EnerChemTek

Battery Grade Nickel: Sustainable Processing Options

Techno-Economic Comparisons of Leading Process for Recovery of Battery-Grade Nickel from Both Sulfide and Laterite Ores

PROPOSAL FOR A NEW MULTICLIENT STUDY FROM

EnerChemTek, Inc.

ECT Proposal 23-10-2-MCR

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PROPOSAL

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INTRODUCTION

The "Energy Transition," driven by climate change agendas around the world, will require an enormous investment in battery energy storage, both to stabilize intermittent generation from renewables and to power the transition to electrified mobility. This stored energy will, in effect, replace the global inventory of fossil fuels currently held in reserve for peak load abatement, in refinery product storage tanks, and in the fuel tanks of the billions of cars and trucks on the road worldwide.

Nickel is the preferred metal for electric vehicle (EV) lithium-ion batteries (LiBs) with high energy storage density and good power characteristics. There are other metals used in LiBs such as manganese, cobalt, and iron, but nickel offers the best combination of performance and price.

The global need for battery grade nickel is urgent and is very large. Tesla in its "Master Plan Part 3" issued in April 2023, has estimated that about a cumulative *40 million tons of nickel will be required* for the transition to a global sustainable non-fossil energy system. Tesla also estimates that the associated investment in nickel supply will be about $200 billion in mines and nickel refineries, plus another $172 billion of battery recycling investment.

The implied need is for 20-50 or more new nickel mines, plus associated refining capacity (based on typical nickel mine output of 30 to 80 kilotons per year of nickel over a 15 to 30 year mine life) to be established over the next few decades.

Only Class I nickel is acceptable for LiB applications, meaning that all these 20-50 mines & refineries must produce exclusively nickel of purity 99.8% and higher. This has a significant impact on the range of processing technologies that may be used.

These 20-50 mines & refineries must also be as sustainable as practically possible, producing the lowest carbon nickel consistent with the mine/refinery location. Effluents will have to be minimized and innocuous to protect the local environment, process energy requirements will be as low as possible, and end-of-life remediation must be included in any operational plan.

Process Technology Options for Nickel Extraction & Refining

In broad terms there are three process technology options for nickel recovery and refining, as follows:

- **Hydrometallurgies** that are based on dissolution of metals from the ore into aqueous solutions, followed by differential precipitation, crystallization, and solvent extraction to obtain the individual metals. Class I nickel is obtained by final electrowinning.
- **Pyrometallurgies** that are based on high temperature ore processing (smelting) at well above red heat to essentially burn off impurities, leaving metal mixtures. They cannot yield Class I nickel without adding a hydrometallurgical or vapometallurgical purification/refining step.
- **Vapometallurgies** that use chemical extractants in gaseous or vapor form, often with internal recycling of reactants to minimize effluents. They can yield very high purity metal products, particularly Class I nickel and iron, via a simple two-step process. However, the feed stream – ore, smelter matte or flotation concentrate – must first be reduced or heat treated to release the metals.

The environmental profiles of these three options differ markedly as do their processing economic profiles.

This proposed study aims to provide six case studies of these primary options that are directly comparable in terms of nickel output. The objective is to give prospective mine developers and investors the tools they need to assess the prospects for Class I nickel production from new mining and refining operations.

Note that all the ~40 million tons of nickel going into the global battery infrastructure will be recycled, indefinitely, along with all the other battery metals. Battery chemicals companies will become the "oil refiners" of the sustainable energy future. The same three types of technologies will be used to recover the battery metals, replacing the ore raw materials with recycled "black mass." It is highly likely that at the end of mine life some of the refineries built to handle the nickel output from the 20-50 new mines will be adapted to the LiB recycling network.

STUDY SCOPE & CONTENT:

Study Scope

Global nickel resources are currently estimated to be about 300 million tons, so there is no shortage of new nickel required by industry. The challenges facing producers relate to the composition of nickel ores and the declining concentration of nickel in the deposits being developed for mining.

About 40% of resources occur as sulfide ores that are relatively easy to process, while the other 60% occur as laterite ores that are complex high-iron mixtures of limonite and saprolite minerals containing different quantities of iron, magnesium and silicon compounds, all difficult to process and requiring different processing techniques.

While the three basic processing options can be used with all these ores, a meaningful technoeconomic comparison of options must necessarily involve six cases: three cases relating to the treatment of sulfide ores by the three processing options (hydrometallurgy, pyrometallurgy and vapometallurgy) and three cases relating to the treatment of laterite ores. **The six cases are summarized below.**

Sulfide ore treatment:

The first step in all sulfide ore treatment schemes is the beneficiation of the ore by froth flotation to yield a nickel concentrate: ores may contain about 0.2% to 4% nickel whereas concentrates contain at least 10% nickel up to about 40% nickel. The flotation step is simple, low cost and usually has a high overall yield in nickel recovery. The step allows the removal of the major portion of unwanted parent rock that can be disposed of in an efficient and environmentally friendly way.

The three sulfide ore process cases in this study are all based on the same concentrate feed stream and are as follows:

> ***Process S1: Hydrometallurgy***. The concentrate is subjected to an oxygen leach step to dissolve the metals, followed by solvent extraction steps to

recover and separate the metals. Class I nickel is obtained in a final electrowinning step.

Process S2: Pyrometallurgy. The flotation concentrate is smelted in a flash smelter to yield a nickel metal matte containing about 50% nickel. The matte is then leached with acid followed by recovery of other metals according to a hydrometallurgy process (***Process S2a***.) Alternatively, nickel and iron may be recovered from the matte via a vapometallurgy process, with only the residue passing through hydrometallurgy to recover other metals, if economically viable (***Process S2b***.)

Process S3: Vapometallurgy. The flotation concentrate is dried and then reduced with hydrogen to release the metals. The metals-containing solid stream is treated with carbon monoxide gas at moderate temperature and pressure to form nickel and iron carbonyl vapors that are condensed and distilled to separate the two metals as carbonyls. The liquid carbonyls are fed to thermal decomposers where the carbonyls revert to carbon monoxide gas for recycle and high purity Ni and Fe metal powders. This nickel powder is the industry basis for the Class I nickel designation. When appropriate, residual solids from the carbonylation reactor can be treated by hydrometallurgy to recover other metals such as cobalt, copper, manganese and aluminum.

Laterite ore treatment

Laterite ores are formed by prolonged weathering of ultramafic rock forming layered deposits near the soil surface. There are commonly two primary layers of laterite ores: an upper layer of high iron content (>40%) and low nickel content (typically <0.8% - 1.6%) and a lower, older and harder layer containing lower iron content (10% to 25%) and higher nickel content (1.6% to 3%). The upper layer is termed limonite (or oxide type) ore and the lower saprolite (or silicate type) ore. Miners usually segregate these two types for sale at different prices and for treatment by different processes.

The three laterite ore process cases evaluated in this study are as follows:

Process L1: Hydrometallurgy. The high pressure acid leach (HPAL) process is the most common technology currently applied in new laterite ore treatment plants. These plants can process both limonite and saprolite ores, with saprolites having a high nickel content being preferred. HPAL involves the use of sulfuric acid at high temperatures and elevated pressures to dissolve nickel and other valuable metals from the ore. Metals are recovered from the leach solution via a combination of filtration, solvent extraction, precipitation at various pH levels and final electrowinning of the battery grade nickel.

Process L2: Pyrometallurgy. Pyrometallurgy is widely used in China to treat laterite ores. Saprolites are preferred to produce ferronickel containing about 30% nickel, 70% iron as feedstock for stainless steel production. Limonites with lower nickel content yield nickel pig iron (NPI) containing about 4% to 13% nickel, also for use in steelmaking. As for sulfide ores, the ferronickel or NPI from laterite ores must be treated to recover battery grade nickel via hydrometallurgy (***Process L2a***) or alternatively via a vapometallurgy process (***Process L2b***.)

Process S3: Vapometallurgy. Both limonite and saprolite ores can be treated via carbon monoxide vapometallurgy to directly extract high purity Class I nickel as a powder or pellets, as well as high purity iron powder. The ores must first be dried and reduced with hydrogen to release the metals. Nickel extraction efficiency is very high while iron extraction efficiency is significantly lower. Sales revenues from the iron are of the same order of magnitude as revenues from nickel.

Study Content

To provide a deep understanding of all 6 Case Studies, the study report will include the following information:

- A basic pricing and inflation scenario with projected price indices for energy, chemicals & labor and plant construction, to be used throughout the study.
- An executive summary discussing the strengths, weaknesses and sustainability aspects of each of the 6 technologies and a ranking in terms of nickel production costs, return on investment and sustainability, based on analyses of the 6 individual technologies.
- Each technology analysis will include:
  - A review of the status of the technology in terms of estimated global capacity and capacity share, and the identity of important users.
  - A process flowsheet showing all major equipment.
  - A detailed process description.
  - Material and energy balances for major process streams.
  - Schedule of all effluent streams, including flow rates and average compositions
  - Raw material, product, byproduct and utilities price estimates and projections relevant to each process.
  - A production cost analysis indicating:
    - Capital cost estimates for the entire plant from ore intake to product dispatch, including necessary materials and products storage, utilities supply facilities & networks, effluent treatment and tailings disposal, segregated between the battery limits process plant and all offsite facilities.
    - Operating costs such as:

        - Raw materials, process chemicals, catalysts and utilities consumptions and costs per ton of nickel produced.
        - Operating labor requirements for the battery limits plant.
        - Plant & labor overheads, and insurance costs.
        - Annualized maintenance costs.
    - Annualized cash flow projection.
    - Estimated simple return on investment and NPV.
    - Sensitivity analysis of economics to key cost variables.
- A discussion of process variants used in the industry or under development and likely impact on economics as well as the potential impact on ranking, where relevant.
- An estimate of the net carbon emissions of the process plant and its utilities.
- A qualitative assessment of all effluent streams and their environmental impacts.

DELIVERABLES

The study will be delivered as a written report with the executive summary prepared in Microsoft PowerPoint format and the six technology analyses prepared in Microsoft Word format, all delivered as Adobe Acrobat pdf documents. The executive summary and technology analyses will be prepared as seven individual documents to be made available as soon as completed, with the final report containing the combined seven sections.

Summary cash flow estimates will be available on request in Microsoft Excel format for an additional charge.

SUPPLEMENTAL ANALYSES

EnerChemTek (ECT) recognizes that metal extraction and refining technologies are complex, with many process variations due in large part to variations in ore compositions and morphology. There are also variations in the primary nickel product: Class I metal powders or pellets, battery grade nickel sulfate, battery grade nickel hydroxide or mixed Ni/Co hydroxide precipitate. Depending on subscriber needs and requests, therefore, ECT plans the future publication of supplementary studies & analyses covering specific variations in technologies & ores that will be directly comparable to the benchmarks developed in this current proposed study.

These supplemental studies will be published under separate subscription either as variations of the individual technologies made available as separate reports, or as second (or 3rd) editions of the current 6-technology study.

The Direct Nickel Process

Of particular importance, one of these supplemental studies will be a directly comparable analysis of the Direct Nickel process (DNi Process™) developed by Altilium Group in collaboration with CSIRO Australia. This technology uses a nitric acid leach of laterite ores (the whole ore, including limonite, saprolite and the transition zone) at atmospheric pressure and low temperature, with 99% of the nitric acid being recovered and recycled to the leach reactors.

A project using this technology is currently under development by Queensland Pacific Metals near Townsville, Queensland, Australia – the TECH Project. The plant will treat laterite ore imported from New Caledonia, dissolving all saleable metals from the ore (Ni, Co, Sc, Fe, Al) leaving a dry inert silicate tailings that accounts for about half of the ore feed. The process has no liquid process effluents and has a high ESG rating. In its basic configuration, the process yields a battery grade Ni/Co mixed hydroxide precipitate (or Ni and Co sulfates), a high purity alumina powder, hematite sinter pellets, and magnesia. With carbon credits through the use of gas recovered from coal mining operations, Queensland Pacific Metals aims to produce carbon negative nickel.

Further Information

Work on the study is scheduled to begin in November, 2023, and is scheduled for completion in the first quarter of 2024.

For additional information on this multi-client study please complete the following request form and return it to Dr. Mauricio Dávila at the address below:

Re: Battery Grade Nickel: Sustainable Processing Options

Name: ____

Title: ____

Company: ____

Street Address: ____

City: _______________________ State: __________________________

Zip: ________________________ Country: ________________________

Phone: ______________________ Fax: ___________________________

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Pre-publication subscribers – those subscribing before the study report is completed and published – will receive a discount!

SERVICES TO THE ENERGY & PETROCHEMICAL INDUSTRIES

This study is part of EnerChemTek's on-going new-energy single- and multi-client services aimed at providing critical thinking and insights into the main drivers impacting the global energy industry, monitoring industry trends and changes, and evaluating the role of technology and its exploitation in the achievement of competitive advantage.

This multi-client report is an offshoot of our services to the power battery segment prompted by the extraordinary growth in demand for energy storage in electric vehicles and in back-up power for renewables and the power grid. We monitor electric vehicle demand, outlook and technologies, as well as the EV and other battery producers, and the producers and recyclers of battery materials for electrodes, electrolytes, current collectors and separators. We concentrate on providing insight into development of the global battery industry, mapping the continuing evolution of this segment, updating all the data presented in our previous studies while adding detailed new market, product, technology and supplier analyses that address these developments.

Our specialized services are founded on extensive databases and proprietary methodologies built and perfected over the past two decades. We maintain up-to-date and detailed information on leading energy and petrochemical producers worldwide and continually monitor their activities and apparent strategies.

We also provide specialized advice on technology selection, technology exploitation and strategy development. Our clients include energy suppliers, refiners, petrochemical producers, suppliers to the petrochemical industry such as catalyst & additive developers and producers, and technology-leading customers and market developers who exploit new products based on novel technologies.

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