Key considerations for the dissolution of metals and alloys in the production of battery grade metal sulfates

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With the global transition towards electrification, the demand for battery metal sulfates is growing rapidly. One of the processing routes – metal dissolution, involving the dissolution of metals or alloys and producing battery-grade metal sulfates, is a strategic solution to help meet this increasing demand. The metal dissolution process provides a pathway for producers to swiftly enter the battery market and it is a proven and viable means for the production of metal sulfates. This paper discusses the key technical considerations for designing a metal dissolution processing plant from the raw metal feed through to the final, battery grade specification sulfate. The paper encompasses various aspects, including (i) selection of metal feed and dissolution reactor types; (ii) description of key parameters that drive the dissolution process and its stability; (iii) development of the overall flowsheet to meet battery grade specifications and optimise costs; (iv) design of targeted experiments to study and de-risk critical areas of the process and identify suitable materials of construction; (v) sizing and scale-up considerations; and (vi) use of specialised analysis such as computational fluid dynamics and finite element analysis to assist in the design, scale-up, and technical de-risking.

INTRODUCTION

Global trends in climate change and sustainability continue to push the decarbonisation of transportation via electrification and the shift from fossil fuels to renewable power in the electricity grid. Lithium-ion batteries (LiBs) are arguably the core enabling technology to facilitate this energy transition. Electric vehicle (EV) adoption is accelerating and the need for lithium-ion batteries is increasing rapidly, resulting in a demand for battery-grade metal sulfates to produce these batteries. The metal dissolution process and subsequent purification and recovery via hydrometallurgical processing is one pathway to help meet the industry demand for metal sulfates immediately. A simplified block flow diagram of this process is shown in Figure 1.

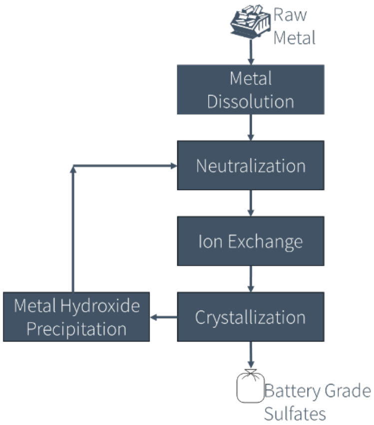

Figure 1. Block flow diagram of a metal dissolution plant using a patented process

An extensive test work program was run by Hatch to study the key parameters that drive the nickel dissolution process and its stability including acidity, pH, acid concentration, oxidant concentration, superficial velocity, temperature, and dissolved metal strength. Additionally, test work programs to design the purification and recovery process to ensure battery-grade nickel sulfate specifications are met were completed. Targeted experiments to study and de-risk critical areas of the process and identify suitable materials of construction were completed. The purpose of these test work programs was to assist with the path to commercialisation of the metal dissolution plant by informing the design and scale-up of the unit operations. Computational fluid dynamics and finite element analysis can also be used in addition to lab testing and piloting to assist in scaling up the design and overall technical de-risking of the process.

METAL DISSOLUTION

Metal Feed and Dissolution Reactor Types

The first consideration in designing a metal dissolution plant is the feed material and the reactor type. Due to the various characteristics of different feed materials, this often dictates the type of dissolution reactor that can be used for the process. Reactors for metallurgical processing include many options such as continuously stirred reactors (agitated tanks), columns, packed beds, fluidised beds, and plug flow reactors, which can be used based on the application and feed material.

In the case of nickel, raw nickel metal can be purchased as nickel powder, pellets, full sheet cathodes, cut cathodes, briquettes, and other feed types. Agitated tanks are mainly suitable for dissolving nickel powder as large particles do not stir well and can become unevenly distributed relative to the dissolving solution, with a tendency for the large particles to sink towards the bottom of the tank due to weight. Additionally, large particles may also damage the impellers. On the other hand, moving packed bed reactors are preferred to accept larger feeds such as pellets, cut cathodes, and briquettes, but can also operate as a fluidised bed to accept powder feeds.

Smaller feeds provide greater surface area for the dissolution reaction to occur resulting in an increased specific dissolution rate and decreased reactor volume requirements. However, these feeds are often formed through additional processing and therefore may come with higher costs. Trade-off studies can be conducted and are recommended to determine the optimal coupling of feed type with the reactor design.

Dissolution Process, Kinetics, and Stability

In designing a metal dissolution reactor, it is critical to understand the chemistry and the process stability to optimise the kinetics and ensure efficient operation. Nickel dissolution is an oxidative dissolution reaction, where the solid nickel in elemental state converts to an ionic state. Sulfuric acid solution is a common and preferred lixiviant for nickel dissolution as it directly produces the sulfate salt. The nickel dissolution reaction can be completed through an addition of strong oxidant, such as hydrogen peroxide for example, to enhance the reaction kinetics and eliminate hydrogen gas generation as per the following reaction:

$$Ni_{(s)} + H_2SO_{4(aq)} + H_2O_{2(aq)} \rightarrow NiSO_{4(aq)} + 2H_2O_{(l)} \quad [1]$$

The parameters that drive the nickel dissolution rate and the stability of the above reaction in packed bed reactor were studied through a test work program completed by Hatch to assist with de-risking the process and scaling-up to the commercial operation. These parameters include temperature, hydrogen peroxide concentration, dissolved nickel concentration, superficial velocity, hydrogen peroxide to acid ratio, and pH.

It was found that superficial velocity, hydrogen peroxide concentration, and dissolved nickel concentration are the key levers that drive the nickel dissolution rate, while the relative effect of temperature is smaller. The dissolution results for the impact of temperature, superficial velocity, dissolved nickel concentration, hydrogen peroxide concentration and temperature are shown in Figure

2. All experiments were run using a fixed nickel mass. These results indicate that overall dissolution rate is largely film diffusion limited as shown by the impact of superficial velocity and nickel concentration on the dissolution rate.

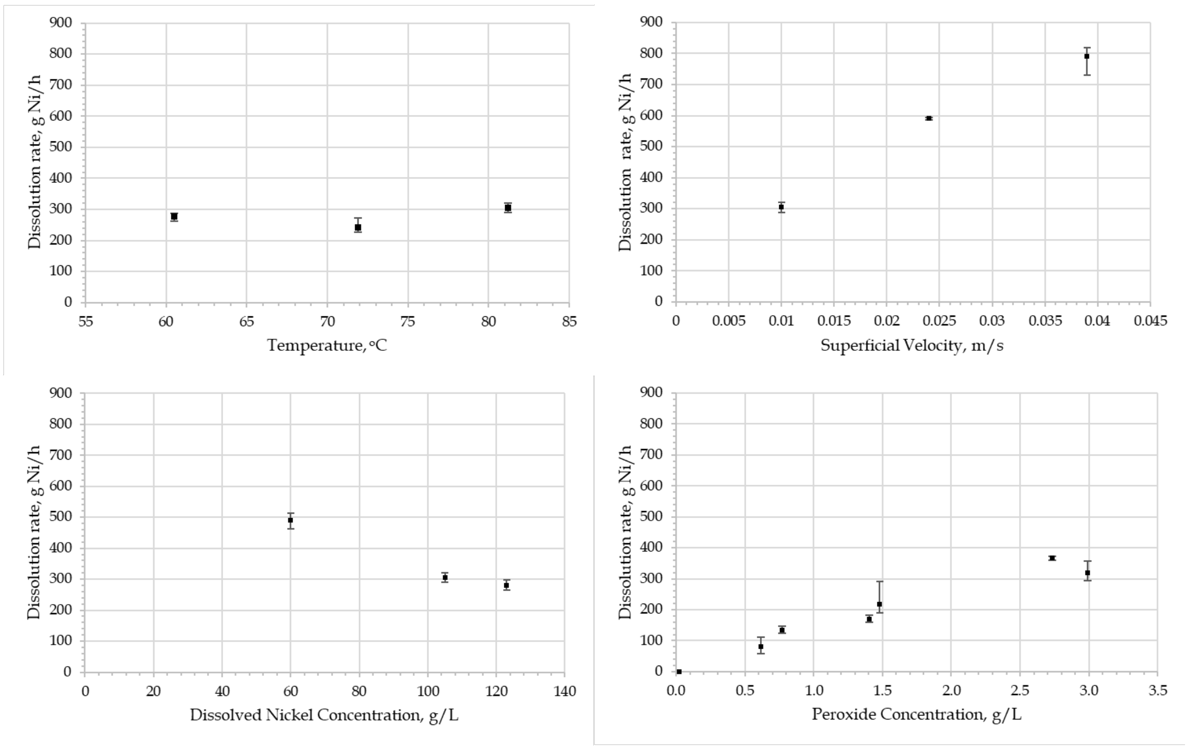

Figure 2. Impact of temperature, superficial velocity, dissolved nickel concentration, and hydrogen peroxide on dissolution rate.

It is important to note that although higher hydrogen peroxide and lower dissolved nickel concentrations increase the overall dissolution rate and reduce the reactor sizing requirements, the balance of plant must also be considered. A higher residual hydrogen peroxide concentration in the pregnant leach solution (PLS) that goes to downstream for further treatment results in higher losses of hydrogen peroxide reagent and therefore higher operating costs. A lower dissolved nickel concentration will increase the volumetric PLS flowrate (to achieve the same nickel production rate) and hence the size of the unit operations downstream of the dissolution circuit and therefore the capital cost. Additionally, a lower concentration of nickel sulfate in solution will increase the required evaporation rate in the crystallisation circuit and result in an adverse effect on the operating and capital costs if nickel sulfate crystals are being produced. Therefore, it is critical to consider the entire operation of a metal dissolution plant to determine which levers for dissolution can be manipulated without impacting the balance of plant. The dissolution circuit should be operated at a dissolved nickel concentration such that a sufficient dissolution rate is maintained and the nickel concentration to the balance of plant does not pose a risk of saturation or crystallisation at the solution handling temperatures.

Parameters impacting the stability of the dissolution process were also studied as part of the test work program. It was observed that hydrogen peroxide decomposition occurred when the stability criteria was not maintained. Three criteria were found that impact the stability of the process; these include terminal acid concentration and pH, as well as the molar ratio of hydrogen peroxide and sulfuric acid in solution. It is generally recommended that a pH below 1.5–2.0 is maintained at the outlet of the dissolution reactor to eliminate the risk of hydrogen peroxide decomposition.

Previously, a dissolution test work was performed on a Ni/Co/Mn alloy and showed many similar dissolution characteristics as nickel (Gray, 2023). Therefore, many conclusions captured in this paper may be equally applicable for the dissolution of other metals (e.g. Co) and multi-component alloys.

Dissolution and Hydrogen Gas Production

The dissolution process described above uses hydrogen peroxide to eliminate hydrogen gas production. However, nickel sulfate can be produced through the reaction with sulfuric acid alone to produce hydrogen gas, as per the following reaction:

$$Ni_{(s)} + H_2SO_{4(aq)} \rightarrow NiSO_{4(aq)} + H_{2(g)} \qquad [2]$$

The above reaction results in a slower dissolution rate due to the elimination of hydrogen peroxide, resulting in higher surface area requirements to meet the target dissolution rate. A higher surface area can be achieved through smaller particles such as nickel powder or a larger quantity of material resulting in a greater number of dissolution reactors. A trade-off study can be completed to evaluate the economics of a higher capital cost due to a larger number of dissolution reactors versus a reduced operation cost due to the elimination of hydrogen peroxide. Trade-off studies can also be completed to evaluate capturing hydrogen as a value-added product versus the dilution of hydrogen for safe plant operation.

DEVELOPMENT OF THE OVERALL FLOWSHEET

The acidic PLS leaving dissolution is high in desired product metal, but also contains impurities from the original feed. Most metal feeds have higher levels of impurities than is acceptable in most battery-grade metal sulfate specifications, due to the stringent specifications required. Therefore, the impurities from the PLS must be selectively removed for a battery grade salt to be produced. Purification steps must be developed with consideration of the feed material and identification of the elements of concern. It is possible to first determine the estimated product composition if no purification is performed and compare this composition to the product specification to determine the elements of concern.

For this test work program, LME Grade Ni (ASTM specification B39-79 (2023) – min 99.80% purity) was considered for the overall plant feed composition, and the flowsheet was designed to produce battery-grade nickel sulphate. Elements of concern in LME Grade Ni include, among others, Cu, Fe, Mn, and Zn. Removal of these cationic elements is well understood in hydrometallurgical flowsheets, however this test work program aimed to de-risk the challenges presented by the very high Ni concentration (>100 g/L) and low initial impurities concentration with an even lower final target concentration in the product. Additionally, the small projected product premium over the feed material cost ensures that operating costs and nickel losses throughout the process must be minimised.

Flowsheet Description

Purification of the nickel sulfate solution is done in three main steps:

1. Neutralisation and precipitation
2. Ion exchange
3. Crystallisation

Neutralisation and precipitation serve multiple purposes. First, the liquor leaving dissolution is acidic (pH of 1.5–2.0). If this acidic solution was to feed the crystallisation circuit directly, where water is evaporated and acid concentration would further increase, it would result in a highly acidic solution within the crystallisation circuit which would necessitate expensive materials of construction. Therefore, it is desirable to increase pH before crystallisation. Raising pH is beneficial for ion exchange (IX) as well, as the operating conditions for many applicable IX resins to selectively remove impurities from Ni are less acidic than the dissolution liquor. Raising the pH also serves to precipitate some of the impurities as hydroxides, and this reduces the load on the IX circuit.

IX is known to be an effective method for removing the majority of divalent and trivalent cationic elements down to very low concentrations. This is necessary for producing a clean feed to the crystallisation circuit to produce a high-quality product with minimal bleed. However, IX has multiple drawbacks in addition to the capital cost. First, for each mole of impurity loaded, at least one mole of acid and one mole of base must be spent to strip and then regenerate the resin. The use of a base to maintain pH during loading of the IX columns also results in addition of an impurity to the system, in this case Na from the base NaOH. Finally, while IX conditions can be chosen to selectively remove impurities from the nickel rich liquor, there will always be co-loading of nickel with the impurities. This co-loading is a source of nickel loss for the process. Therefore, it is beneficial to reduce the load on IX, where possible, by first removing higher concentration impurities upstream by precipitation.

Crystallisation involves evaporation of water to increase the concentration of nickel sulfate in solution beyond the solubility limit, causing it to crystallise. Further evaporation drives further crystallisation of nickel, while the impurities (ideally) remain in solution. While crystallisation is a recovery step, it can also serve as a purification step when correctly designed. As nickel is crystallised, it remains approximately at the solubility limit in solution while the impurity concentrations in solution continue to rise. For this reason, a bleed must be taken from the crystalliser to limit the build-up of impurities. While increasing the bleed rate is one solution to limiting impurity concentrations, this can also result in greater nickel loss and increased operating costs.

Most of the nickel in the bleed from crystallisation can be recovered using a patented process (Fraser *et. al.*, 2021) in which nickel is precipitated by using a base, with the trade-off being some additional recirculation of impurities in the process. Nickel precipitates as a basic compound (e.g., $Ni(OH)_2$ precipitated by NaOH addition) which can be used for the purpose of neutralisation of the PLS upstream in the process. Neutralisation using a common basic reagent such as NaOH would introduce a significant amount of Na to the system as an impurity. However, using precipitated $Ni(OH)_2$ to perform the neutralisation step prevents this contamination of the PLS and slightly raises the Ni concentration. Effective washing of the $Ni(OH)_2$ becomes critical to remove the Na contained in the liquor and prevent it from entering the main process stream.

As with many hydrometallurgical flowsheets, each of the above process steps are heavily influenced by the operation of the other steps due to the effect of recirculation. Test work was conducted on each step to select the desired conditions.

Experimental Work

Test work for neutralisation and impurity removal centred around selection of the optimum terminal pH to maximise removal of impurities while minimising nickel loss and residence time. While iron is effectively removed at most pH levels considered, Cu removal increases significantly as pH 5 is approached or exceeded. As expected, impurities such as Ca, which typically precipitate at higher pH than nickel, are not removed as shown in Figure 3.

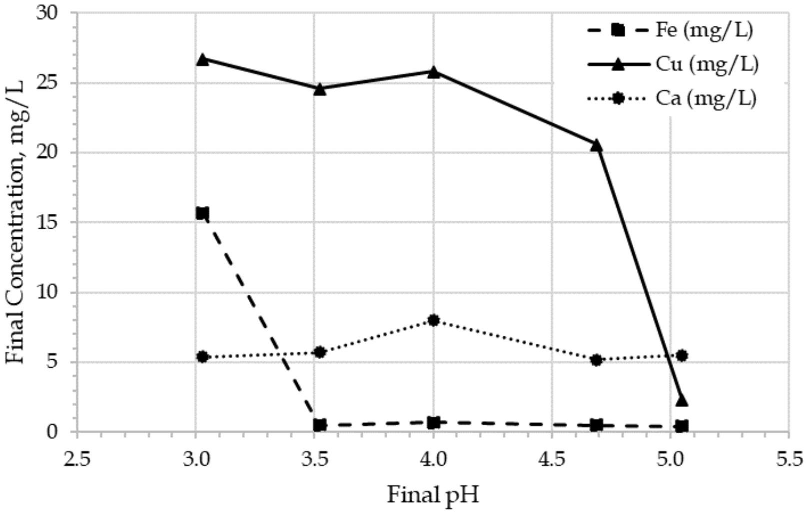

Figure 3. Final concentration of Fe, Cu, and Ca at varied final pH.

While selection of a pH greater than 5 is desirable for reducing the Cu concentration before IX, the maximum pH achievable is ultimately limited by the solubility of nickel. This is due to both the desire to limit nickel precipitation from solution, but also a result of the use of nickel hydroxide as the base reagent. It was found during the test work that the rate of the nickel hydroxide dissolution and resulting pH increase of the solution is reduced significantly as pH 5 is approached and exceeded. This can be seen in Figure 4, which shows pH vs. time for one of the tests where the target final pH was greater than 5. For the test shown in Figure 4, additional base was added after ~40 minutes. The impact of this addition on the rate curve is unclear since the initial base addition was already in excess of the acid neutralisation requirement so the additional base simply increased the excess. At the end of this test there was significant nickel residue recovered by filtration in a Buchner funnel. Therefore, increasing Cu removal, by targeting a pH of 5+, is associated with longer residence time and increased nickel loss.

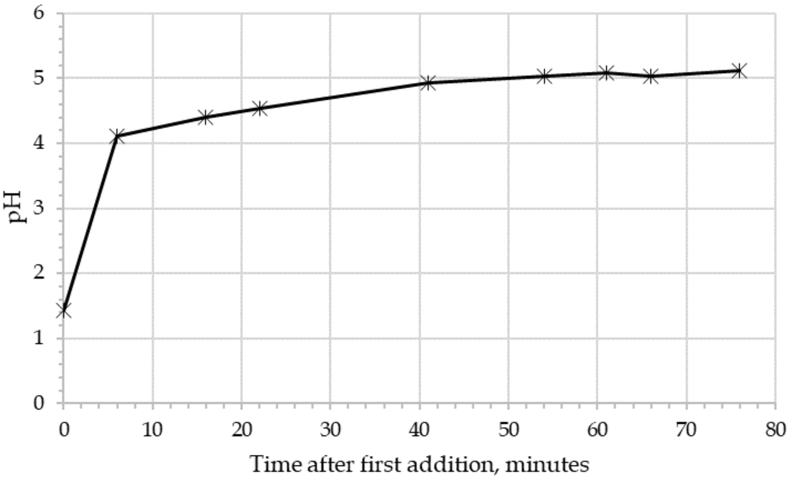

Figure 4. Plot of pH vs. time for one test where the target final pH was >5.

A test work program for ion exchange was developed to compare different IX resins to select the preferred resin and pH for selective removal of the target elements, with minimised co-loading of nickel. This involves performing an equilibrium rate test and an equilibrium capacity test to generate adsorption isotherms for each impurity. The IX test plan follows the methodology described by DuPont (2019). This experimental work is still ongoing and is not presented in this paper.

For crystallisation tests, a synthetic feed was generated based on simulation results to represent a conservative estimated feed composition. As part of the test program for crystallisation, a small 1 L batch evaporative crystalliser equipped with a Metller Tolado EasyMax probe was used to produce nickel sulfate hexahydrate as the final product. The crystallisation was conducted at 50°C, under vacuum, and the evaporation rate was set to produce the target size crystals similar to industrial scale productions. The final crystals were harvested, dried, and characterised using XRD and ICP-OES for their final composition. The final crystals met typical battery grade specifications for almost all elements and indicated which elements must be further removed upstream by IX (e.g., Cu) for battery grade specification to be met. This provides a performance target for the IX test work and crystallisation of the IX treated solution can be performed once available.

Test work for nickel hydroxide precipitation with NaOH centred around selection of the optimum terminal pH as well as conditions such as pH steps, residence time per step, feed nickel and NaOH concentration, and seed ratio to help develop good quality crystals that can be washed effectively. Precipitation of $Ni(OH)_2$ using 50% NaOH in a single step, with no seed, resulted in a very thick slurry that was difficult to pump and had very ineffective washing of the filter cake. Alternatively, precipitation of $Ni(OH)_2$ following a similar methodology as described by Sist (2004) resulted in a much higher quality cake with effective washing of Na.

One additional challenge encountered throughout this work was that the typical limits of detection for some elements of interest were comparable to or exceeded the target final concentrations in some steps. This made it challenging to confirm that the targets had been met and difficult to compare the results of different test runs. This is primarily due to the high concentration of nickel which can interfere with detection of the low concentration impurities. Significant effort was required to optimise the ICP-OES procedures to produce accurate, usable results. Continued further advancement of procedures for determining trace impurity concentrations in high concentration Ni solutions is likely required to improve understanding of this space.

MATERIALS OF CONSTRUCTION

The integrity of metal dissolution as a critical part of the facility is vital for the plant reliability and essential for achieving a plant life. In support of the mechanical design, a comprehensive desktop study and test work program were completed to determine the most reliable material and the required corrosion allowances to ensure the safe operation of the dissolution reactor. The results of this study will also be used for the development of the future inspection plan for the dissolution reactor.

Corrosion resistance alloys including duplex stainless steels (2205, 2304, 2707, and Zeron 100), high nickel alloys (Hastelloy G35, C-276, C-2000, Alloy 686, and Alloy 625) and austenitic stainless steels (904L, Alloy 20, and Alloy SMO 254.), which are typically used as the materials of construction in sulfuric acid and hydrogen peroxide, were evaluated for their corrosion performance under the specific conditions of the dissolution reactor.

The filtered materials were then ranked considering the key parameters including the cost, mechanical strength, availability, ease of fabrication, corrosion resistance and wear resistance. In the absence of sufficient corrosion data, to lower the risk of failure to as low as possible, the candidate corrosion resistant alloys which achieved the highest ranking in the weighted scoring matrix were tested both in-situ and using electrochemical techniques in laboratory. A summary of the testing program is given in Table I.

Table I. Summary of corrosion test work program

Type of experiment	Experiment	Standard	Purpose of experiment
Electrochemical- (Accelerated) Testing	Potentiodynamic polarisation and Tafel extrapolation	ASTM G5	- Corrosion rate - Corrosion behaviour - Susceptibility to localised corrosion
	Potentiostatic polarisation	ASTM G150-18 ISO 18089:2015(E)	- Critical Pitting Temperature (CPT) - Critical Crevice Temperature (CCT)
	Electrochemical Impedance Spectroscopy (EIS)	ASTM G 106	-Characterising corrosion product formation
Immersion (Long-term) Testing	Immersion Testing followed by solution testing (ICP) and weight loss measurement	ASTM G31	- Validation of electrochemical test results - Susceptibility to intergranular corrosion. - Corrosion resistance of weld joints

Hydrogen peroxide acts as the main oxidant, and the sulfuric acid changes the pH; thus, various ratios of hydrogen peroxide to sulfuric acid were tested to study the governing corrosion mechanisms at various expected scenarios. A freshly prepared solution was used for each experiment and the hydrogen peroxide concentration was monitored and adjusted when required.

The CPT and CCT of 2205 DSS, Zeron100 SDSS, and Hastelloy C-2000 were identified to be above 95°C in all tested conditions. Notably, no current transients were observed during the potentiostatic CPT and CCT experiments, indicating the absence of formation of metastable pits on the alloys' surface. Furthermore, post-test optical microscopies on immersed and polarisation samples did not reveal any evidence of pitting, crevice, or intergranular corrosion. Tafel extrapolation data showed corrosion rate to be <0.1 mm/yr which is acceptable. The results of polarisation were confirmed by electrochemical impedance spectroscopy data which revealed a high resistance of passive layer for the three alloys under the tested conditions. Hastelloy C-2000 showed the highest corrosion rate, i.e., lowest corrosion resistance when hydrogen peroxide was present. Chromium is the key element promoting passive film formation in corrosion resistant alloy in an oxygenated sulfuric acid medium. The presence of nitrogen can enhance the enrichment of chromium in the passive film and improve the corrosion resistance. Thus, the increased performance of duplex stainless steels over Hastelloy C-2000 in the tested environment can be attributed to the effect of nitrogen.

The highest corrosion rates for 2205 DSS were recorded in the absence of hydrogen peroxide. This highlights the role of hydrogen peroxide in the passivation of the alloy's surface and therefore the decreasing corrosion rate. The influence of temperature on the corrosion rate of 2205 DSS and Zeron100 DSS was found to be dependent on the sulfuric acid to hydrogen peroxide ratio. Post-test inductively coupled plasma solution studies revealed that the differences in alloying elements released between the bulk and weld samples for all three alloys were negligible.

SIZING AND SCALE-UP CONSIDERATIONS

There are many guidelines in literature indicating what scale-up steps are required, the more important factors to consider are the individual technology challenges and risks, be it new processes, components, process integrations or combinations of these. Test work is a key component of de-risking and scaling up new technologies as indicated by the sections above. Findings from Gordon and Kumar (2014) show that each technology is unique with respect to its scale-up challenges. His review of new technology scale-ups for packed bed processes in the iron and steel industry shows that different technologies, processes, and pieces of equipment all have different critical scale-up parameters and recommended scale-up factors. For instance, cylindrical furnaces have different critical parameters than rectangular or angular furnaces. As such, to ensure optimal performance, it is essential to identify the critical scale-up parameter(s) of the processes and equipment when scaling up a technology.

In the roadmap to commercialisation, Technology Readiness Level (TRL) is a scale often used to represent the overall level of development of a technology. TRLs are assigned based on a scale of 1 (lowest level, basic principles reported) to 9 (commercially implemented). Some broad definitions of each TRL can be found in Table II.

Table II. Example of TRL scale and general definitions (U.S. Department of Energy, 2015)

TRL	Definition
1	Basic principles reported
2	Technology concept and/or application formulated
3	Experimental and analytical critical function and/or characteristic proof of concept
4	Component or proof-of-concept validation in laboratory environment
5	Component or pilot validation in relevant environment
6	Engineering/pilot scale similar (prototypical) system validation in relevant environment
7	Full-scale, similar (prototypical) system demonstrated in relevant environment
8	Actual system completed and qualified through test and demonstration
9	Actual system operated over the full range of expected conditions

While an overall measure is too broad to be helpful in creating a commercialisation path, this scale can be applied to various sub-systems or elements of the technology to assess the current level and the level that could be attained through various validation methods such as bench scale, pilot plants, and demonstration plants. It is recommended that a TRL is provided for each subsystem using the weakest link methodology; the minimum TRL of the topics within that subsystem dictates its overall TRL. It should be noted that not all elements evaluated need to be fully demonstrated, as contingencies (additional equipment or design margins) can address the technical risk in certain cases. There are however elements of high importance that represent the highest risk which needs to be demonstrated in an integrated way on a scale that is indicative of the intended commercial operation.

A guideline for scale-up is the size of the unit operation increases by a factor of 10 for each level of demonstration (bench scale → pilot plant → demonstration plant → commercial operation). Examples of scale-up factors for various hydrometallurgical operations are provided in Table III. As noted above, this serves only as a guideline, and each unit operation will have a unique scale-up factor.

Table III. Examples of scale-up factors for hydrometallurgical operations

Type of Facility	**Name/ Operation**	**Commercial Scale-up Factor**
Large Plant-Scale Test Facility	Codelco BioCop Demo Plant	Single Line 1:1
Large Integrated Pilot Plant or Demonstration Plant	LionOre Activox NiCu Leach/Refinery	170:1
	Inco VBN Ni Refinery Modules to Site	100:1
	QIT UGS HCl Leach Reactor	65:1
	CVRD UHC Chalco High Pressure Acid Leach	25:1
Small Integrated Pilot Plant	BHP Gag Island Laterite Ni High Pressure Acid Leach	>1000:1
	WMT Activox P/P	>3000:1
Bench Scale Lab Work	BHP San Felipe Laterite Ni High Pressure Acid Leach	>1000:1
	WMC Pinares Lateriate Ni High Pressure Acid Leach	>1000:1
	BHP Ravensthorpe Ni High Pressure Acid Leach	>1000:1

In addition to scale-up factors, the experimental equipment must be designed using the correct sizing requirements. When designing a packed bed, the experimental setup and commercial design should be sized such that the diameter of the packed bed is ideally 40 times the mean particle size of the feed for spherical mono-sized particles and 20 times the mean particle size for poly-sized particles. This reduces the flow short-circulating along the walls (wall effects) as there will always be higher void space at the walls than the bulk portion of the packed bed. Additionally, all equipment should be designed such that the correct aspect ratios are maintained. For example, for ion exchange columns it is recommended to maintain a resin bed height to diameter ratio of 4:1 to 10:1 for any experimental setup to allow for correct scale-up to the commercial operation.

Reactor Sizing and Use of Specialised Analysis

Packed bed reactors used for metal dissolution are subject to various axial gradients that impact dissolution performance such as hydrogen peroxide concentration, dissolved nickel concentration, temperature, and particle size distribution. Due to the complexities involved, multiple process considerations are required for the sizing and scale-up of packed-bed reactors:

- The reactor should be designed such that operating envelope throughout the reactor volume adheres to the process stability constraints discussed earlier, as well as permitted materials of construction limits.
- The operating conditions should be designed for high dissolution rate conditions to optimise the size, based on the understanding of dissolution kinetics.
- It is ideal to have low residual acid and oxidant concentrations at the reactor outlet to reduce reagent losses.

A multi-variable kinetic rate function was developed based on lab and pilot test work results to begin sizing a packed bed dissolution reactor. Subsequently, a 1-dimensional mathematical model of the reactor was developed, incorporating the kinetic rate equation and using numerical integration methods to size the reactor. The model can predict the overall dissolution rate and profiles for different inputs, ultimately allowing for an optimised reactor size.

While this model is simplified and provides a good estimate of the reactor size and operating conditions, it assumes ideal reactor flow conditions (e.g., perfect plug flow of fluid through a packed bed of material) similar to lab scale test conditions. However, it is often challenging to maintain such ideal flow conditions for equipment design on a commercial scale; there would be flow non-uniformities such as bulk channeling and cross-sectional gradients of velocity, temperature, and species concentrations. It is very important to account for these factors for the success of a metal dissolution plant as it is critical that the dissolution reactor performs to its target throughput to meet the overall plant throughput.

Specialised engineering analysis such as computational fluid dynamics (CFD) were used to address the limitations of a 1-dimensional mathematical model by incorporating the effects of flow non-uniformity and three-dimensional distribution of parameters throughout the reactor to determine a more refined reactor design. The CFD models were first developed to simulate the lab and pilot scale designs and validated against the measured data. Once validated, the CFD models were run to simulate the performance of a commercial sized dissolution reactor. The models can predict full-scale three-dimensional distribution of flow velocity, pressure, temperature, and reagent concentrations throughout the commercial scale reactor design. CFD modelling can also be used to optimise the design of a feed flow distribution system to achieve a desired flow condition (e.g., plug flow). Furthermore, local heat spots can be analysed to verify that permitted materials of construction limits are not exceeded. Overall, this process allows for optimised sizing and operating conditions, while significantly reducing the risks associated with the scale-up of the dissolution reactor design.

Careful attention to structural and mechanical considerations should also be made early on when designing the reactor in addition to process considerations. This can be completed by using Finite Element Analysis (FEA) which is an additional specialised engineering analysis tool. FEA models can be used to determine the optimal reactor platework thickness and stiffening requirements for various feed types and process design requirements. Impact load assessments can also be completed to determine the mechanical wear on the reactor from freefalling solid feed material, due to the reactor being completely empty during first fill and from material loading during normal operation when the reactor is full. Incorporating FEA in the engineering design can assist in determining the load path and identifying design issues early and assessing the safety and performance prior to manufacturing. Additionally, it can reduce the need for expenses prototypes by optimising the design by simulating many design scenarios. This saves engineering time and development costs.

CONCLUSIONS

This paper summarised the engineering work that was completed to de-risk and scale-up metal dissolution plants. These steps included designing and implementing test work programs for metal dissolution, overall flowsheet development, and materials of construction. Additionally, specialised engineering analysis tools such as CFD modelling were used to further de-risk metal dissolution reactors by simulating the performance of a commercial-sized dissolution reactor.

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Umesh is a professional chemical engineer with 20 years of experience in metal/mining industry with a particular focus on process equipment design and analysis. He has advanced level training in fluid mechanics, heat transfer, and numerical methods. His core expertise includes applying computational fluid dynamics techniques to design and analyse the thermal/hydraulic performance of process systems and equipment. Some of his recent project experience involves the scale-up and design of nickel and cobalt dissolution reactors, the design assessment of a CAM reactor, as well as the hydrodynamic evaluation of high-pressure autoclave reactors, slurry heater vessels, and pressure let-down flash vessels.