolio/tankcell/>

^{xiii} The Application of High Intensity Flotation Technology at Mt Keith Nickel Concentrator; Hussey et al; MetPlant 2017.

^{xiv} Cu-Ni Processing Improvements at First Quantum's Kevitsa Mine; Musuku et al; Minerals Engineering (2015)

^{xv} Shakespeare Project Feasibility Study Technical Report; Table 22-7; Magna Mining Inc (2022)

^{xvi} Flowsheet Development, Commissioning, and start-up of the Voisey's Bay mill; Wells et al; CIM Journal 8 (2017)

Nickel Sulfide Processing – Another Reason It Is the Devil’s Metal

Part 2: Pyrometallurgy of Nickel Concentrate

Lyle Trytten - President, Trytten Consulting

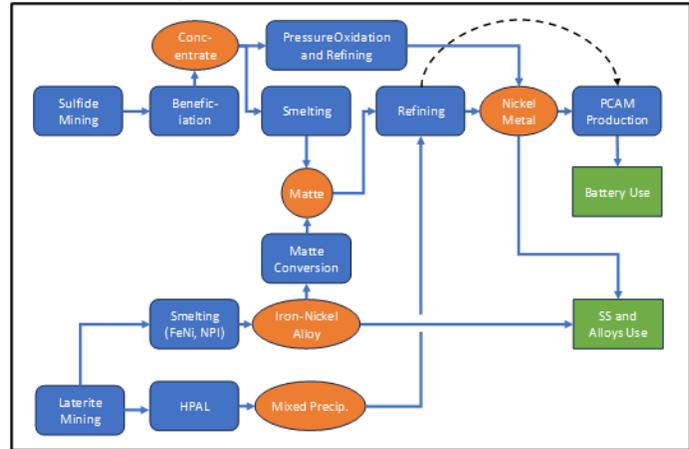
Dec 2023

Recap

Part 1 included a high-level overview of the nickel production industry, including laterite ores and sulfide ores, as well as a brief discussion on lateritic nickel processing and the start of the nickel sulfide processing chain - beneficiation. More detail of operational and potential processes is available in several publications, including Crundwell et alⁱ, Warner et alⁱⁱ, Moskalyk and Alfantaziⁱⁱⁱ, Faris et al^{iv}; and Kerfoot^v. The [author](#) has previously published white papers¹ on a number of nickel topics. A great video introduction to the nickel industry was compiled by the Metallurgical Society of the Canadian Institute of Mining in 2021^{vi}.

Summary information in this white paper is derived from these and many more sources as well as the author’s personal experience – which is much more hydrometallurgy than pyrometallurgy-based. There are many processes which have been suggested for nickel but never commercialized and go beyond the scope of this paper.

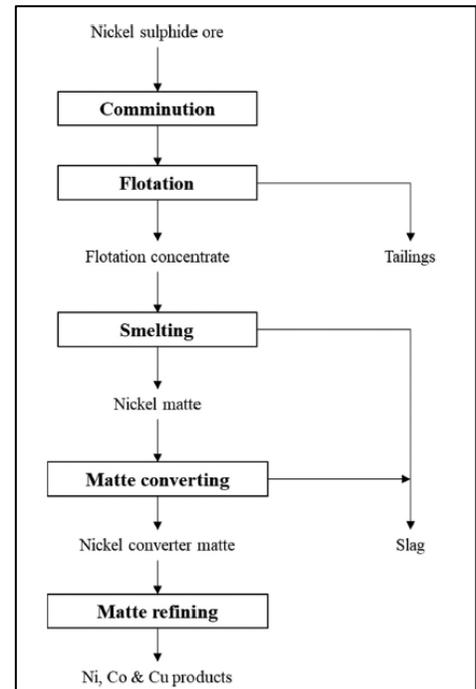
A high-level overview of the nickel production chain is shown right. A glossary is appended; elemental abbreviations are widely used in this white paper.



Smelting

Smelting is a process of melting the concentrate using embodied energy (released via sulfur oxidation) and added energy (largely electricity). The chemistry involved is controlled oxidation to oxidize most of the sulfur and convert it to SO₂ gas (which can be captured) while converting much of the Ni (and other value elements) to a metal form while leaving some in reduced sulfur mineral forms² that deport with the metallics as **matte**. The controlled oxidation is used to reject most of the iron to **slag** along with silicates and other gangue materials.

A generic concentration and smelting process is shown in the figure at right (Faris 2022). Primary processing can be by flash smelting (with elevated oxygen gas) or electric furnace smelting (with or without prior **roasting** to remove sulfur). In some cases, converting is bypassed by using a modified flash smelting approach (DON process), whereby most of the iron is reacted with oxygen and departs to slag in the smelting furnace and only a small amount is converted to metallic forms deporting to matte. Matte and slag are removed from the furnace in the molten state (>1000°C). Slag cleaning (via a separate electric furnace or a furnace section) is often employed on both smelter slag and converter slag to reduce the value metal losses; slag grinding and flotation has also been used. Smelter matte has an elevated iron content; converting is the process of rejecting additional iron to make a low-iron final matte, which is a sulfur-bearing product typically containing 40–70% Ni (with combined NiCuCo >70%), 0.5–5% Fe, 20–25% S, and varying PGE content. Nickel matte bulk composition (primarily Ni:Cu ratio) varies widely depending on the ore and beneficiation process.



¹ www.linkedin.com/in/lyle-trytten

² Sulfur occurs in a number of oxidation states. Fully reduced sulfur (sulfide, S²⁻) binds well with many metallic elements to form minerals such as pentlandite and pyrite. Elemental sulfur (S⁰, no charge) is the form seen in big yellow piles at oil and gas sites where it is removed before pipelining or combustion. Fully oxidized sulfur (S⁶⁺) is most commonly encountered as sulfate (SO₄²⁻) in materials such as gypsum drywall and Epsom salts.

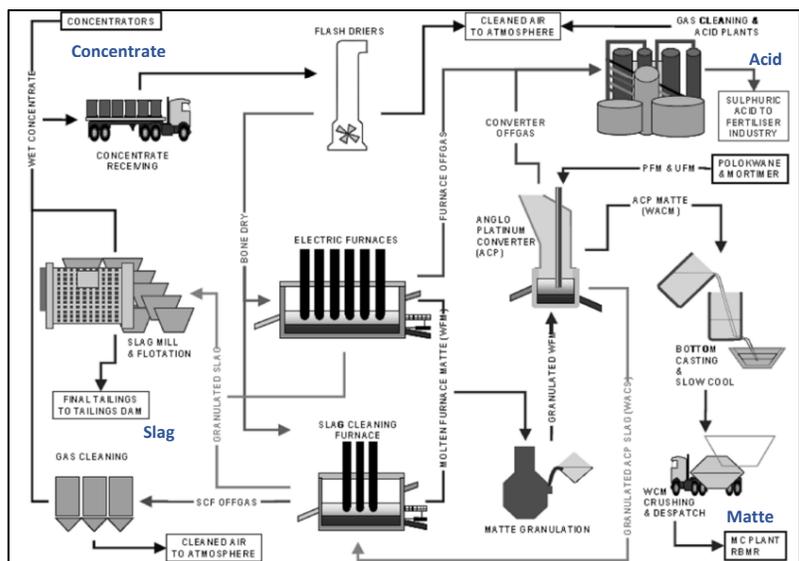
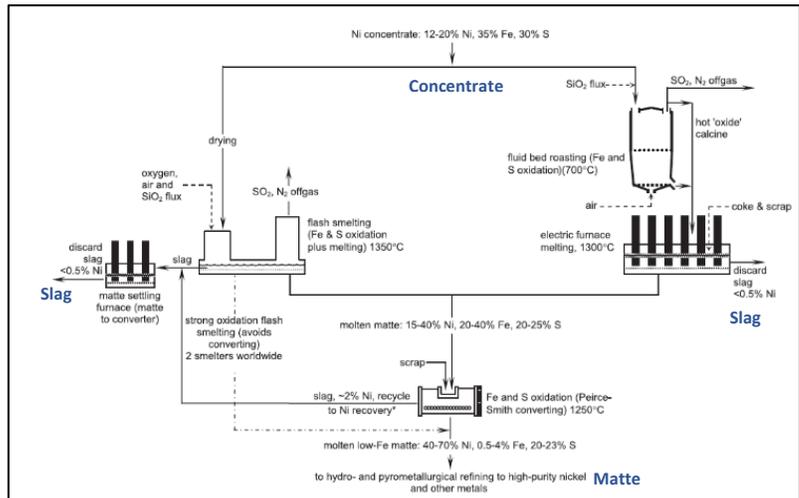
Faris does a good job summarizing the pros and cons of smelting. Some of the key points include:

- Generally a good method for dealing with the major impurities: S, Fe, NSG; S departs to smelter off-gas (SO₂) for recovery as sulfuric acid, NSG and most iron depart to slag. Slag may be a low-value byproduct.
- Smelters are excellent at recovering copper and PGE values, but not great at recovering cobalt (behaves more like iron)
- Smelters use flux materials (typically silica) and sometimes coal/coke (particularly in slag cleaning) to help control the furnace chemistry. Few other reagents are required (high-purity oxygen for flash smelters). Carbon-based electrodes are slowly consumed in the process, adding additional chemical reduction. Substantial amounts of electricity are required in electric furnace components.
- Today, a smelter is unlikely to be installed if there is no viable market for sulfuric acid produced from the SO₂. Canadian smelters without a viable route for sulfuric acid to market have closed. The world's largest single anthropogenic SO₂ source is a nickel smelter in Russia^{vii} (1.8 Mt/y, almost 3x the next largest facility). Capture of the majority of the SO₂ (from roaster and/or smelter gas) is reasonably straight-forward. Converter gas is more dilute and is more difficult to economically capture and process. This can influence technology/equipment selection.
- Smelters may struggle to deal with certain impurities such as arsenic and mercury which are easily volatilized.
- Smelter operating temperature is derived from the slag chemistry, which is influenced by the magnesium content of the feed (high-magnesium slags have higher melting points, requiring higher operating temperatures and power inputs). PGE smelters (typically smaller) often operate at >10% MgO, while most larger nickel smelters operate at <10% MgO (Warner).

Generic flowsheets for the major smelting techniques (flash smelting, roaster-electric furnace smelting) are shown at right (from Crundwell). There are different versions of both routes commercialized, but they represent the majority of nickel smelter production (such as Vale Sudbury, Glencore Sudbury, etc).

Some smaller facilities in the PGE industry (i.e. South African facilities) use electric furnace smelters without prior roasting, on concentrates that are comparatively low in sulfur (i.e. 5-10% rather than 20%+). This reduces the amount of sulfur dioxide (and therefore sulfuric acid) produced compared to a traditional nickel smelter. A flowsheet for the Anglo Platinum Waterval Smelter is shown right^{viii}. These facilities are often not included in nickel smelter information as their primary product by value is considered to be PGE, but the base metals content (nickel, copper) form the primary products by mass.

It is beyond the scope of the author's expertise and this white paper to discuss the specifics of the different roasting (i.e. fluid bed, traveling grate), smelting (i.e. Inco flash, Direct Outokumpo, conventional EF, Ausmelt), and converting (i.e. Peirce-Smith, top-blown rotary) operations. There are impacts on the requirements for air vs oxygen and the strength of SO₂ gas produced for recovery, the size and energy consumption of the equipment, the nickel and cobalt recovery, and other factors. A little knowledge is a dangerous thing!



Physical processes for matte treatment including slow-cooling (multiple days), crushing, grinding, and flotation and/or magnetic separation are used in some installations to obtain multiple matte-derived products, achieving further Ni-Cu-PGE separation and allowing separate refining steps. Where such processes are not used, molten matte is often granulated by spraying into water.

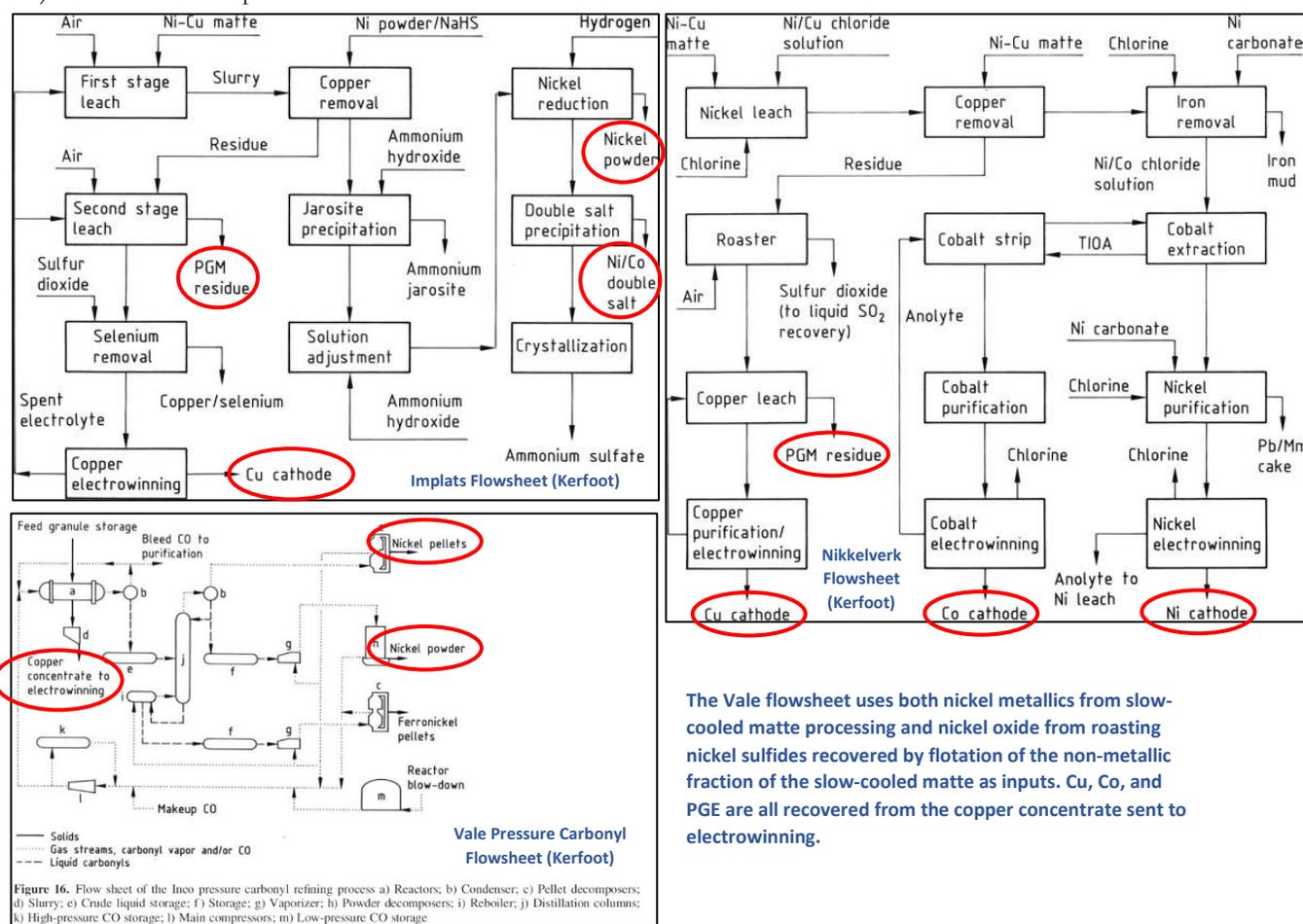
Refining

There are multiple methods used to chemically treat nickel matte for nickel recovery, including electrorefining from cast metallic/matte anodes (i.e. Nor-nickel), hydrochloric acid leaching (i.e. Glencore Nikkelverk, SMM Niihama), vapour carbonyl refining of metallized matte (i.e. Vale Sudbury), sulfuric acid leaching (i.e. Implats Springs), and ammoniacal leaching (i.e. BHP Kwinana). Nickel can be recovered from these processes as a vapour-deposited powder from the carbonyl process, as a solution-deposited powder via hydrogen reduction, or as solid metal from electrolytic processes. Nickel powders can be used in specialty processes or compacted and sintered to create easily handled materials that exhibit high dissolution rates. Solid metal products, which can be produced as full cathode sheets which are then cut or as smaller units by masking the cathodes, tend to have slow dissolution due to low surface area but are excellent for adding to melt furnaces for alloy production.

Cobalt and remaining copper are recovered by separation processes (solvent extraction or precipitation) in the acidic and ammoniacal sulfate and chlorine-based leaching systems. Copper is generally removed before nickel whether by SX or precipitation for separate residue treatment, but depending on the techniques and reagents employed, the cobalt can be recovered before or after nickel recovery. The nickel and byproduct departments are highlighted in the diagrams below.

PGE and gold deport to leach residues, and then are recovered by more intensive processing from those. The Implats and Stillwater base metals refineries (BMR), for example, reject a PGE-rich residue (up to 50% or more PGE) after the second stage leach, which is then sent to a precious metals refinery (PMR) for separation and recovery of the individual PGE.

The Implats sulfate leach (below left), Nikkelverk chloride leach (below right), and Vale pressure carbonyl flowsheets (bottom left) are shown as examples.



The Vale flowsheet uses both nickel metalics from slow-cooled matte processing and nickel oxide from roasting nickel sulfides recovered by flotation of the non-metallic fraction of the slow-cooled matte as inputs. Cu, Co, and PGE are all recovered from the copper concentrate sent to electrowinning.

Although all of these flowsheets work, there are a number of pros and cons related to the feed material, location, etc. The complexity of choices of downstream processing of matte derives from the widely varying concentrate, and subsequently matte, compositions, as well as locational issues. Some of these include:

- Sulfate-based processes (acid or ammonia) use oxygen to oxidize sulfur to sulfate, which can be produced as a byproduct (i.e. ammonium sulfate fertilizer). Oxygen is simple to make where electricity is readily available at an economic price (production takes 300-400 kWh/t O₂). This reduces total waste and adds a modicum of value. These processes can make less-stable residues depending on precipitation conditions, but are well-suited to restrictive effluent regimes as the sulfate is easily reduced in any effluent solution through precipitation techniques.
- Ammonia leaching has been a commercial process since its first incorporation for concentrate treatment by Sherritt Gordon Mines Ltd in 1954. The process uses more complex chemistry than some later processes for historic reasons. The process requires a significant amount of energy in the internal recycling of ammonia and needs an economic supply of ammonia – which might require a captive ammonia production plant running on low-cost natural gas for steam reforming.
- Chlorine leach processes are efficient (chlorine is a powerful oxidizer) and produce some of the highest purity nickel metal but pose a disposal challenge due to loss of chlorides to effluent solutions. These types of facilities are best suited for tidewater locations. Chlorine poses safety challenges; chlorides pose materials challenges. Washing sufficient chloride out of residues can impact the overall water balance and ability to dispose of residues.
- Vapour (carbonyl) refining produces high-quality products due to the unique aspects of metal carbonyl chemistry but uses particularly toxic materials^{ix} compared to other toxic gases encountered in metals processing such as chlorine and hydrogen sulfide. Addressing solids handling with toxic gases presents particular challenges.
- In general, sulfuric acid processes use more widely-understood chemistry, sulphuric acid processing being common to many metals. Chloride, ammonia, and carbonyl processes may be well-understood within portions of the nickel community but are less familiar to the broader metals industry and, relative to sulphate, present different processing challenges in terms of corrosion, toxicity of reagents, etc. while also presenting some opportunities for additional byproduct streams.

Choice of End Product

Converter matte is already a high-grade intermediate, so processing of matte is to a final nickel product destined for end use. Today, nickel matte is converted primarily into nickel cathode (electrolytic) and nickel powder (via hydrogen reduction or carbonyl processing). Some of this nickel powder has been then dissolved in sulfuric acid to make nickel sulfate, which can be transported and used to make PCAM. There is a viable route to PCAM more directly, though, using solvent extraction to recover high-purity nickel sulfate solutions from matte leaching, to make either nickel sulfate or use directly to make PCAM. This route is understood to be in use to a limited extent in China and could see wider adoption in future years should substantial additional matte become available on the global market. Using SX to remove minor impurities (i.e. Cu, Co, Zn) from the major constituent (Ni) is more straightforward than using SX to remove the major component (Ni) from the bulk solution.

Observations

Smelting of nickel concentrates is a well-established process but one with many different installation specifics. Smelting or roasting of other metals (i.e. copper, zinc) have more uniformity in their processing approach, which makes for easier conceptualization of the supply chain.

Smelting is an efficient way to deal with the major impurities in nickel concentrates: sulfur, iron, and silicates. However, sulfur capture and metals emissions remain points of concern that may make permitting of new smelting facilities challenging in many locations. Excellent gas cleaning and high rates of sulfur capture are minimum requirements for widespread social acceptance.

Refining of nickel matte recovers a very high proportion of all value metals, but flowsheets can be complicated. Like smelting, there is no single dominant approach. Chlorine leaching works well in some locations but may be ill-suited to inland refining locations. Sulfate leaching works but can result in larger solution quantities and more voluminous residues, but effluents are more easily treated.

With a fast-growing battery supply chain, the old paradigm of smelter (matte) to refinery (metal) to end use may not be appropriate for new facilities. Conversion of matte to sulfates or PCAM without going through metal may be more efficient, but making metal remains an extremely reliable method of purification – important for a battery industry with very stringent

specifications, and approved metal brands can be accepted for delivery to physical exchanges like the LME, offering a secondary market.

As we look forward to a largely decarbonized world – perhaps many decades away – there is likely to be a sulfur issue. Most sulfur is produced today from oil and gas treatment, and most sulfur is used in fertilizer production. Demand for sulfur is unlikely to decrease without major changes to the global population and agriculture industry, which could pose a late 21st century dilemma. The world may need much more sulfuric acid supply from the minerals industry in order to meet the needs. This could prove important for smelting routes, and for refining routes that produce fertilizer byproducts. It may be many decades away, but smelter and refinery lifespans are measured in decades and generally outlast the mines for which they may have been originally built.

Acknowledgments

Thank you to [Chris Martin](#) and [John Marsh](#) for helpful comments on drafts of this section. I have learned – and continue to learn - from many highly knowledgeable colleagues. The bulk of the information provided here is summarized from decades of work by many skilled people.

Glossary

CAM	cathode active material, the blend of nickel-cobalt-manganese oxides and lithium chemicals used to make batteries
Concentrate	an intermediate produced by beneficiation of a nickel ore to reject most of the impurities
EF	electric furnace
IDLH	Immediately Dangerous to Life and Health
Matte	a high-grade metallized intermediate material derived from smelting a sulfide concentrate
NSG	non-sulphide gangue, a mix of minerals typically in the silicate or carbonate families
OSHA	Occupational Safety and Health Administration (US)
PCAM	the blend of mixed metal (nickel-cobalt-manganese) hydroxides precipitated with specific purity and form to be used along with lithium chemicals in making CAM
PEL	Permissible Exposure Limit (may be time-weighted average or instantaneous)
PGE	Platinum-group elements (platinum, palladium, rhodium, ruthenium, iridium, osmium), all of which have high economic value
Roasting	A process of burning the sulfur out of concentrate with air at temperatures below the melting point of the solids
Slag	Waste material from smelting, largely comprised of silicates and iron oxides. Sometimes used for construction purposes.
Smelting	A process of melting minerals under controlled oxidation conditions to collect metals of interest into the matte phase and reject most mineral impurities to the slag phase.
SX	solvent extraction, a process for selectively extracting a specific metal ion from solution to be subsequently stripped out into a new solution

Disclaimer and Disclosure

This analysis is the author's current review and is intended to be indicative of the general state of the industry and potential future paths. Some suggested process routes have been left out of this discussion for the sake of brevity. All material is copyright Trytten Consulting Services. This material may be used and disseminated with credit to the author.

The author has previously worked for Sherritt International Corporation, a producer of nickel and cobalt from laterite resources and a developer of base metals processing technologies. The author's current business includes an ongoing consulting arrangement with Giga Metals which is developing the Turnagain nickel sulfide project, life-cycle analyses in the metals industry, and contribution to technology and project due diligence studies.

ⁱ Extractive Metallurgy of Nickel, Cobalt and Platinum-Group Metals, Crundwell et al; (2011) [610 pg]

ⁱⁱ JOM World Nonferrous Smelter Survey Part III: Nickel: Laterite and Part IV: Nickel Sulfide; Warner et al; JOM (2006, 2007) [10 pg, 15 pg]

ⁱⁱⁱ Nickel Sulfide Smelting and Electrowinning Practice; Moskalyk and Alfantazi; Mineral Processing and Extractive Metallurgy Review, 23, (2002) [42 pg]

^{iv} The Direct Leaching of Nickel Sulfide Flotation Concentrates – A Historic and State-of-the-Art Review Parts 1-3; Faris et al; Mineral Processing and Extractive Metallurgy Review, 43 (2022) [total 75 pg]

^v Ullman's Encyclopedia of Industrial Chemistry – Nickel; Kerfoot; (2012) [66 pg]

^{vi} From Mine to Money-What Investors Need to Know About Nickel; MetSoc; 2021 (<https://metsoc.org/events-posts/value-chain-series-nickel/>)

^{vii} Ranking the World's Sulfur Dioxide (SO₂) Hotspots: 2019-2020; Dahiya et al; CREA, Greenpeace; 2020.

^{viii} The smelting operations of Anglo American's platinum business: an update; Hundermark et al; Southern African Pyrometallurgy 2011

^{ix} Nickel carbonyl OSHA PEL, IDLH = 0.001, 2 ppm; chlorine OSHA PEL, IDLH = 1, 10 ppm; hydrogen sulphide OSHA PEL, IDLH = 20, 100 ppm

Nickel Sulfide Processing – Another Reason It Is the Devil’s Metal

Part 3: Hydrometallurgy of Nickel Sulfides

Lyle Trytten - President, Trytten Consulting

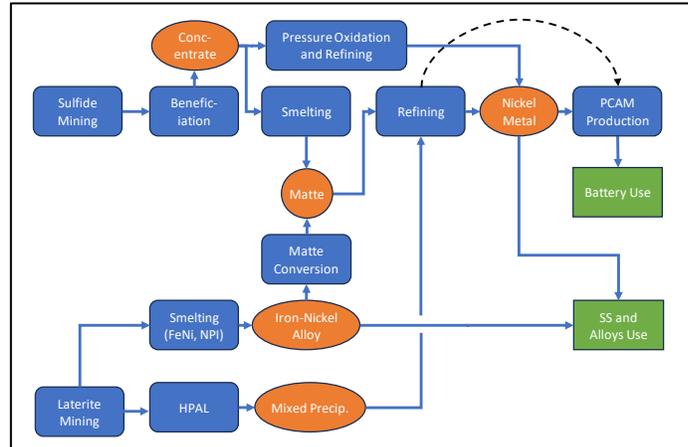
Dec 2023

Recap

Part 1 included a high-level overview of the nickel production industry, including laterite ores and sulfide ores, as well as a brief discussion on lateritic nickel processing and the start of the nickel sulfide processing chain - beneficiation. Part 2 covered smelting of nickel sulfide concentrates, and the various refining processes for the resulting nickel matte. More detail of operational and potential processes is available in several publications, including Crundwell et alⁱ, Warner et alⁱⁱ, Moskalyk and Alfantaziⁱⁱⁱ, Faris et al^{iv}; and Kerfoot^v. The author has previously published white papers¹ on a number of nickel topics. A great video introduction to the nickel industry was compiled by the Metallurgical Society of the Canadian Institute of Mining in 2021^{vi}.

Summary information in this white paper is derived from these and many more sources as well as the author’s personal experience. There are many processes which have been suggested for nickel but never commercialized and go beyond the scope of this paper.

A high-level overview of the nickel production chain is shown right. A glossary is appended; elemental abbreviations are widely used in this white paper.



Hydrometallurgical (Hydromet) Processing of Concentrates

Today there are 4 commercial facilities operating that were built to process nickel concentrates. Two earlier plants built in the USA (Garfield, Fredericktown) which used sulfuric acid pressure oxidation on Co-Ni mine concentrates have been closed since 1960. Good information on these facilities was presented by Berezowsky^{vii}. Currently operating plants include:

- The two ammonia leaching-hydrogen reduction facilities built using the Sherritt process producing Class 1 nickel
 - Fort Saskatchewan Canada (1954, currently processing mixed sulfides from the Moa Cuba laterite operations)
 - Kwinana Australia (1970, currently processing nickel matte from the Kalgoorlie smelter)
- Norilsk’s sulfuric acid leaching facility (1979) treating low-grade nickeliferous pyrrhotite concentrate (upgrading the concentrate for smelting, not producing a pure nickel product directly)
- Vale’s Long Harbour Canada chloride-assisted sulfuric acid pressure oxidation facility treating high-grade concentrate to produce Class 1 nickel from the Voisey’s Bay mine. This is the only facility currently leaching nickel concentrate to produce nickel metal.

A fifth facility using oxidative sulfuric acid leaching was operated by Outokumpo (HIKO) from the early 1990s to 2015 (Berezowsky, Faris) on a low-nickel high-magnesium concentrate from the Hitura Mine.

Current and Potential Direct Hydrometallurgical Flowsheets

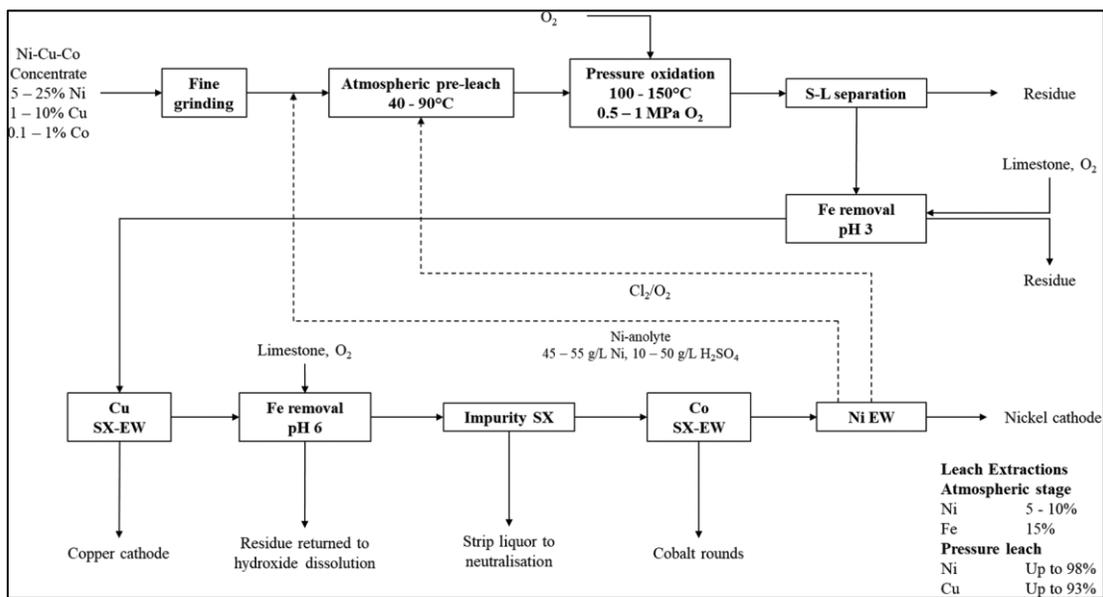
There are a number of flowsheets that have been tested for direct leaching of concentrates. The “best” flowsheet for the particular application is likely to depend on the specific attributes of the concentrate and various factors impacted by the location of the facility. There are a number of options for treating concentrates to get nickel into solution, and following that, a number of options for solution purification and metals recovery. In general, hydrometallurgical flowsheets offer better cobalt recovery but increased problems in PGE recovery compared to pyrometallurgical operations. A number of the options are identified below.

¹ www.linkedin.com/in/lyle-trytten

Sulfuric Acid Pressure Oxidation

There are three operating regimes for potential sulfuric acid pressure oxidation operations: low-temperature, medium-temperature, and high-temperature. These each have their pros and cons.

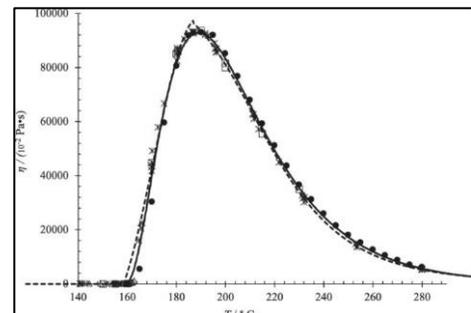
- **Low-temperature:** the operating regime is below the melting point of sulfur (118°C), typically 110°C, and the goal of the process is to oxidize sulfur primarily to the elemental form, with only necessary oxidation to sulfate for metals solubility. To enhance the reaction rate at low temperatures, fine grinding (in the range of 10 µm) is usually proposed. The basic principles have been known for decades, but no commercial operations constructed. A demonstration plant was operated at Tati Nickel in Botswana, but the commercial plant project was shelved in 2008.
- **Medium-temperature:** the operating regime is above the melting point of sulfur but in a range where substantial elemental sulfur production is expected, typically 150-160°C. Elemental sulfur is problematic, as it can coat sulfide particles and impede leaching rates. Additives are used to help manage molten elemental sulfur which exists as a second liquid phase, including organics and chloride (i.e. Long Harbour facility and processes piloted by CESL). Various levels of success have been demonstrated with different additives at controlling both elemental sulfur behaviour and the extent of oxidation of sulfur to sulfate. The Long Harbour flowsheet is presented below (Faris).



- **High-temperature:** the operating regime is designed to promote the full oxidation of sulfide to sulfate with no elemental sulfur production, typically 200-220°C. This eliminates the potential problems of elemental sulfur and the need for additives, operating in a similar fashion to the well-established refractory gold pressure oxidation industry.
- Claims as to process novelty and intellectual property have sometimes been overstated in this industry. Chloride addition is reported to have been patented in the early 1970s in Russia and has been tested in the West periodically since then. Fine grinding impacts have been known for at least as long; CANMET demonstrated low-temperature leaching of finely-ground concentrate in the 1970s. Berezowsky provides excellent coverage of historical developments.
- Copper and iron are well-known to be important solution components as they act as “transfer agents” for the oxygen to the particle surface. Leaching in the absence of Cu/Fe is generally slow.

Some of the many challenges and differences between these are identified below:

- Elemental sulfur can be problematic. Sulfur has unique physical properties (i.e. viscosity-temperature curve at right^{viii}) that must be considered if it is produced, including phase transitions. Elemental sulfur can lead to difficulties with solid-liquid separation and complicates the recovery of PGE which deport largely to leach residues. Sulfur and remnant sulfides may be floated off in some circumstances, leading to a sulfur-sulfide concentrate with PGEs that could then be separated by melting the sulfur and creating a PGE-



sulfide concentrate for smelting, but the circuit is challenging. The HBMS zinc pressure leach at Flin Flon ran such a circuit for gold recovery in the early 1990s^{ix}.

- Producing sulfur instead of sulfate may be of economic value in a high-sulfur concentrate, as less oxygen is required. Producing sulfate may be required for concentrates which are well-balanced in sulfur:metals ratio, especially with sulfur-consuming NSG minerals. Producing sulfate may be of value where it can be sold as a byproduct (i.e. ammonium sulfate fertilizer).
- Mineralogy matters. Each sulfide mineral has its own oxidation behaviour. Pentlandite bears some similarities to pyrrhotite and sphalerite; pyrite behaves very differently. Other nickel minerals such as heazlewoodite and millerite have not been extensively tested.
- Some concentrates are sulfur-deficient and will require acid addition to solubilize the metals at high extractions. In general, high extraction of Mg, Ni, Cu, Co is anticipated. At lower operating temperatures, and in less oxidizing environments, a greater proportion of iron is expected to remain in solution. Iron is most easily handled as a ferric oxyhydroxide precipitate in the autoclave residue. Processes which use lower oxidation potential (i.e. produce elemental sulfur) may produce more iron in solution which is harder to remove. Some iron precipitates – like jarosite – can drag sulfate into the residue where it can pose additional stability problems; ferric hydroxides precipitated at ambient conditions can have very challenging solid-liquid separation behaviour.
- Temperature and pressure are related. Higher temperatures require higher pressures due to the increased vapour pressure of water. Oxygen partial pressures of 500 to 700 kPa are common. The addition of the water vapour pressure adds 40 kPag at 110°C, 375 kPag at 150°C, and 1800 kPag at 210°C. Depending on the form (purity) of oxygen addition, nitrogen pressure may also be significant. Cryogenic oxygen is usually preferred to minimize nitrogen partial pressure. Oxygen utilization from a cryogenic source is typically considered around 85%, lower for lesser purity due to the inerts purge. Oxygen recovery from vent gases has been proposed in refractory gold pressure oxidation^x where carbonates generate significant inert CO₂, but economics of oxygen recycle in a nickel system where nitrogen is the only inert component are expected to be challenging.
- Fine grinding is power-intensive, but resulting lower-pressure operation can reduce equipment cost and complexity.
- Materials of construction for higher-temperature oxidizing acidic environments can be challenging. Chloride and chlorine complicate materials choices significantly.
- Operating with molten sulfur (medium temperature) is similar to zinc pressure leaching, which has been used commercially since the early 1980s. A cautionary note: some sulfide pressure leach facilities have had problems at some point with agglomeration of elemental sulfur and sulfide solids, sometimes leading to “thermal runaway events” inside process equipment. This can be very problematic when titanium internals are required.
- In a hydrometallurgical facility, managing water balance is always critical. Depending on location and chemistry, liquid effluent may be difficult to dispose. Tide-water locations can simplify effluent disposal (permit-specific).
- Managing the energy balance is important – oxidizing sulfur (to elemental or sulfate) releases energy, more for sulfate and less for elemental. Operating at higher temperatures can simplify energy and water balance management by rejecting heat as waste steam from a flash tank and recycling cooled slurry or solution. Operating at low temperatures can require substantial cooling depending on the concentrate characteristics. There are various internal and external cooling methods, all of which have their issues relating to erosion, corrosion, fouling, etc. The presence of molten elemental sulfur can provide additional challenges in cooling applications.

Pressure Oxidation – Other Acids

Hydrochloric acid has been promoted (HydroNic, described briefly in Faris) and shares benefits and drawbacks with hydrochloric acid leaching of matte. In the case of concentrate, with higher levels of impurities and lower payable metals grades, issues of chloride loss to residues will be larger, and water balance and effluent challenges will likely be larger. The use of a combined non-oxidative/oxidative two-step leach process bears similarities to the Nikkelverk flowsheet.

Nitric acid and mixed sulfuric-nitric acid leaching has been proposed, but not commercialized for nickel concentrates. Nitric acid is a strong oxidant and poses a set of interesting challenges related to its particular behaviour – nitric acid has been implicated in a number of safety incidents in other applications where it can decompose with explosive tendencies. Separating sulfates and nitrates in solution is challenging where required. Recovering high-purity nickel products from nitric solutions is likely to be a

challenge but may not be insurmountable. The Sunshine Refinery in Idaho used a batch nitric-catalyzed sulfuric acid oxidation process to treat a highly reactive silver-containing copper concentrate material (Berezowsky).

Ammonia Pressure Leaching

The ammonia pressure leach developed by Sherritt Gordon Mines Ltd (based on work by Dr Frank Forward of University of British Columbia) was first implemented in 1954. The technology is well-documented in numerous publications (Kerfoot has a good description) and uses the differential solubility of multiple ammine² complexes of base metals in sulfate solutions to effect separations that would today likely be done by solvent extraction in a sulfuric acid environment. The chemistry of sulfur is more complex in the ammonia environment, with multiple sulfur oxidation states such as thiosulfate possible. This adds complexity over the acid system where sulfate tends to be the single stable form at normal operating conditions. As well, the presence of high levels of ammonia in solution creates safety and hygiene issues and precludes the use of common techniques such as flash discharge from autoclaves to manage water balance issues.

Biohydrometallurgical Processing of Concentrates

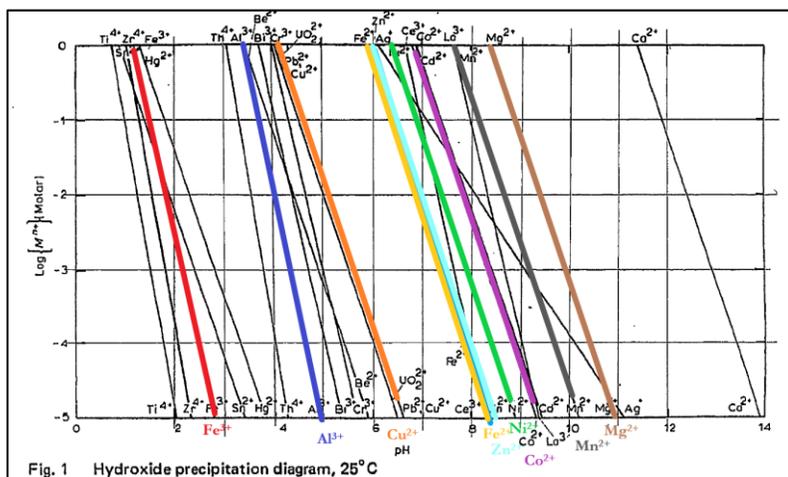
Bioleaching of nickel concentrates is typically considered using sulfate media. At least two facilities have been constructed to process nickel sulfide concentrates with high arsenic levels produced as byproducts from mines in Finland and Australia (Faris), producing upgraded intermediates for further processing. Arsenic is a particularly problematic element for smelters, so bioleaching has been demonstrated to be economically feasible – at least some of the time. Bioleaching takes place at temperatures well below the melting point of sulfur (45-55°C), and therefore these facilities have increased issues of slow reaction time and necessary heat removal compared to the low-temperature sulfuric acid leaching noted above. Reaction rates are slow, with retention times on the order of several days. Judicious choice of operating conditions can influence the extent of extraction of certain impurities.

The bioheapleach approach of Terrafame (formerly Talvivaara) is a unique application. The high-sulfur zinc-nickel-copper black schist ore is resistant to standard beneficiation since substantial amounts of nickel are in low-grade minerals posing significant grade-recovery challenges (33% of Ni in pyrrhotite). The use of bioheapleaching in a northern climate works due to the substantial heat generated due to the high sulfide content of the ores. A low-sulfur ore may not be as successful in winter operation. The process features sequential sulfide precipitation of copper, zinc, and nickel+cobalt from the low-grade solutions^{xi}. However, there have been environmental concerns raised related to the project and leaks of contaminated solutions^{xii}. Uranium byproduct recovery was investigated and is now planned for 2024.

Acidic Leach Solution Purification

Hydrometallurgical acid leach solutions have a low pH with multiple metals dissolved, and a total metals concentration in the range of 70-120 g/L. Typical practice sees a first stage of neutralization to remove acid and iron (often with air addition to oxidize ferrous to ferric) followed by either recovery of a mixed metal intermediate or by sequential solvent extraction to remove copper and cobalt. Certain impurities can also be removed by neutralization, as shown in the hydroxide precipitation diagram at right (author, from Monhemius^{xiii}).

The order of operations in solvent extraction will depend on the reagent selected; Cyanex 272 is common for Ni-Co separation, but not the only choice. A typical SX isotherm (for Cyanex 272) is given overleaf^{xiv}. The order of extraction is often written out algebraically as follows.
 $Fe^{3+} > Zn^{2+} > Cu^{2+} > Co^{2+} > Mg^{2+} > Ca^{2+} > Ni^{2+}$



Manganese and zinc can be problem elements but are typically low in sulfide concentrates and dealt with by differential extraction and/or stripping and precipitation as a waste or low-value byproduct. Cadmium is likewise an infrequent contaminant.

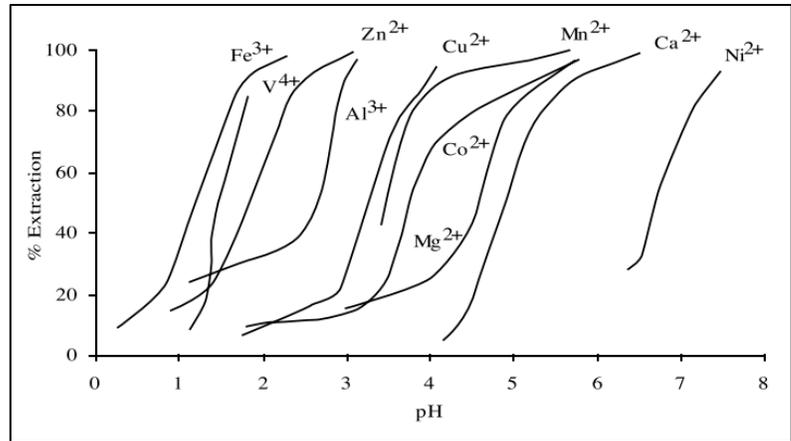
² Ammines are co-ordination compounds with metals and molecular ammonia, such as nickel hexammine or copper tetrammine

Magnesium, which can be high in concentrates derived from ultramafic ores, can be problematic depending on flowsheet selection.

Copper is often extracted with a different reagent prior to Cyanex 272 separation of Ni and Co. Copper can be stripped from SX systems and electrowon as cathode or precipitated as an intermediate byproduct. Cobalt can be recovered as a metal using similar recovery systems to nickel – electrowinning or hydrogen reduction.

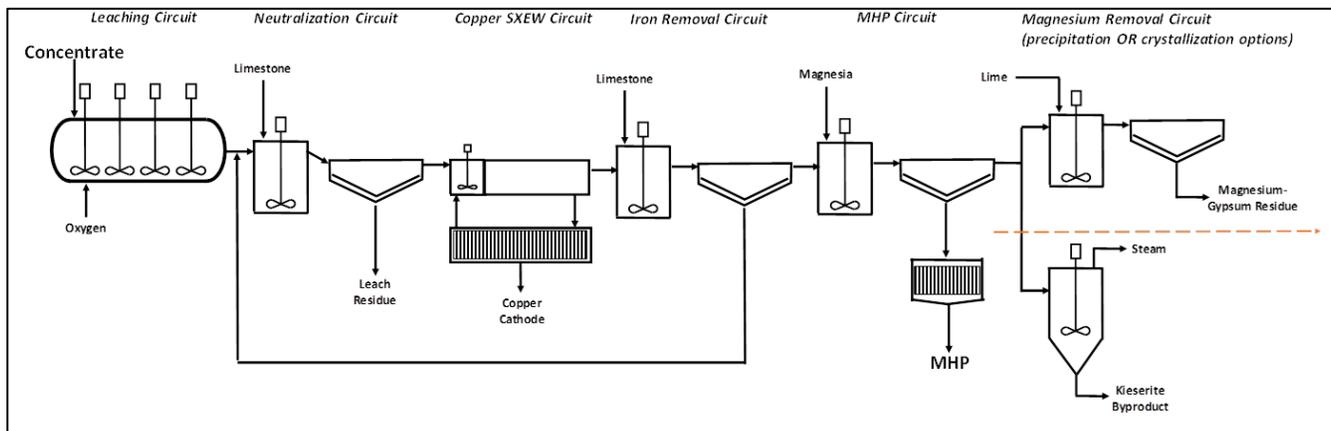
Choice of End Product

Direct nickel concentrate leaching can be conducted to a number of endpoints. There is no best answer: location, grade, and overall supply chain integration are important factors. Berezowsky gives a good list of recovery options for nickel and cobalt for acid solutions.



- Precipitation of a higher-grade, lower-impurity intermediate for refining elsewhere (i.e. mixed hydroxides, mixed sulfides, mixed carbonates). MHP will be ~20% Ni as transported, MSP at ~50% Ni as transported.
- Recovery of Class 1 nickel (powder/briquette or cathode)
- SX of nickel followed by recovery of high-purity nickel sulfate solid (~22% Ni) for transport to make PCAM or direct production of PCAM from SX strip solutions

A simplified example flowsheet for producing an intermediate MHP is shown below, with magnesium removal as waste or byproduct following MHP recovery. MHP recovery circuits typically use two stages, a first stage with magnesia to produce a higher-purity product, then a second stage with lime to strip all value metals and recycle the residue back into the circuit to improve overall recovery.



Observations

Hydromet processing is best suited to concentrates with low levels of PGE. The recovery of PGE from leach residues is more complicated and expensive than recovery from smelter matte, however some processes (Kell, Platsol) have been promoted as being able to solve this problem. Commercialization may – or may not - come in due course.

Hydromet processing is more flexible than smelting (can handle some impurities better than smelters) and is expected to be economic on a smaller scale than smelting. Hydromet can produce sulfur as an elemental form for disposal, or as a sulfate for disposal or byproduct sale. Hydromet residues are more voluminous and less stable than smelting residues. Hydromet can be a good choice for locations where the production of sulfuric acid is not viable.

Ammonia leaching is well proven from its near 70 years of operation but is not a likely future route due to environmental challenges of ammonia-contaminated leach residues and higher flowsheet complexity and operating costs due to internal recycle of weak ammonia streams.

Sulfuric acid-based processing may be inherently less efficient than some other routes, but has significant advantages in the simplicity of operations, the well-understood chemistry, and the ability to use oxygen to generate the necessary reagent and dispose of excess sulfate using lime precipitation to make gypsum. Sulfate anions are generally not environmentally hazardous, and residue disposal can therefore be less problematic than using more hazardous anions like chloride and nitrate.

Multiple temperature routes are available to operate in the sulfate space, but medium-temperature leaching requires specialized additives that may create effluent disposal challenges in some locations and poses some different hazards than the other routes. Substantial work has been done on low-cost additives that are more benign, but none have been commercialized.

There is no clear preferred route; the author's bias is towards the chemical simplicity of high-temperature sulphate-based pressure oxidation but low-temperature oxidation is technically viable as well and medium-temperature is in operation today.

Choice of downstream processing flowsheet, byproduct recovery forms, and product forms is dependent on multiple considerations, including feed concentrate properties (byproduct concentrations, sulfur content, contaminant levels), facility location (solid waste disposal, effluent disposal, power costs, skilled labour availability), ability to integrate with supply chain partners, especially if integration into a full battery supply chain is desired.

Running a high-temperature pressure oxidation circuit with simple downstream processing has been proven successful in many jurisdictions in the gold industry. Running a high-purity chemical separations circuit for multiple products demands a higher level of skills than may be readily available in some locations – full installation at a remote mine site may lead to long-term operational difficulties.

Today, smelting is the *de facto* treatment method for sulfide concentrates. Hydrometallurgical treatment is a viable alternative, but significant piloting should be anticipated. Hydrometallurgy is more easily modeled than mineral processing, and well-constructed models operated by knowledgeable specialists can be used to gain a significant depth of understanding for trade-off studies. Following batch testing, continuous piloting of unit operations and eventually the whole flowsheet is required. Any facility incorporating significant recycle would be wise to have extended fully-integrated piloting due to the potential for buildup of impurities. Larger-scale demonstration plants are often not required, as the chemical aspects are well demonstrated at a small scale. Materials handling aspects need to be addressed by experts but may not require large-scale demonstration.

Acknowledgments

Thank you to [Chris Martin](#) and [John Marsh](#) for helpful comments on drafts of this section. I have learned – and continue to learn - from many highly knowledgeable colleagues. The bulk of the information provided here is summarized from decades of work by many skilled people.

Glossary

CAM	cathode active material, the blend of nickel-cobalt-manganese oxides and lithium chemicals used to make batteries
Concentrate	an intermediate produced by beneficiation of a nickel ore to reject most of the impurities
Matte	a high-grade metallized intermediate material derived from smelting a sulfide concentrate or converting iron-nickel alloys with sulfur addition
MHP	mixed hydroxide precipitate, a nickel intermediate typically ~40% nickel with ~50% moisture
MSP	mixed sulfide precipitate, a nickel intermediate typically ~55% nickel with ~10% moisture
NSG	non-sulfide gangue, a mix of minerals typically in the silicate or carbonate families
PCAM	the blend of mixed metal (nickel-cobalt-manganese) hydroxides precipitated with specific purity and form to be used along with lithium chemicals in making CAM
PGE	platinum-group elements (platinum, palladium, rhodium, ruthenium, iridium, osmium), all of which have high economic value
SX	solvent extraction, a process for selectively extracting a specific metal ion from solution to be subsequently stripped out into a new solution

Disclaimer and Disclosure

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ⁱ Extractive Metallurgy of Nickel, Cobalt and Platinum-Group Metals, Crundwell et al; (2011) [610 pg]

ⁱⁱ JOM World Nonferrous Smelter Survey Part III: Nickel: Laterite and Part IV: Nickel Sulfide; Warner et al; JOM (2006, 2007) [10 pg, 15 pg]

ⁱⁱⁱ Nickel Sulfide Smelting and Electrorefining Practice; Moskalyk and Alfantazi; Mineral Processing and Extractive Metallurgy Review, 23, (2002) [42 pg]

^{iv} The Direct Leaching of Nickel Sulfide Flotation Concentrates – A Historic and State-of-the-Art Review Parts 1-3; Faris et al; Mineral Processing and Extractive Metallurgy Review, 43 (2022) [total 75 pg]

^v Ullman's Encyclopedia of Industrial Chemistry – Nickel; Kerfoot; (2012) [66 pg]

^{vi} From Mine to Money-What Investors Need to Know About Nickel; MetSoc; 2021 (<https://metsoc.org/events-posts/value-chain-series-nickel/>)

^{vii} The pressure acid leaching of nickel sulfide concentrates; Berezowsky, R; TMS 129th Annual Meeting. Nashville, TN (2000) [32 pg]

^{viii} The rheology of liquid elemental sulfur across the λ -transition; Sofekun et al; Journal of Rheology; 2018.

^{ix} Operation of the Sherritt Zinc Pressure Leach Process at the HBMS Refinery: The First 15 Months; Collins et al; Proceedings of Zinc and Lead 1995.

^x The Development and Implementation of a Pressure Oxidation Flowsheet for the Getchell Mine; Wicker and Cole; Proceedings of the Gold 90 Symposium; SME; 1990

^{xi} Talvivaara Sotkamo Mine – Bioheapleaching of a Polymetallic Nickel Ore in Subarctic Conditions; Riekkola-Vanhanen; ALTA 2011

^{xii} Multiple mining impacts induce widespread changes in ecosystem dynamics in a boreal lake; Leppänen et al; Sci Rep 7, 10581 (2017).

^{xiii} Precipitation diagrams for metal hydroxides, sulfides, arsenates, and phosphates; Monhemius, A.J.; Trans IMM vol 86; December 1977

^{xiv} Separation of Cobalt and Nickel using CYANEX 272 for Solvent Extraction; Kihlblom, C; M.Sc. Thesis; KTH, School of Engineering Sciences in Chemistry, Biotechnology and Health (CBH); 2021.

Nickel Sulfide Processing – Another Reason It Is the Devil’s Metal

Part 4: Observations and Conclusions

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Jan 2024

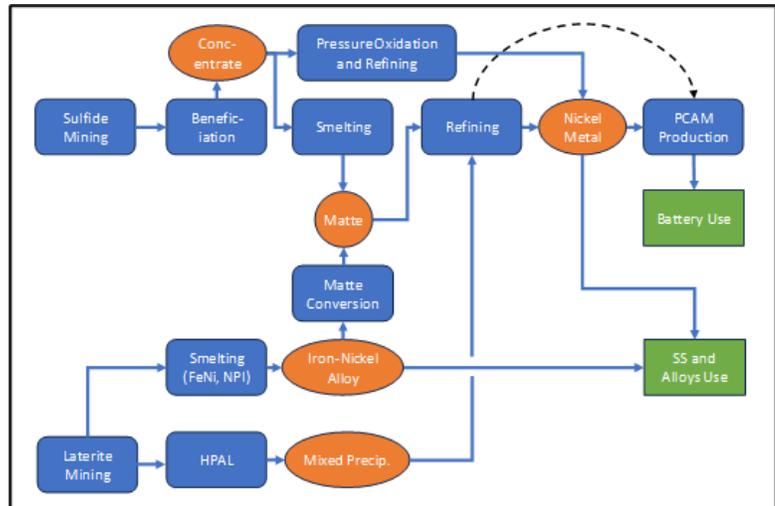
Recap

Parts 1 through 3 of this series discussed current processing methods for nickel sulfides, including beneficiation to produce nickel concentrate, pyrometallurgical treatment of concentrate (including various refining methods), and hydrometallurgical treatment of concentrate, and presented a number of observations along the way.

What’s left? Some discussion of the likelihood of innovative processing techniques in the different areas, and some wrap-up conclusions about what I see as likely paths forward for the industry. I have changed the voice for this part as it relies much more on my experience to develop views of what is likely going forward. Sorry, not much for pretty pictures in this last part of the series!

Summary information in this white paper is derived from the sources quoted in the first three parts (and many more) as well as my personal experience.

A high-level overview of the nickel production chain is shown right. A glossary is appended; elemental abbreviations are widely used in this white paper.



Observations

The nickel industry has tended towards significant specialization – customized flowsheets for different feed materials. There may be no two nickel sulfide beneficiation operations which are identical, due to ore differences (grain size, co-products, gangue mineralogy, age of operations, etc.). Indeed, nickel sulfide concentrator design and operation often changes over time as the ore changes. This aspect is not unique to nickel processing, but it may become more significant in coming years if ore feeds at new (or existing) operations become more variable.

There also may also be no two full processing flowsheets for nickel sulfide concentrates that are identical. This is in stark contrast to the trend in nickel laterite processing of late (NPI, HPAL facilities being built in a standardized fashion) and the standard practice for many other metals such as copper (fairly standard beneficiation-smelting approaches for sulfide ores and heap leach-SX-EW approaches for oxide ores, with some heap leaching of sulfide ores), zinc (global dominance of roast-leach-EW process with a minor set of zinc pressure leach facilities), and aluminum (global dominance of Bayer-Hall/Heroult process).

The dominance of single processing routes for these metals derives from the chemical similarities of global feeds; the common range of specifications for copper and zinc sulfide concentrates is much lower than the common range for nickel sulfide concentrates, in value mineral, byproducts, and gangue. Even so, the nickel industry may be served well by more standardizing of processes – with a possible consequent hit in energy efficiency and/or metals recovery – for the sake of having a consistent industry approach. The dominance of the nickel sulfide industry by several large players with relatively little free global trade in concentrates may act against commonality of approaches, though, compared to copper and zinc where global concentrate trade between miners and processors is common, and where individual smelters may process many different feeds over a relatively short time period.

As industry practitioners, we need to think about the true value proposition of trying to get what is – on paper – the most efficient operation, but which may turn out to be more difficult to build, operate, and maintain than an operation which is similar to many others. Standardizing process design, equipment design, etc could lead to increased mobility of personnel, increased ramp-up speed, uptime, and other benefits. There is much space for debate on this topic, so ***please add your voice in the comments!***

Pyromet

Smelting is an efficient means of treating nickel concentrates and is particularly applicable to concentrates with good to high PGE values and those with a high sulfur:metals ratio (i.e. S:(Ni+Cu+Co) indicating significant excess sulfide minerals like iron sulfides) since that sulfur is energy and can be converted into sulfuric acid byproduct. High-oxidation smelting without converting will require slag cleaning to improve recovery, but this is commercially demonstrated as are processes using lower oxidation with converters.

Smelting produces matte which must be refined. Three very different approaches to refining matte are in use in the world – chloride leaching, sulfate leaching, and carbonyl vapour refining. I cannot answer which is best, as there are many considerations. I would not consider chloride leaching for an inland location due to the challenges of effluent disposal, but the process does make great dense electrolytic product, excellent feed for high-nickel alloy production. Carbonyl refining, which as a global technology has few installations, has some unique attributes including making excellent high-purity powders, which may be well-suited to rapid dissolution. Sulfate refining has attributes that may suit it better to inland locations where managing the water balance is a challenge and effluent disposal is highly regulated – as it should be everywhere.

Permitting new nickel smelters is expected to be more difficult than hydrometallurgical facilities due to the actual or perceived environmental impacts – principally air emissions – that have plagued historic operations. Permitting a matte hydrometallurgical refinery is expected to be easier than a concentrate refinery due to a substantial reduction in solid wastes (leach residues, neutralization residues).

For a future in which the growth for sulfide materials appears highly linked to the battery materials space (considering that most stainless steel production will remain rooted in ferronickel and NPI feeds), production of actual metal product may no longer be desired. Making metal then re-dissolving it to make battery materials is an expensive route. Conversely, making metal does add an inherent purification step that could be critically important. What may be more likely is the development of direct matte processing to battery materials (i.e. PCAM directly or via nickel sulfate production). It is possible that a standardization of the downstream battery supply chain on the MHP → PCAM route may lead to matte processing to MHP to enter the battery supply chain. This feels like a step backwards with addition of additional reagents and energy and extra shipping costs/impacts, but it may become the easier approach than developing a full new PCAM supply chain in parallel to an MHP-based one.

Hydromet

Hydrometallurgical processing of sulfide concentrates is best suited to concentrates with low levels of PGE. The recovery of PGE from leach residues is more complicated and expensive than recovery from smelter matte. Hydromet processing is more flexible on some impurities (like arsenic which can be precipitated as a reasonably stable form such as scorodite) and is expected to be economic on a smaller scale than smelting.

Hydromet can produce the mineralized sulfur as an elemental form (S⁰) for disposal/storage/sale, or as a solid or liquid sulfate for disposal or byproduct sale. Hydromet residues are more voluminous and less chemically stable than smelter slag, being precipitated near ambient conditions. Elemental sulfur may be challenging to consider as a byproduct as it can be difficult to separate effectively from other residues and can contain impurities (i.e. selenium, mercury, arsenic) that are not desired in the dominant use case – fertilizer production. Solid recovered sulfur can be stored above ground for long periods, as is done in the oil and gas industry, but there is a cost and maintenance aspect. Sulfur recovery including melting and filtration has been demonstrated in zinc pressure leaching but nickel is expected to be more challenging since sphalerite has a greater tendency to produce elemental sulfur product than does pentlandite. There may be sulfur uses (such as HPAL sulfur-burning acid plants) where minor chemical impurities are less of a concern, but chemical rather than physical purification of elemental sulfur is difficult (as demonstrated in the 1950s).

Sulfuric acid-based processing may be inherently less “efficient” than some other routes but has significant advantages in the simplicity and safety of operations (can run without highly toxic gaseous materials), the well-understood chemistry, and the ability to use oxygen to generate the necessary reagent. Sulfuric routes also allow disposal of excess sulfate using lime precipitation to make gypsum. Sulfate is stable and one of the least toxic anions, and residue disposal can therefore be less problematic than using more environmentally hazardous anions like chloride and nitrate.

Multiple temperature routes are available to operate in the sulfate space, but medium-temperature leaching requires specialized additives (i.e. chlorides, organics) that may create operating and effluent disposal challenges and poses some different hazards than the other routes. There is no clear preferred route; my bias is towards the chemical simplicity of high-temperature pressure oxidation but medium-temperature with additives and low-temperature oxidation with fine grinding (<20 µm) are technically viable as well. Potential difficulties with liquid-solid separation in the low-temperature and medium-temperature routes need to

be considered – the physical formation of the precipitated materials and the sulfur can be a challenge. Managing the heat balance is also challenging in trying to keep temperatures down with relatively high sulfur grades.

New Technologies

In the smelting area, there seems little appetite to develop any truly new technology. The principles are well-known, and flash smelting or roaster-smelting could equally be used. Necessary high rates of sulfur dioxide capture lead to a preference towards oxygen enrichment rather than ambient air use. Equipment innovations have occurred (i.e. Ausmelt top submerged lance) in some industry segments that have spread to nickel concentrate smelting, and these may continue or expand usage in the nickel business, but they do not fundamentally alter the process. There may be some innovation around gas handling, acid production, carbon reduction, energy integration, etc – perhaps important, but not fundamental changes.

In the less-developed hydromet space, there seems to be more discussion of alternate routes to what has been successfully commercially operated to date – ammonia pressure leaching (Sherritt, Kwinana) and medium-temperature chloride-enhanced pressure leaching (Vale Long Harbour). Alternative lixivants (chloride, nitric, etc) and alternative process conditions (low-temperature, high-temperature) have seen substantial study. But the mining industry is very conservative in adopting new technology. High-temperature sulfate leaching as is used in the gold industry is less of a step-out than changing to a new and commercially unproven reagent.

Precipitation from sulfate solution as a hydroxide, sulfide, or basic nickel carbonate and SX of impurities away from nickel are considered commercially-proven technology. Other recovery methods like ion exchange are proven in certain applications – like boiler feed water purification and stripping low levels of metals from waste solutions – but are not yet well-proven for bulk metals recovery. Solvent extraction of nickel out of solution as a bulk concentration and purification technique has a spotty record. Even if there are significant paper advantages to the use of an alternative lixiviant or recovery system, the hesitation is understandable due to nickel's challenging production history.

Nickel has a reputation as a destroyer of company value due to the many operations that have struggled for years to make commercial rates (i.e. laterite HPAL in Australia, Madagascar, New Caledonia, Long Harbour sulfide refinery) and sulfide mines that have struggled to maintain operations in challenging economic times (Panoramic with its Savannah mine being a recent example). The nickel business is one in which pricing is often well into the cost curve – i.e. some of the producers are operating at a loss on the cash cost of production before accounting for non-cash costs like capital depreciation. These facilities continue to operate because they are strategically or politically important, or the cost of suspension or closure is considered to be less than suffering the ongoing operating losses while maintaining the many supply chain and labour relationships.

Because of the business risk within the industry with even known technologies, the addition of technical risk is very challenging. However, with the advent of the importance of the battery supply chain and some disruption to the last 30 years of globalization with the renewal of geopolitical tensions and subsequent efforts at protecting supply chains (i.e. ally-shoring, friend-shoring, re-localizing production), there is room for hope in the industry.

The nickel industry is seen as critically important in North America and Europe. Government support for new technology development AND project development is becoming significant. The ability to share risk with civil society, and the push to adopt less-polluting technologies, may bring forward new technology adoption. Certainly there is renewed interest in nickel sulfides, especially those with strong ESG credentials, even at a time when massive development of Indonesian laterites is depressing the nickel market. Among those strong ESG credentials is a low carbon footprint for a number of operations and projects, where low-carbon electricity combined with the energy value inherent in sulfide concentrates is reducing overall GHG footprint.

A significant bonus is that a number of these projects are in host rocks that are naturally reactive with carbon dioxide in the atmosphere, sequestering it permanently by the creation of new carbonate minerals. How much atmospheric carbon dioxide can be sequestered with rational operations is an open question, but it is non-zero.

There is potential to sequester large amounts through intensive carbonation techniques involving some combination of pure CO₂, high pressure and/or temperature, and activated minerals, but the added capital and operating cost may not be worthwhile. Credits for sequestered CO₂ are an interesting area in two aspects. For sequestration from atmosphere by tailings reactivity, is there “additionality”? Some of these projects may not proceed without valorization of the credits, so this is an important question. For intensive processing, if a pure CO₂ stream is made by capturing CO₂ (whether directly from air – DAC - or from an industrial facility from which it is transported to the minerals location), how are the credits actually assigned? Is the hard work the CO₂ capture, or the carbonation? Difficult but honest discussion is needed around this area. Blanket assumptions are dangerous.

Path Forward for Nickel Sulfides in the Battery Supply Chain

There are a few different viable paths forward for nickel sulfide projects – and as usual for nickel, it is highly mineralogy dependent.

Concentrates with very low (or no) sulfur are poor candidates for smelting (no fuel value) and require substantial acid addition for leaching.

Where concentrates from a few mines can be amalgamated to make sufficient quantity for sufficient project life, new smelters may be justified, but social acceptance of these facilities may be difficult. My rough guideline is minimum 50,000 t/y for 30 years to justify a new greenfield smelter.

Existing heavy industry areas (i.e. in Canada, Kitimat, Trail, Sudbury, Alberta's Industrial Heartland) may be more accepting of these facilities than greenfield locations, and where infrastructure can be shared, the necessary scale may be reduced.

Leaching of concentrates can be done at the mine site to make intermediate products, but due to the highly specialized nature of metals refining to pure products, refining operations are best done closer to major population centers, where the ability to retain skills is more certain.

Integration of the battery supply chain may allow the processing of intermediates (MHP/MSP, matte) directly to PCAM in close proximity to battery manufacturing, but most accepted routes go through a process where the multiple processing steps would require re-manufacturing of the acids and bases used in the process, such as electro dialysis (to split final ionic compounds into regenerated materials, for example sodium sulfate into sulfuric acid and sodium hydroxide), but the energy cost and practical application of this to manage the water balance is not yet well-demonstrated. Without that integration it appears that pure nickel sulfate production may be required to allow PCAM production elsewhere – however, conversion of nickel sulfate to PCAM in North America may be a challenge due to the subsequent production of large quantities of sodium sulfate as a waste.

Direct pressure oxidation of nickel concentrates with purification and precipitation as PCAM in a single process without intermediates introduces a degree of operating risk that may prevent commercialization. Production of intermediates is of operational value as it allows them to be shipped and stored, providing breaks in processing that allow for more operational flexibility. Full integration is very challenging as very little storage is feasible for solutions (hours to days, but not weeks), necessitating a reduced flexibility in operations. Downstream problems quickly become upstream problems, and vice-versa.

One possibility is that the large low-PGE projects in North America (i.e. on the order of 30 kt/y for 30 yrs) could host hydromet facilities to make MHP or MSP that is then shipped to centralized refineries. Where multiple smaller projects exist in reasonable proximity, it may be feasible to operate a centralized hydromet facility, but the range of feed materials over time needs careful consideration. High-PGE nickel concentrates should be shipped to smelters (new or existing smelters facing declining own feeds) to make Class 1 nickel, which is also a growing market, while maximizing PGE recovery.

Chlorine-based leaching or chloride-assisted sulfate leaching is only practical in tidewater locations due to effluent issues. For North America, with most nickel deposits and most battery facilities inland, this is a more important issue than in some countries.

Closing Remarks

The degree of specialization within the industry means that there are few practitioners with a wide view across the technical range. Those that become skilled in one refining process (i.e. chlorine leaching or carbonyl refining) do not tend to then move into multiple other areas to develop skills there as well. Some larger companies have been able to move technical specialists around, but the days of large technology groups within major mining companies that support a wide range of operations seems to be over – regrettably. I remain grateful to the Sherritt organization for my experiences with new technology development and deployment to clients (primarily nickel, zinc, and copper in my case), auditing and assistance to commercial facilities, as well as direct engineering and operational experience in a commercial refinery. I learned a lot there, experientially and from some great metallurgists and engineers who trod those refinery paths in the 40 years of Fort operation before me. With the wide range of process technologies in nickel, it is beyond anyone to be a specialist in all of them. My knowledge is deep in some areas, shallower in others, so if I have mis-characterized some of the operations and technologies in this series, I apologize.

Lastly, beware the “new idea”. In this business, most new ideas are not. Many approaches have been considered and tested over many decades. Chloride-assisted leaching and fine grinding approaches were not new in the 1990s when they were being touted as the next solution to revolutionize the industry. Hydrochloric acid and nitric acid leaching are not new. Many oxidants and reductants have been tested over the decades. Farisⁱ and Berezowskyⁱⁱ have good discussions of the history of nickel hydromet processing “innovations”. Many patents have been filed and granted which potentially could be challenged as “obvious to one

skilled in the art”. Some new reagents are developed from time to time (i.e. new SX or ion exchange reagents) that offer new choices, but adoption of them carries long-term operability and reagent or equipment degradation risk that are difficult to prove out.

The nickel business is not for the faint of heart. It is a challenging business that requires a long-term view. There is no real path to nickel development which is quick, easy, economic, and low-risk. Anybody who tells you different is selling fantasy.

Development of new projects is necessary if we are going to have the secure, reliable, high-ESG supply chains that western societies like to preach about, but getting there is hard. The support that governments now seem willing to provide is helpful, but it takes industry champions with deep pockets and a sufficient time horizon to bring forward a new commercial reality.

Junior mining companies are not the answer to development; they are answerable to a short-term financing reality. Major mining and processing companies need to be involved. Development via the venture capital space may be possible, but the failure risks are high and the time frames and objectives need to align. **Regardless of the source, those champions need independent real-world advice from people with deep and broad experience – and there aren’t enough of them around.**

Trytten Consulting Services is available to consult on nickel projects and can provide depth and breadth to a due diligence exercise. The long experience in multiple facets of the industry from R&D to design to operations gives an experience background that can provide the necessary insights to separate the better projects from the more challenging.

Glossary

Concentrate	an intermediate produced by beneficiation of a nickel ore to reject most of the impurities
EW	electrowinning
FeNi	ferronickel, an iron-nickel alloy typically in the range of 20-35% nickel, suitable for direct addition to stainless steel mills
HPAL	high-pressure acid leaching, a technique for treating low-magnesium nickel laterites with sulfuric acid
Matte	a high-grade metallized intermediate material derived from smelting a sulfide concentrate or converting NPI/FeNi with sulfur addition
MHP	mixed hydroxide precipitate, a nickel intermediate typically ~40% nickel with ~50% moisture
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PGE	platinum-group elements (platinum, palladium, rhodium, ruthenium, iridium, osmium), all of which have high economic value
SX	solvent extraction, a process for selectively extracting a specific metal ion from solution to be subsequently stripped out into a new solution

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ⁱ The Direct Leaching of Nickel Sulfide Flotation Concentrates – A Historic and State-of-the-Art Review Parts 1-3; Faris et al; Mineral Processing and Extractive Metallurgy Review, 43 (2022) [total 75 pg]

ⁱⁱ The pressure acid leaching of nickel sulfide concentrates; Berezowsky, R; TMS 129th Annual Meeting. Nashville, TN (2000) [32 pg]