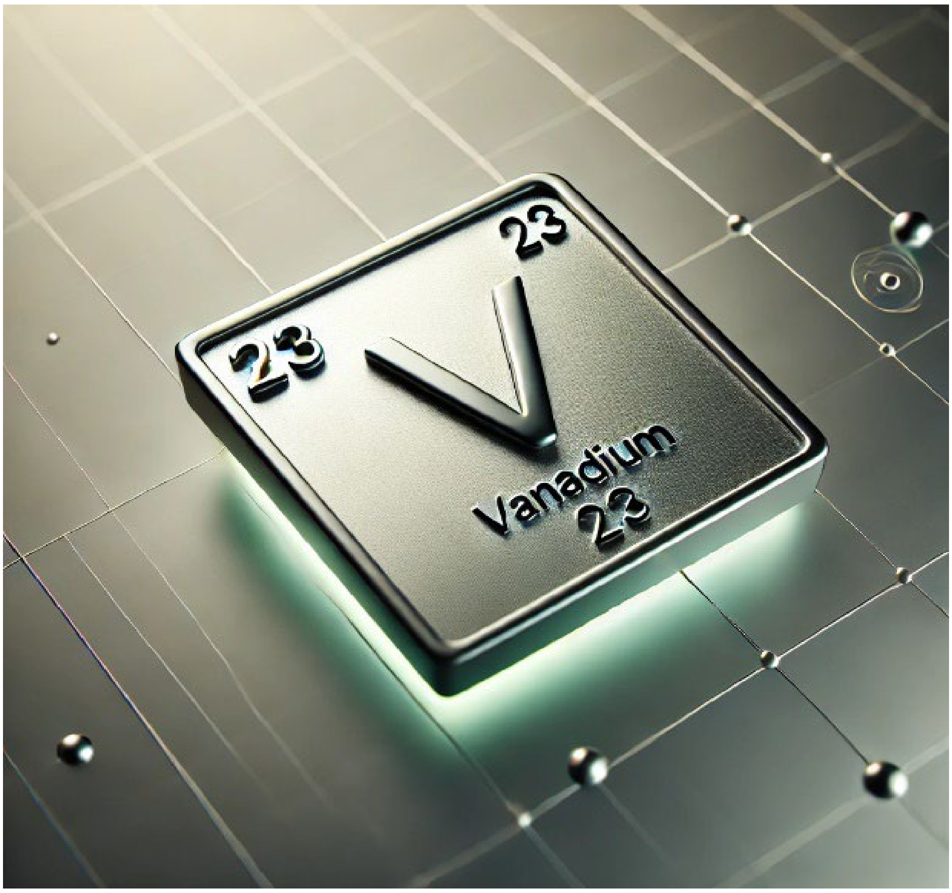
Attachment 4: **Siecap Metallurgical Review Taranaki VTM Project Concentrate 4 February 2025**



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Trans-Tasman Resources Limited

Metallurgical Review:

Recovery of Vanadium from Taranaki VTM Project

New Zealand

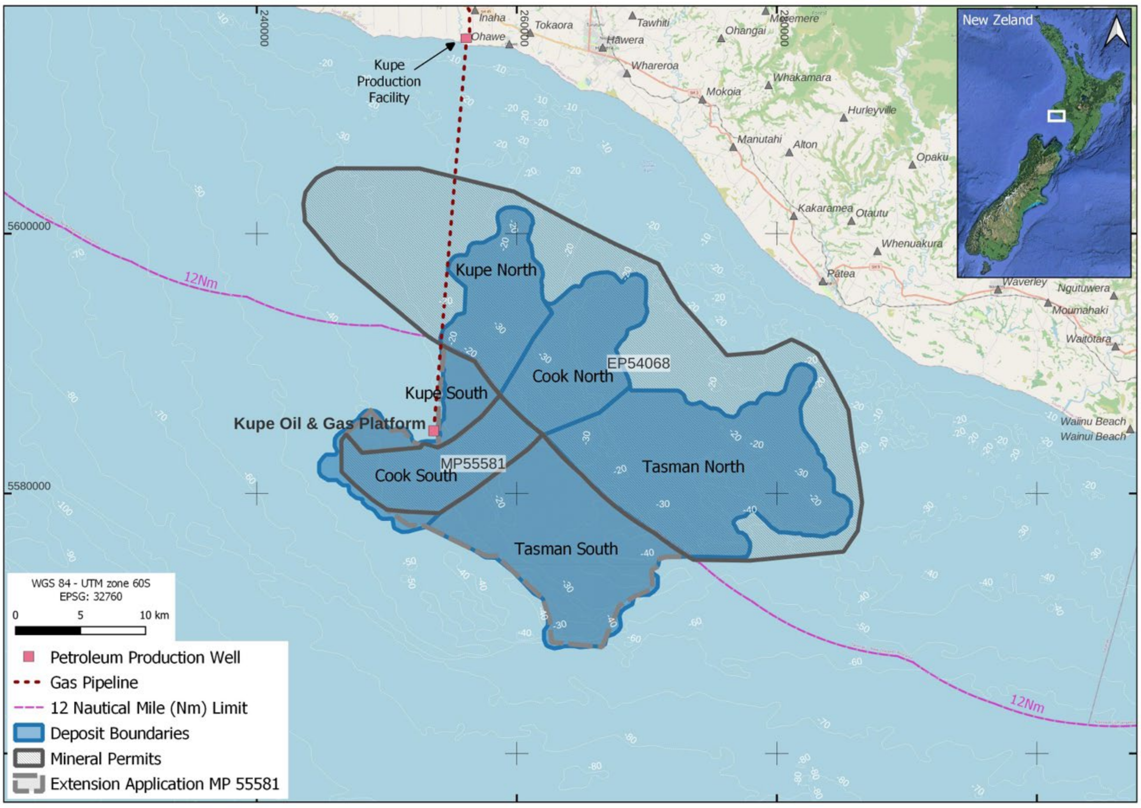
4 February 2025

Executive Summary

Objective and Scope

This metallurgical review for Trans-Tasman Resources (TTR) focuses on optimising the recovery of vanadium from its Taranaki VTM Project titanomagnetite iron sands.

TTR has reported JORC mineral resource estimates for its VTM (a vanadiferous titanomagnetite iron sand) "VTM" project located in the South Taranaki Bight off the west coast of the North Island, New Zealand (Figure 1) of combined Indicated and Inferred mineral resource of 3,157Mt @ 10.17% Fe_2O_3, 1.03% TiO_2 and 0.05% V_2O_5 at a 7.5% Fe_2O_3 cut-off grade containing 1.6Mt of vanadium pentoxide (V_2O_5)[1].



Location Plan of Taranaki VTM Deposits, South Taranaki Bight, New Zealand

Vanadium is present as a co-product in the TTR resource and would be a substantial source of the metal or its compound from future processing. The study encompasses laboratory-scale testing, highlighting process flow sheet development for further process optimisation followed by a one (1)-tonne-per-hour (tph) pilot plant, and a preliminary economic and environmental assessment to evaluate scalability, efficiency, and sustainability. The test work completed since 2018 has been very encouraging and demonstrates pathways to capturing this critical metal as a separate product stream using conventional technology.

[1] Manuka Resources Limited ASX Announcement 1 March 2023

Key Findings

- *Vanadium as a Critical Mineral:* Vanadium is a strategic mineral vital for construction, aerospace, and renewable energy technologies, particularly vanadium redox[2] flow batteries (VRFBs) used for large-scale energy storage. Global demand continues to outpace supply, emphasizing vanadium's critical role in decarbonisation and energy resilience resulting in its inclusion on several country and state government critical metals lists.
- *Extraction Method:* The recent test work and the subsequent study concluded that the Salt Roasting and Water Leaching process holds significant promise for extracting vanadium from New Zealand's ironsands, especially when operating conditions were carefully optimised. Achieving a 79% vanadium recovery rate under laboratory conditions underscored the process's viability.

Laboratory Testing: Summary and Analysis

- Laboratory testing was conducted by the University of Canterbury and Callaghan Innovation to validate the sodium salt roasting-water leaching process, optimise key parameters, and highlight areas for further testing and analysis associated with recovery from titanomagnetite.

Findings of the Laboratory Testing

- *Optimised Conditions:* Recovery rates peaked at 79% under conditions including:
    - Pre-roasting at 800°C.
    - Sodium carbonate roasting at 1000°C.
    - Acid leaching for 2 hours.
- These results of the testing and the testing conditions are encouraging and point to a viable full-scale process
- *Complexities Identified:* Formation of silicon and aluminium compounds during roasting, high-salinity wastewater, and gas emissions were aspects of the process flow route requiring mitigation strategies.
- *Feedstock Variability:* Consistency in feedstock composition was critical to achieving optimal recovery rates and typical of efficient ore flow sheets.

Recommended Bench Scale Testing

Further Bench Scale Testing is recommended to refine process parameters, validate initial findings, and ensure optimal performance before scaling up to pilot or full-scale operations.

Development of a One (1) tph Pilot Plant to confirm the Process Flow Sheet

- *Objective:* Translate laboratory-scale and bench scale testing findings into a scalable, efficient, and sustainable industrial process.
- *Key Components:*
    - Milling and Magnetic Separation
    - Air Roasting
    - Salt Roasting
    - Water Leaching
    - De-Silication
    - Ammonium Metavanadate (AMV) Precipitation
    - Calcination

[2] Redox batteries are fire safe and present minimal safety risks compared with solid state batteries

Economic and Environmental Considerations

- *CAPEX and OPEX:* Preliminary estimates for a Pilot plant set capital costs at USD 1.92 million and identify labour and reagent costs as the cost most impacting the operating economics, again typical of a process flow sheet regardless of scale.
- *Environmental Considerations:* Key factors include wastewater salinity, CO_2 emissions, and solid waste. Implementing mitigation strategies, such as advanced scrubbing systems and renewable energy integration, can help manage these impacts effectively.

Next Steps

- *Bench Scale Testing:* This is to refine, optimise and confirm the process flow sheet.
- *Pilot Plant Implementation*: This will validate the proposed flow sheet under pilot-scale conditions and provide data essentially for the scalability of the design.
- *Optimisation Trials*: Refine roasting and leaching parameters to further enhance efficiency to capture the maximum amount of vanadium in the most economical manner – trade-off studies.
- *Sustainability Initiatives:* Develop waste reduction and energy optimisation strategies.
- *Stakeholder Collaboration:* Further the company's existing multiyear engagement with industry, government, and academia to secure continued support and partnerships.

Conclusion

Laboratory tests conducted by the University of Canterbury and Callaghan Innovation confirm the viability of sodium salt roasting-water leaching process for the sustainable recovery of vanadium from the TTR VTM concentrate.

The TTR test work not only achieved high recovery rates of Vanadium (79%) but also exemplifies a model that balances economic viability with environmental stewardship. This dual focus ensures that resource extraction aligns with sustainable development goals.

The additional bench scale testing and development of the proposed pilot plant will confirm and derisk the process further, providing empirical data to feed into the bankable feasibility study to allow a full evaluation of vanadium pentoxide as a separate product stream as compared to just selling a vanadium rich iron concentrate.

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Introduction

This updated metallurgical review has been prepared for Trans-Tasman Resources, expanding on its test work into advanced mineral processing techniques to optimise the extraction and separation of vanadium from New Zealand sourced vanadiferous -titano-magnetite iron sands concentrate. The scope of this study is to provide an analysis of available processing methods, detailed analysis of TTR commissioned and completed metallurgical testing, the identification of a preferred extraction methodology and the estimated capital and operating costs of a process aimed at maximising the yield and quality of vanadium.

Vanadium, a transition metal with unique properties, is gaining recognition for its strategic importance in the decarbonisation of heavy industry and the emergence of renewable energy technologies. Known for its ability to enhance the strength, durability, and corrosion resistance of steel and other alloys, vanadium is essential in industries such as construction, aerospace, and renewable energy.

Of particular interest is its role in vanadium redox flow batteries (VRFBs), a leading technology for large-scale energy storage critical to the global transition toward low-carbon energy systems. With the significant recent development of vanadium redox flow batteries (VRFB) (Olabi et al., 2023), they have gained significant popularity in large-scale applications, particularly in renewable energy storage. One of the critical advantages of VRFBs is their capability to safely store large amounts of energy for extended durations, making them ideal for grid-scale energy storage.

The largest battery built to date is the 500MW/2000MWh Hybrid Energy Storage Project located in Wushi, China in 2024, of which 50% of the storage is VRFM[3]. Closer to home, Western Australia, whose main grid is the biggest isolated network in the world is building a number of big batteries, some among the world's largest. The Western Australia state government has committed to build a 50 MW, 10 hour vanadium flow battery to support the grid around the mining town of Kalgoorlie[4].

Studies suggest that coupled to a wind source, a 1 MW, 8.3 MWh installation would save up to 0.058 MT of CO_2 over its lifetime (20-years) due to a reduction in renewable energy curtailment, which is equivalent to ca. 29,000 MT of coal burned (Santos et al.,2021).

Globally, vanadium demand is projected to grow significantly, driven by its critical applications. According to Vanitec[5], approximately 90% of vanadium produced is used in the steel industry, where it improves strength and durability in construction-grade steels. The remaining 10% is increasingly utilised in energy storage and high-tech industries, with the VRFB market expected to grow at a compound annual growth rate of over 20% by 2030.

Current global vanadium production is concentrated in countries with complex geopolitical characteristics such as China, Russia, and South Africa, with secondary recovery from steel slags contributing to supply. Despite this, demand is anticipated to outpace supply, underscoring the need for new, stable suppliers, particularly in the southern hemisphere which make use of innovative processing and sustainable sourcing.

Critical Minerals

A critical mineral is defined as a mineral that is indispensable to the functioning of modern economies and technologies but faces supply risks due to factors such as geopolitical tensions, limited production sources, or technical challenges in extraction and processing. These minerals are vital across various sectors, including energy, manufacturing, and technology, and any disruption in their availability could have far-reaching economic and national security consequences. Furthermore, critical minerals play a pivotal role in addressing technologies to counter climate

[3] China Electric Equipment Group Supports Successful Grid Connection of Largest Hybrid Energy Storage Project | Vanitec
[4] Biggest vanadium flow battery in Australia promised for ailing Kalgoorlie grid. https://reneweconomy.com.au/
[5] Vanitec represents the mining, processing, manufacture, research and use of vanadium and vanadium-containing products. https://vanitec.org/

change and advancing renewable energy production. They are essential for the development of low-carbon technologies such as wind turbines, solar panels, and battery storage systems, enabling the transition to cleaner energy systems and supporting global sustainability goals.

In New Zealand, the Ministry of Business, Innovation, and Employment (MBIE) has identified vanadium as a critical mineral in its Critical Minerals List for New Zealand[6] , highlighting its significance to both domestic and international supply chains. This designation reflects vanadium's growing demand, its applications in emerging technologies, and its limited global production, which is currently concentrated in only a few countries. It is important to note that Vanadium is regarded as having an elevated supply risk due to the sourcing of most current global production and global shortages will continue to impact on the ability of New Zealand and our international partners to secure Vanadium.

Vanadium is considered a critical mineral for several important reasons, which relate to both its unique properties and its role in key industries:

1. Enhancement of Steel Strength and Durability: Vanadium is primarily used in the production of high-strength steel alloys, which are essential for the construction, automotive, and energy sectors. These alloys are vital in manufacturing infrastructure, transportation vehicles, and energy infrastructure, making vanadium indispensable for modern economies.
2. Advancements in Energy Storage: Beyond its role in steel production, vanadium is increasingly critical in the field of energy storage. Vanadium redox flow batteries (VRFBs), which use vanadium to store and release energy, are being developed as an alternative to traditional battery technologies. VRFBs offer benefits like long cycle life and scalability, which make them ideal for grid-scale energy storage solutions. As renewable energy sources (such as wind and solar) increase, there is a growing need for efficient and reliable energy storage systems, driving up the demand for vanadium.
3. Geopolitical and Economic Considerations: The global production of vanadium is highly concentrated in a few countries, such as China, Russia, and South Africa, which leads to supply risks and geopolitical concerns. Countries like the United States have recognized vanadium's importance by listing it as a critical mineral, signifying its essential role in national security and economic stability.
4. Strategic Importance: The strategic importance of vanadium is further underscored by its role in aerospace, and energy sectors. Its ability to enhance the properties of metals and energy storage systems makes it essential for industries that are vital to a nation's security, infrastructure, and energy independence.

In January 2025, the New Zealand Government released its Minerals Strategy to 2040 [40], in which it outlines the guiding principles and outcomes for the development of critical minerals. As a critical mineral, TTR's development of the vanadiferous -titano-magnetite iron sands concentrate supports the current New Zealand Government Minerals Strategy, ensuring a stable and secure supply of vanadium is crucial for supporting infrastructure development and advancing energy storage technologies, particularly as countries transition to cleaner, more sustainable energy sources.

The key objectives of this metallurgical review are:

- To evaluate the findings from the research already completed.
- To incorporate additional experimental test work and advances within the industry.
- To address challenges related to emissions, reagent behaviour, and the recovery of by-product fractions such as titanium and iron.
- To recommend next steps for pilot-scale testing and industrial application.

[6] https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/minerals-and-petroleum/critical-minerals-list

Vanadium Extraction Methods Review

Vanadium extraction methods are broadly classified into two principal categories: pyrometallurgical and hydrometallurgical processes. These methods cater to a range of feedstocks, including naturally occurring vanadiferous titanomagnetites and secondary sources like industrial by-products, each with unique chemical and physical characteristics. Pyrometallurgical processes rely on high-temperature operations to achieve the thermal separation and concentration of vanadium , in contrast, hydrometallurgical processes utilise chemical reactions in aqueous solutions to selectively dissolve and recover vanadium, emphasising precision and purity.

Pyrometallurgy Process Overview

The pyrometallurgical extraction of vanadium from vanadiferous titanomagnetites (VTM) involves high-temperature processing to recover vanadium as a valuable byproduct. The process typically begins with smelting VTM in a blast furnace or electric arc furnace to separate the molten iron-rich phase from the slag. Vanadium primarily concentrates in the slag as vanadium oxides. The vanadium-rich slag is then treated through oxidation and roasting to produce vanadium pentoxide (V_2O_5), which is subsequently purified and converted into various vanadium products. The method is widely used due to its efficiency in handling large-scale deposits, though it requires careful management of energy consumption and environmental emissions (Amirreza Nasimifar, 2022).

New Zealand Steel utilises the pyrometallurgical process to extract vanadium as a byproduct from titanomagnetite ironsand mined in the Waikato region. The ironsand is smelted in electric arc furnaces at the Glenbrook steel plant, where molten iron and a vanadium-rich slag are separated. Along with coal and limestone, the primary concentrate (ironsand) is heated and dried in one of four multi-hearth furnaces. It is then fed into the four reduction kilns, where it is converted to 80% metallic iron. Two melters then convert this into molten iron. The iron, at around 1480°C, is transferred to the Vanadium Recovery Unit (VRU), where vanadium-rich slag is recovered for export and further processing.

In the 2000s, an estimated 12,000 tonnes per year were exported to China. However, heightened environmental regulations and stricter enforcement of waste management standards led to a ban on slag imports. Concerns over the environmental impact of processing slag, including emissions, waste disposal, and contamination risks, were key drivers of this decision. As a result, countries like New Zealand, which generate vanadium-rich slag as a byproduct of steel production, had to seek alternative markets. The United States has since become a significant importer of this slag, leveraging its own industrial infrastructure and regulatory frameworks to process and recover vanadium in an environmentally controlled manner. This shift underscores the impact of environmental policies on global supply chains and trade dynamics for industrial byproducts.

Hydrometallurgy Process Overview

Hydrometallurgical extraction of vanadium from vanadiferous titanomagnetites (VTM) utilises advanced chemical processes to recover valuable metals through aqueous chemistry techniques. Hydrometallurgy broadly involves the use of leaching, solution concentration, and purification steps to extract and separate metals from ores, concentrates, or recycled materials, often offering a more environmentally friendly and energy-efficient alternative to traditional pyrometallurgical methods. A number of hydrometallurgical processes are in use globally.

The TIVAN® process, developed by TNG Limited, employs a unique acid leach and solvent extraction method to achieve high recovery rates of vanadium, titanium, and iron with minimal environmental impact. Similarly, Neomet's proprietary process uses chloride-based leaching and recycling to efficiently separate and purify metals, emphasising sustainability and cost-effectiveness. The ARGEX process focuses on producing high-purity titanium dioxide but also extracts vanadium as a byproduct, utilising low-temperature leaching and innovative separation techniques.

Together, these methods demonstrate the growing potential of hydrometallurgical technologies to sustainably and economically recover critical metals from complex ores like VTM.

Preferred Vanadium Extraction Method

The sodium salt roasting - water leaching process, a subset of the hydrometallurgical process is an established and robust technology employed to extract Vanadium from the VTM and with a high vanadium recovery rate has been widely utilised in the vanadium production plants in South Africa and Brazil, accounting for20–30% of the world's total vanadium production annually (Gao et al. 2022).

TTR chose the Salt Roasting and Water Leaching process for extracting vanadium from New Zealand ironsands due to its proven performance, technological maturity, environmental benefits, and compatibility with this unique resource. This softer environmental process reduces reliance on harsh chemicals by using a straightforward roasting step with readily available salts, such as sodium carbonate or chloride, to transform vanadium into water-soluble compounds, which are then efficiently extracted through water leaching.

The Salt Roasting and Water Leaching process comes with challenges that must be addressed to optimise extraction. One key issue is the reaction of sodium salts with elements like silicon (Si) and aluminium (Al) in the ore, forming stable solid compounds that can reduce vanadium recovery. Additionally, the use of ammonium salts during vanadium precipitation generates significant volumes of high-salinity, ammonium-rich wastewater, increasing treatment costs and environmental management requirements.

But compared to more complex and energy-intensive alternatives described in the preceding sections, this process generates fewer hazardous byproducts and greenhouse gas emissions and allows for easier management of waste streams. These environmental benefits, combined with its adaptability to the composition of New Zealand ironsands, make Salt Roasting and Water Leaching the ideal choice for sustainable vanadium recovery and TTR's preferred route.

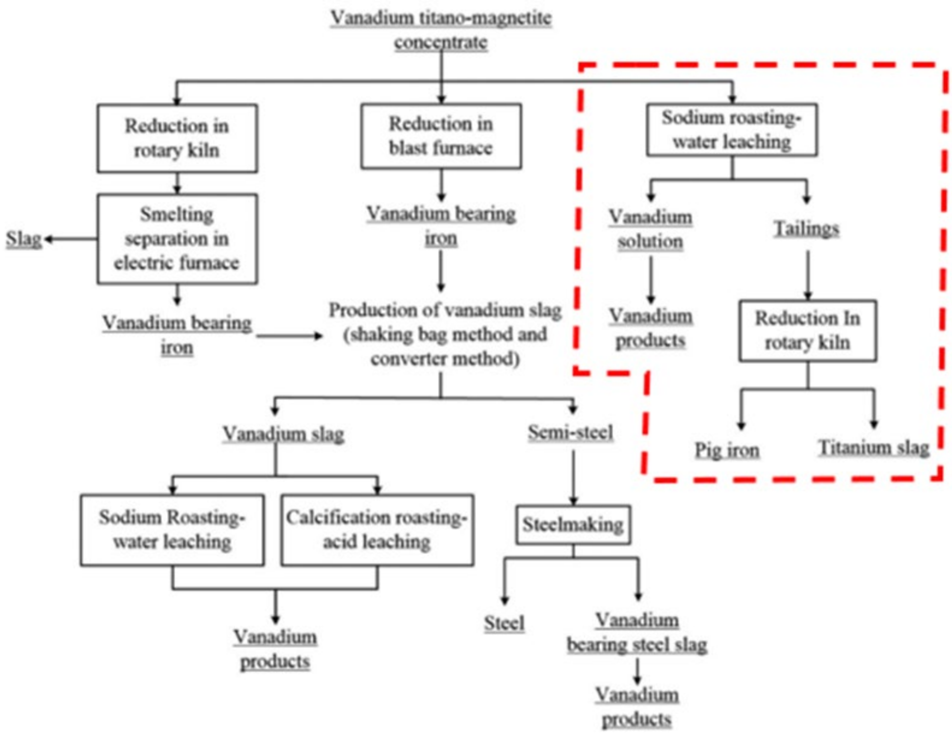


Figure 1: General approaches to Vanadium Extraction(Gao, 2022) , with the Proposed TTR process shown in the red box

Vanadium resource	Vanadium concentration (V)	Method	Optimum Conditions								Vanadium recovery
			Roasting			Leaching					
			Temp	Time	Salt content	Reagent	Acid/base	Time	Temp	Liquid to solid ratio	
Vanadium-bearing	0.8%	Sodium roasting-	1100 °C	3 hours	13 wt.%	Water	-	3 hours	90 °C	-	>80%
Vanadium- bearing	0.35%	Sodium roasting-	1010 °C	2.1 hours	41 wt.%	Sulfuric	4.25 mol/L	4.7 hours	85 °C	12.4	>83%
Vanadium-bearing titanomagnetite	0.48%	Sodium roasting-water leaching	1100 °C	2 hours	16 wt.% Na_2CO_3	Water	-	1 hour	90 °C	4	>80%
Cr-V slag	-	Sodium roasting-	800 °C	2 hours	-	Water	-	1 hour	25 °C	3	>87%
Steel converter slag	0.95%	Sodium roasting-	1000 °C	45 min	10 wt.%	$Na_2CO_3$and	Na2CO3: 40-50	60 min	80 °C	15	>80%
Cr-V slag	5.16%	Sodium roasting-	850 °C	90 min	15 wt.% NaOH, 35	Water	-	30min	90 °C	3	>95%
Steel converter slag	1.2%	Sodium roasting-	1000 °C	2 hours	20 wt.%	Sulfuric	2.05 mol/L	60 min	70 °C	19.99	>96%
Vanadium slag	4.73%	Sodium roasting-	850 °C	60 min	10 wt.%	Sodium	160 g/L	150 min	95 °C	10	>90%
Steel converter slag	3.5%	Sodium roasting-	850 °C	60 min	50 wt.%	Water	-	-	-	-	>85%
Cr-V slag	-	Calcium roasting two-step acid	800 °C	1 hour	12.3 wt.% Na_2CO_3	Sulfuric acid	-	Step 1: 20 min Step 2: 20 min	Step 1: 50 °C Step 2: 50°C	Step 1: 10 Step 2: 5	>87%
Titanomagnetite concentrate	-	Sodium roasting-water leaching	1150 °C	-	6-8 wt.% sodium salt	Water	-	-	90 °C	-	>75%

Table 1: Comparison of vanadium extraction from vanadium-bearing ore/concentrate and slag based on research. Reference (Amirreza Nasimifar, 2022) (Feng Gao, 2021)

Laboratory Testing in Collaboration with University of Canterbury and Callaghan Innovation

University of Canterbury – Department of Chemical and Process Engineering

In 2021, the University of Canterbury (UC) and Callaghan Innovation (CI) conducted lab-scale testing on titanomagnetite concentrate sourced from three New Zealand locations, including TTR concentrate. The TTR sample and a second sample (Labelled as "PC" to maintain confidentiality, as its identification is restricted due to commercial sensitivity) shared nearly identical major oxide compositions, leading to comparable performance during testing. In contrast, the third sample exhibited a significantly different composition and performed notably worse in the testing program, highlighting the impact of ore variability on extraction efficiency.

The TTR and PC samples are ironsand concentrates while the VRC sample (Labelled as "VRC" to maintain confidentiality, as its identification is restricted due to commercial sensitivity) was a pyrometallurgical product i.e. vanadium enriched slag which understandably performed differently.

Sample	Name	Fe_2O_3	MnO	TiO_2	CaO	K_2O	P_2O_5	SiO_2	Al_2O_3	MgO	Na_2O	V_2O_5
1	TTR	82.90	0.68	8.60	0.74	0.09	0.29	2.42	3.79	3.09	0.11	0.57
2	PC	84.30	0.63	7.96	0.51	0.05	0.09	2.16	3.79	2.84	0.07	0.60
3	VRC	32.11	10.39	13.84	2.86	0.01	0.09	17.56	1.55	1.13	0.13	13.72

Table 2: Sample Major Oxide Compositions

The testing program explored the potential of the Salt Roasting and Water Leaching process, described in the previous section, the method favoured for its simplicity, established performance, and adaptability to local resources. The laboratory-scale testing evaluated and optimised the process for vanadium recovery from New Zealand ironsands.

The study evaluated roasting conditions, leaching solvents, and pre-treatment steps, and aimed to identify optimum operational parameters while addressing challenges such as byproduct management and environmental impacts.

The study concluded that the Salt Roasting and Water Leaching process holds significant promise for extracting vanadium from New Zealand's ironsands, especially when operating conditions were carefully optimised. Achieving a remarkable 77% vanadium recovery rate under laboratory conditions underscored the process's viability. However, challenges such as managing byproducts, addressing environmental impacts, and accommodating variations in sand composition were identified as hurdles to industrial-scale implementation. To advance this work, the study recommended future efforts focus on reducing wastewater and gas emissions, further enhancing the process's environmental sustainability, and conducting pilot-scale tests to confirm its commercial feasibility.

Experimental Procedure:

The experimental procedure detailed in the report outlines the steps taken to evaluate the Salt Roasting and Water Leaching process for vanadium extraction from the ironsand samples. Key steps included:

Sample Preparation:

- The samples were homogeneously mixed with sodium salts (e.g., sodium carbonate or chloride) using a ball mill for 60 minutes to ensure even distribution.

Roasting:

- The prepared mixtures were roasted in a furnace equipped with temperature control to explore various roasting conditions, including temperature and duration.
- After roasting, the samples were cooled to room temperature and ground to ensure uniformity.

Leaching:

- The roasted materials were leached using distilled water or acidic solvents under controlled conditions.
- Residual solids were separated using centrifugation and washed three times with distilled water to remove any remaining salts or impurities.

Analysis:

- The composition of the roasted and leached samples was analysed using X-ray fluorescence (XRF) to determine metal content.
- The leachate was further analysed using inductively coupled plasma mass spectrometry (ICP-MS) to quantify the vanadium and other elements extracted.

Process Optimization:

- Experiments were conducted to optimise pre-treatment, roasting, and leaching parameters. These included varying temperatures, roasting times, sodium salt compositions, and leaching solvents.

This methodical approach provided critical insights into the conditions that would maximise vanadium recovery, laying the foundation for further refinement and scalability of the process.

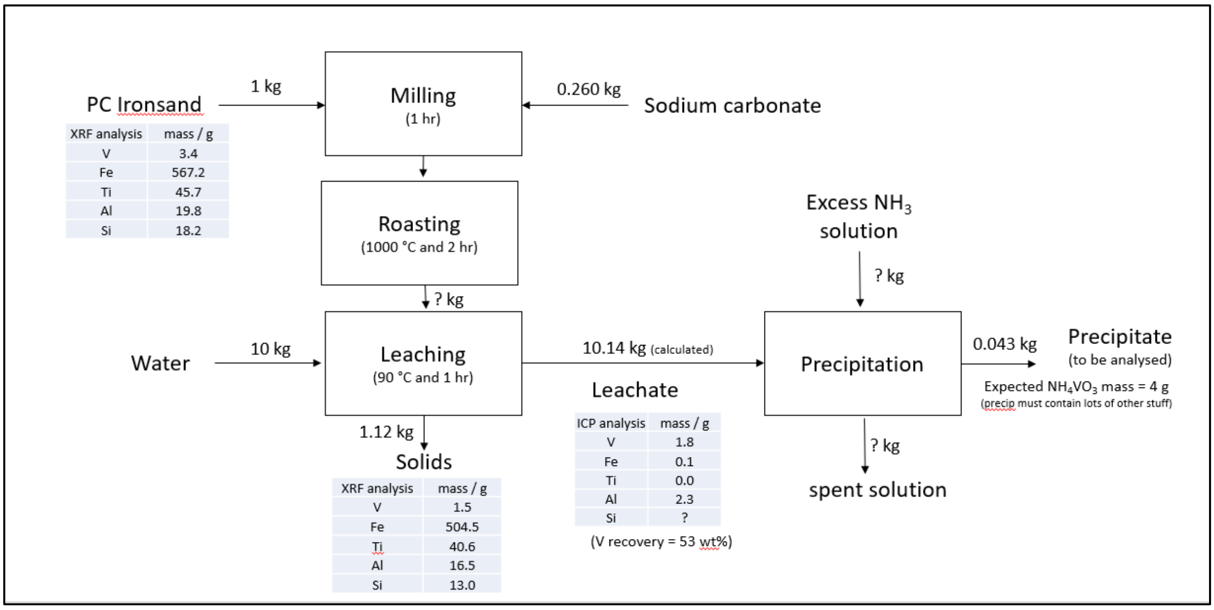


Figure 2: Mass balance of the PC sand through the University of Canterbury laboratory testing process

Analysis of the Results

The third sample (VRC) was excluded from the Siecap conducted analysis due to its differing composition compared to the TTR and the second (PC) sample. While the TTR and PC samples shared similar major oxide compositions and demonstrated comparable performance, the VRC sample's distinct chemical makeup resulted in a vanadium recovery rate of only 9% under the baseline processing condition. As such, this analysis study focused on the two representative samples to provide meaningful insights into optimising vanadium extraction.

Average Vanadium Extraction Across Samples (Baseline Test)

The study evaluated vanadium recovery from the representative samples under identical baseline roasting and leaching conditions (roasting a 20g sample with 5 g of sodium carbonate at 1000 °C for 2 hours, followed by leaching at 90°C with distilled water for 1 hour). Under these baseline conditions, the results revealed varying levels of vanadium recovery.

On average, the baseline testing yielded a vanadium recovery rate of approximately 55% across the two representative sand samples.

1. Optimisation of Vanadium Extraction

The study then systematically investigated the effect of various parameters on vanadium extraction:

- Whilst the UC/Callaghan Innovation test work references a coarse leach it does not elaborate on what defined the coarse leach. However, Goso et.al. 2016 [11] detailed the impact of a coarse leach on vanadium recovery and clearly defined the effect of the particle size distribution (PSD) i.e. D100 of 1000 µm and D90 of 25 µm, in which case the pulp density and pH were kept constant at 65 m/m% and 7.8, respectively. The results show that the best vanadium extraction was generally achieved when the coarser material (D100 of 1000 µm) was used as feed.
- Pre-treatment: Air roasting the sand prior to sodium salt roasting improved vanadium recovery from 55% to 65%.
- Roasting Conditions:
  - Temperature: Vanadium recovery increased with roasting temperature, peaking at 1000 °C.
  - Duration: Recovery improved with time, reaching a maximum of 56% after 4 hours. However, the difference in recovery between 2 and 4 hours was minimal, suggesting diminishing returns with extended roasting times.
  - Sodium Salts: Sodium carbonate and a mixture of 50 wt.% sodium chloride and 50 wt.% sodium carbonate both achieved comparable recovery rates.
- Leaching Conditions:
  - Time: The leaching duration had a marginal effect, with vanadium recovery stabilizing at 57% after 2 hours.
  - Solvent: Acidic solvents demonstrated superior performance compared to distilled water, achieving up to 65% vanadium extraction. However, the use of acidic solvents presents several adverse environmental impacts that must be carefully managed. Acidic solvents are inherently more reactive and, if not handled properly, can pose risks to soil and water quality through potential leakage or improper disposal. These solvents may produce hazardous by-products or residues, requiring robust waste management systems to prevent contamination of ecosystems.

2. Vanadium Extraction under Optimum Conditions

The detailed composition analysis showed efficient recovery of vanadium alongside other elements such as iron (Fe) and titanium (Ti). This demonstrates the effectiveness of an optimised process.

Combining optimal parameters (air roasting at 800 °C for 2 hours, sodium carbonate roasting at 1000 °C for 2 hours, and water leaching for 2 hours), on a coarse leached representative sample the test work achieved an average vanadium recovery of 77%.

A slight increase in the vanadium recovery i.e. 79% was achieved using an acidic leach. The additional handling and storage protocols that are demanded by the use of acidic solvents would preclude its use in a full-size plant.

3. Challenges Identified

The process identified the following challenges:

- Formation of stable solid compounds during roasting, particularly with silicon (Si) and aluminium (Al), reducing vanadium availability.
- Generation of high-salinity ammonium-rich wastewater during vanadium precipitation, increasing treatment costs.
- Emission of harmful kiln gases, requiring advanced gas scrubbing systems to minimise environmental impacts.

Contributing New Zealand Based Research

Extraction of Vanadium from New Zealand Titanomagnetite Sand and Vanadium Recovery Concentrate University of Victoria – Lachlan Gaudin MSc Thesis

This thesis was undertaken to explore the potential methods of selectively extracting vanadium first from vanadium recovery concentrate (VRC) and then from iron sand (IS) sample materials. The research undertaken as part of this thesis showed that Vanadium can be selectively leached from both the New Zealand Iron Sands and Vanadium Recovery Concentrate (Vanadium Rich Slag).

The results of this research pertaining specifically to the roasting and leaching of the Ironsand sample was used for the analysis of this review.

Name	Fe_2O_3	MnO	TiO_2	CaO	K_2O	P_2O_5	SiO_2	Al_2O_3	MgO	Na_2O	V_2O_5
TTR	82.90	0.68	8.60	0.74	0.09	0.29	2.42	3.79	3.09	0.11	0.57
PC	84.30	0.63	7.96	0.51	0.05	0.09	2.16	3.79	2.84	0.07	0.60
IS	84.7	0.73	7.8	0.4	-	0.1	1.61	3.89	2.68	0.1	0.58

Table 3 – Major Oxide Composition Comparison with UC/Callaghan Innovation Laboratory Tests

The first stage of experiments conducted on the ironsand concentrate entailed the HCl leaching of a non-roasted sample and determining the percentage of each targeted element that could be extracted during a 2hr leaching period using hydrochloric acid (HCl) at specific concentrations.

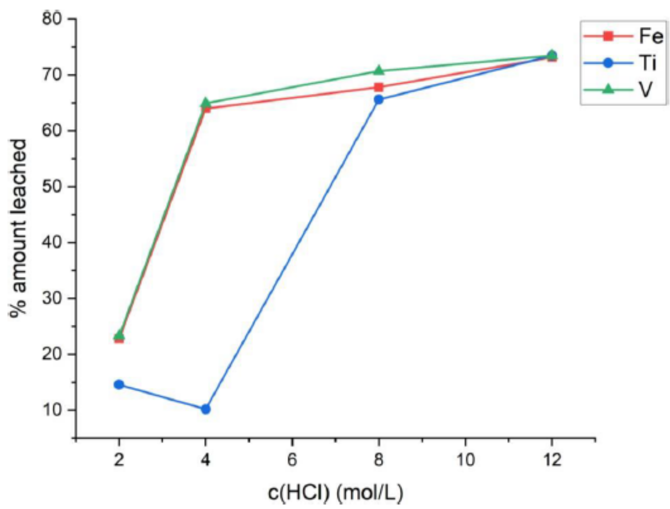


Figure 3 : Final extraction values at 2 hr as a function of HCl concentration

The second stage of experiments conducted on the ironsand concentrate entailed first roasting of the sample at 900 C for 3 hours in air. and then determining the percentage of each targeted element that could be extracted during a 2hr leaching period using hydrochloric acid at specific concentrations.

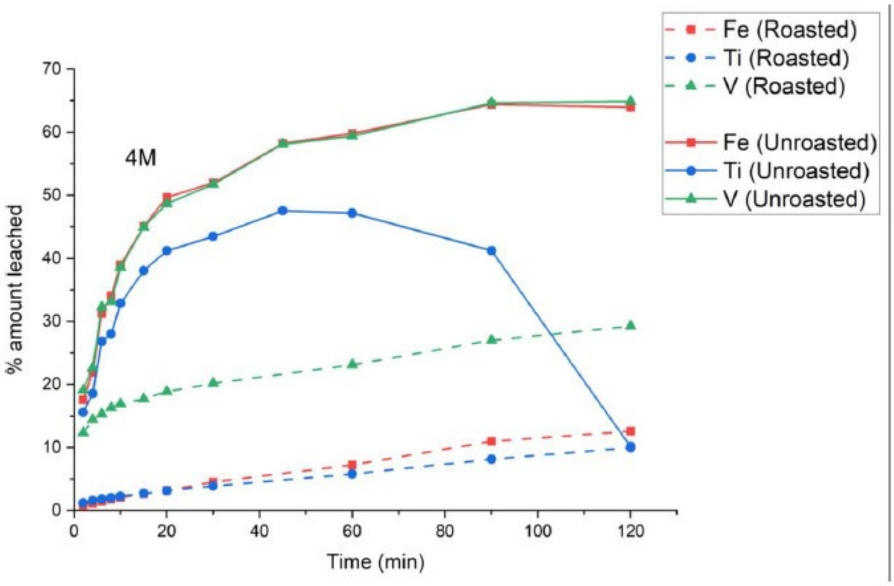


Figure 4 – Comparison of Non-Roasted vs Roasted Leached Samples

Generally, the leaching rate of each element (Fe, Ti, and V) decreased after the roasting procedure. This was because the roasting of the ironsand sample formed HCl-resistant phases.

The total % amount leached during the unroasted experiment was approximately 65 %, and this dropped to approximately 30 % for Vanadium after roasting. Also importantly, in the unroasted leaching experiment, the Vanadium curve closely followed the Fe curve indicating that the Vanadium was locked up in the ferrous mineral. After roasting while the Vanadium curve did not follow the Fe curve, it did take on the same slope after the first few minutes. This observation seems to indicate that the Vanadium leached over the first few minutes is not bound in the Fe mineral phase whilst the Vanadium leached thereafter seems to indicate that this portion of Vanadium is found in the ferrous mineral phase.

Insights

The findings from the thesis contribute to and reinforce the knowledge gained in the UC/Callaghan Innovation laboratory tests by providing additional insights into the behaviour of Vanadium during the extraction process. Specifically:

- Comparison of Compositions: The thesis highlights the similarities in major oxide compositions across ironsand samples (TTR, PC, and IS), validating the comparison across the samples used in the UC/Callaghan Innovation tests. This alignment strengthens the reliability of findings about the impact of roasting and leaching on vanadium extraction.
- Selective Leaching: The thesis demonstrates that vanadium can be selectively leached from ironsand concentrates, providing evidence for the efficacy of hydrometallurgical techniques. This aligns with the UC/Callaghan Innovation findings where roasting and leaching processes were optimised for better vanadium recovery.
- Roasting Impacts: The thesis identified that roasting forms HCl-resistant phases, thereby reducing vanadium leaching rates from approximately 65% (unroasted) to 30% (roasted). This supports the selection of water based leaching methods.
- Behaviour of Vanadium: The thesis reveals how vanadium's leaching behaviour differs between roasted and unroasted samples. In roasted samples, vanadium appears to partially decouple from the ferrous mineral phase, a nuance not uncovered in the UC/Callaghan Innovation tests but which provides deeper context for the importance of pre-treatment and phase changes during roasting.

- The thesis's focus on HCl leaching expands the understanding of solvent efficacy, providing a comparison with the distilled water and acid leaching investigated by UC/Callaghan Innovation. This broader solvent exploration can guide future optimisation efforts.
- Whilst the thesis generally supports a water leach, tests conducted by UC Callaghan on a "BC" (Best Case) sample, sourced from a representative sample indicates that using a salt roast process then leaching with a HCL formulation could result in a Vanadium recovery of 79%. One issue that will have to be resolved if an HCL Leach is pursued, is the effect of the increased presence of AL_2O_3 in the leachate and its effect on the efficiency of the precipitation process.

Overall, the thesis deepens the understanding of vanadium extraction mechanisms, validating the methodologies used by UC/Callaghan Innovation while introducing additional perspectives on phase behaviour, leaching efficiency, and sample variability. These insights can inform process refinement and scalability for industrial applications.

Recommended Bench Scale Test Program

The transition from laboratory-scale research to a scalable, efficient, and sustainable industrial process has identified key areas that require further investigation. These areas must be thoroughly examined through an additional, well-structured bench-scale testing program to provide critical data supporting the development of a Pilot Plant.

To advance the evaluation of vanadium recovery from the TTR titanomagnetite concentrate, it is recommended that the next phase of testing involve an expanded bench-scale program. This program should be designed to systematically assess and optimise the conditions for each stage of the industrial process, ensuring maximum vanadium recovery while addressing technical and economic feasibility for commercial-scale implementation.

To facilitate a comprehensive evaluation, it is proposed that the bench-scale tests be conducted on a representative 20 kg sample of titanomagnetite concentrate. This larger sample size will allow for detailed testing of key parameters, including but not limited to:

- *Leaching Efficiency:* Identifying optimal reagent concentrations, temperature, and retention times to maximise vanadium dissolution.
- *Precipitation and Purification:* Refining methods to selectively recover vanadium while minimising impurity co-extraction.
- *Solid-Liquid Separation*: Assessing filtration and settling characteristics to optimise process efficiency.
- *Residue Management:* Evaluating tailings characteristics and potential reuse or disposal strategies.
- *Process Scalability*: Simulating continuous processing conditions to validate operational feasibility.
- *Economic Viability:* Identifying cost drivers and potential optimisations for pilot- and full-scale operations.

By conducting this expanded bench-scale testing program with a 20 kg concentrate sample, the study will generate robust data necessary for refining process parameters, de-risking scale-up challenges, and further informing Pilot Plant design. Siecap regards this step as critical to establishing a commercially viable and technically sound vanadium recovery process.

Recommended Approach

The test work should involve a systematic evaluation of processing steps to determine the repeatable optimal conditions that will achieve the most efficient recovery of vanadium from the TTR sample. From these results, TTR will be able to refine the proposed pilot plant setup, recommended within this report. In addition, it is recommended that TTR review the byproduct streams with the proposed process flow and the development of pig iron and titanium credits.

The key focus areas should include:

Material Assessment and Preparation

- Conduct preliminary analysis to understand the TTR concentrate composition (i.e. particle size density, pulp density) and the effects it may have on vanadium extraction.
- Air roasting of ore pre-reactant and optimisation with water leaching

Processing Evaluation

- Assess the impact of roasting on vanadium extraction efficiency and impurity removal.
- Investigate different reagent applications for optimising the roasting and leaching processes.
- Identify potential operational challenges such as material handling, reagent consumption, and by-product formation.
- Investigate the areas provided in this report under the section Next Steps.

- The Siecap Phase 1 report provided a high-level metallurgical flow chart (Figure 5), which provides the basis for testing of bench scale samples, with agreed testing parameters to be identified with TTR and the metallurgical consultant / laboratory.

Technical and Environmental Considerations

- Review the formation of silicate compounds and other impurities that could impact vanadium recovery.
- Evaluate the waste streams and the impact of roasting and leaching, including wastewater salinity and gas emissions.
- Develop mitigation strategies for process waste and emissions control.

Financial and Economic Considerations

- Estimate costs associated with reagent usage, energy consumption, and waste management.
- Evaluate the overall economic feasibility of implementing the extraction process.

Bench Scale Testing - Recommendations and Next Steps

A flexible approach to the bench-scale testing is recommended, allowing for iterative refinements based on initial findings.

The study should focus on identifying the most efficient and cost-effective methods before proceeding to the pilot-scale validation. Ensuring technical viability alongside environmental and financial sustainability will be key to sustainable vanadium extraction from the TTR concentrate.

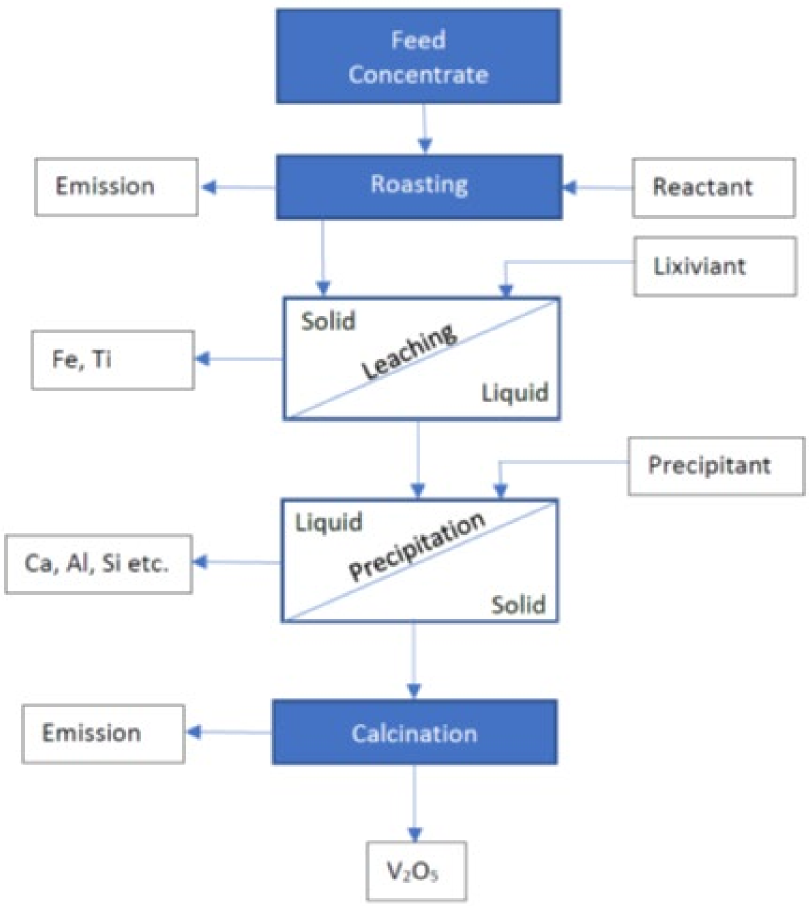


Figure 5: Outline of the Process Flow Sheet for the basis of the bench scale testing

Updated Flow Sheet Development – One tph Pilot Plant

Introduction to Process Flow Sheet Development

The development of a pilot plant process flow sheet is a critical step in translating the laboratory-scale research and the proposed additional bench scale testing program into a scalable, efficient, and sustainable industrial process.

The laboratory-scale research has allowed the designing of a logical sequence of unit operations to achieve the desired product quality, maximise recovery rates, and minimise environmental impacts and has also highlighted areas that need to be studied further in the additional proposed bench scale testing program.

For vanadium extraction from ironsand, flow sheet development integrates key steps such as pre-treatment, roasting, leaching, and purification, each optimised based on experimental findings. This process ensures that the chosen methods, including roasting conditions, leaching solvents, and byproduct management strategies, are not only technically feasible but also economically viable. By aligning laboratory results with practical operational requirements, the process flow sheet serves as a roadmap for transitioning to pilot-scale and eventually full-scale production.

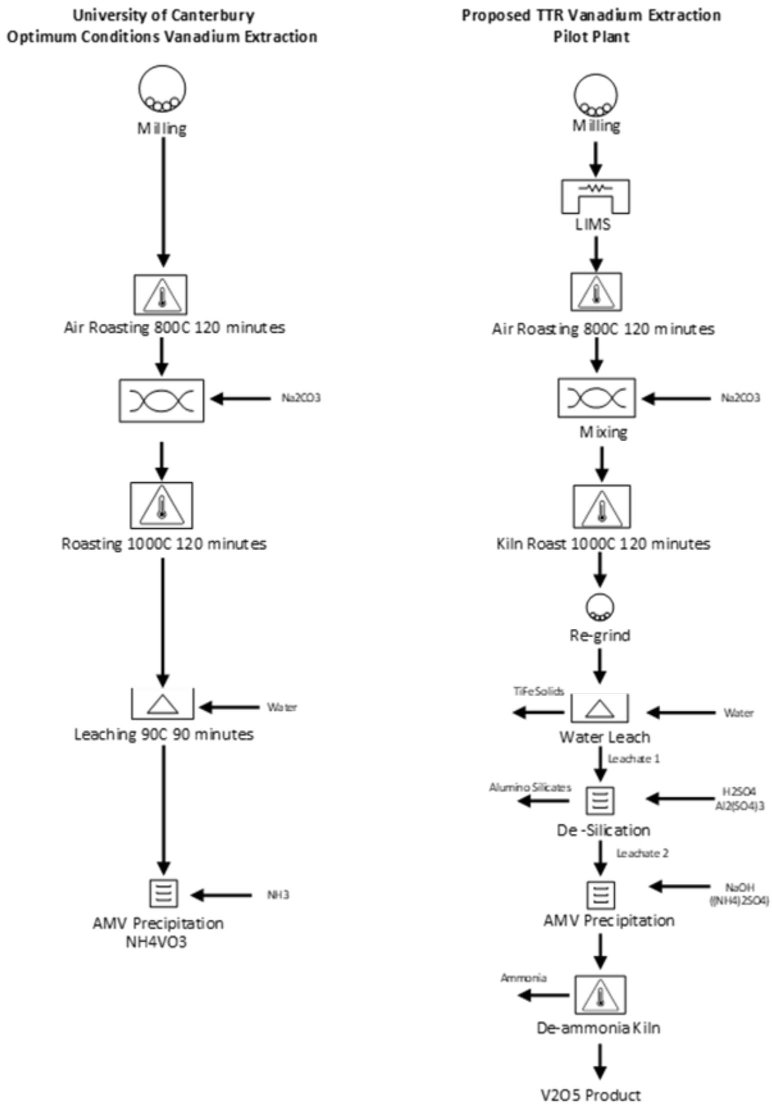


Figure 5: Process Flow Diagram, referencing the UC/Callaghan Innovation Laboratory Test work Against Pilot Scale Flow Sheet

Sizing the pilot plant at a 1 ton per hour (tph) feed rate allows TTR to mitigate technical, financial, and operational risks associated with scaling up from laboratory or bench-scale processes.

A 1 tph capacity will allow for comprehensive testing of the process under conditions closely resembling full-scale operations while maintaining manageable capital and operating costs. This scale is large enough to generate reliable data on process efficiency, recovery rates, and waste management, yet small enough to enable flexibility in modifying equipment or processes in response to unexpected challenges.

Additionally, the 1 tph capacity reduces potential environmental impacts during the pilot phase, ensuring compliance with regulatory requirements and easing community acceptance. By optimising at this intermediate scale, the project can build a robust foundation for a successful transition to commercial-scale production.

Development of the TTR Process Flow Sheet

Milling

The impact of particle size distribution (PSD) on vanadium extraction was evaluated by Goso et.al. (2016), and the results of the UC/Callaghan Innovation test work highlighted that the highest vanadium extraction was generally achieved using coarser material (D100 of 1000 µm) as feed.

The reduced vanadium extraction observed with the finer grind size was attributed to potential oxidation during milling, which may have led to the formation of insoluble phases. (Goso, 2016)

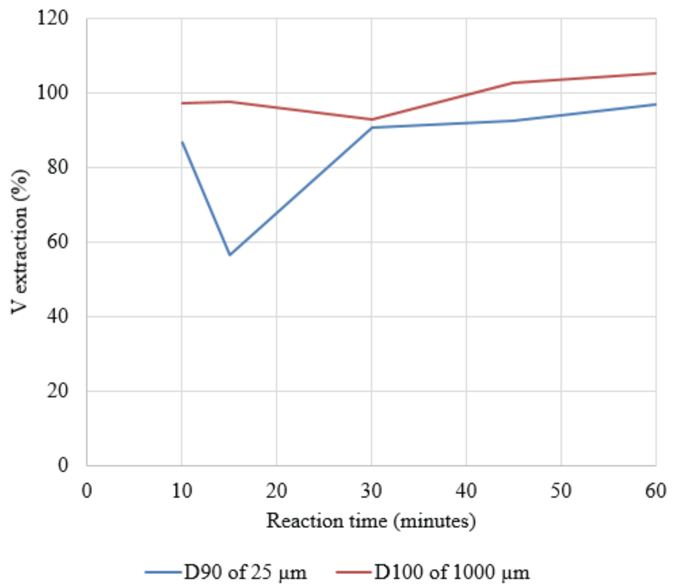


Figure 6: Effect of PSD on the vanadium extraction from titanomagnetite roast. Taken from (Goso, 2016)

As part of any ongoing testing, it is recommended that the particle size distribution be subjected to further testing to confirm the optimum range that will provide maximum vanadium extraction.

Low-Intensity Magnetic Separation

The inclusion of a LIMS circuit will remove any further non-magnetic material from the concentrate, post milling, thereby removing any liberated silicates. This would enable the process to further advance quality consistency and provide a slight uplift in the vanadium percentage in the roasting feed.

Air Roasting

The UC/Callaghan Innovation test work (Montecillo, 2021) clearly showed that air roasting the concentrate prior to a blending and roasting process increased the vanadium extraction.

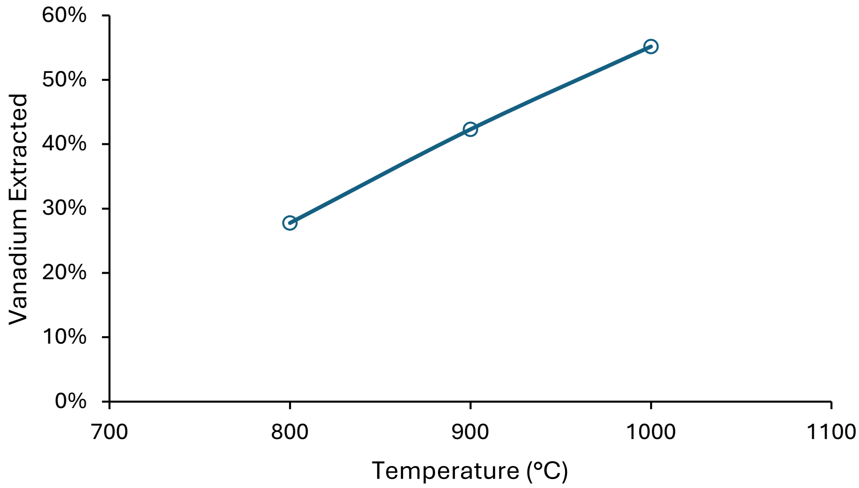


Figure 7: University of Canterbury Vanadium Recovery from the pre-heating of the TTR concentrate

Salt Roasting

The quality of the roasting process significantly influences vanadium recovery, and roasting additives are typically used to enhance its effectiveness. However, traditional additives such as sodium and calcium salts present several challenges. Sodium salt additives require large quantities to achieve high vanadium leaching efficiency, leading to the generation of polluting gases and challenges in their treatment. In the case of the TTR titanomagnetite concentrate the salt addition could be as high as 25% of the feed material. Similarly, calcium salt additives pose issues like high additive consumption, selective compatibility with roasting materials, and potentially high costs associated with vanadium extraction. (Li, 2018).

The UC/Callaghan Innovation test work (Montecillo, 2021) undertook analysis of different sodium salt additive to determine if there was an improvement in the vanadium extraction. The results showed there was a slight advantage with the use of sodium carbonate, however this was minimal. In comparison, the roasting conditions (time and temperature) play a critical part in the extraction of vanadium. This is supported by a number of the technical references.

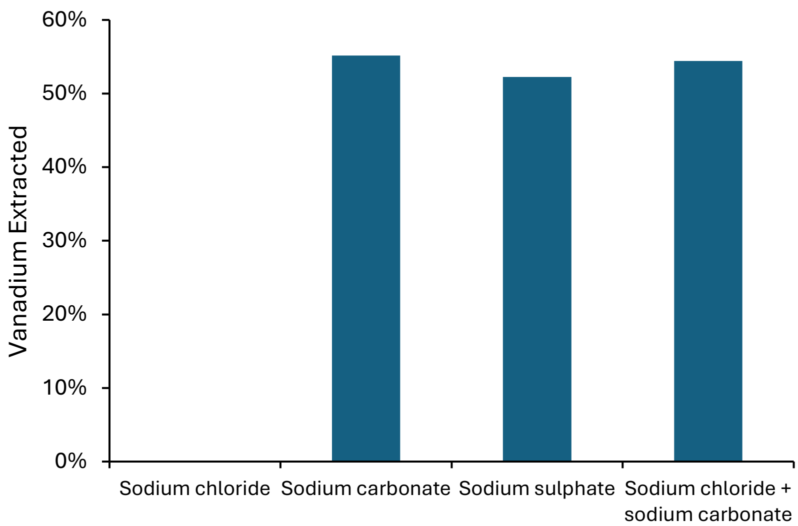


Figure 8: University of Canterbury salt roast additive test results

Sodium Carbonate (Na_2CO_3):

- Chemical Interaction: Sodium carbonate reacts with vanadium oxides in the feed to form water-soluble sodium vanadates during roasting. This enhances vanadium recovery in the subsequent leaching process.
- Temperature Stability: Sodium carbonate is stable at high temperatures and facilitates effective roasting at elevated conditions (e.g., ~1000 °C).
- Byproducts: The reaction typically produces CO_2 as a gas, which is less challenging to scrub compared to some other gaseous emissions.
- Effectiveness: It is often more effective for vanadium recovery due to its strong reactivity with vanadium-containing compounds.
- Environmental Impact: Produces relatively manageable gaseous byproducts, primarily CO_2, but requires attention to carbon emissions.

Sodium Chloride (NaCl):

- Chemical Interaction: Sodium chloride can enhance the mobility of certain metal ions during roasting by creating volatile metal chlorides. However, its reactivity with vanadium oxides may not be as strong as sodium carbonate.
- Chlorination Effects: NaCl may volatilize and form chlorides during roasting, which can lead to the loss of valuable metals or cause operational challenges.
- Byproducts: Roasting with NaCl can produce harmful chlorine or hydrochloric acid gases, necessitating advanced scrubbing systems to mitigate environmental and safety risks.
- Effectiveness: While NaCl can aid in the extraction of other elements, its efficiency for vanadium recovery may be lower compared to sodium carbonate unless used in specific combinations (e.g., with Na_2CO_3).
- Environmental Impact: The release of chlorine-containing gases poses a higher environmental and health risk compared to sodium carbonate.

Key Differences:

- Reactivity: Sodium carbonate is more directly reactive with vanadium oxides, forming soluble compounds, while sodium chloride primarily influences mobility and may have limited direct reactivity with vanadium.
- Byproducts: Sodium carbonate produces CO_2, whereas sodium chloride can release more hazardous chlorine-based gases.
- Efficiency: Sodium carbonate is typically more effective for vanadium recovery under standard roasting conditions.

Re-Grinding

Due to the salt roasting and cooling process, the material sinters into a crusty slag-like texture. The post salt roast material will require to be ground to facilitate an efficient leaching process.

Water Leaching

Salt roasting followed by water leaching is an efficient process for enhanced vanadium recovery, converting vanadium in titano-magnetite into water-soluble vanadates such as sodium or potassium vanadate. Water leaching effectively dissolves these compounds, ensuring high recovery rates while selectively separating vanadium from insoluble materials like iron and titanium oxides. This enhances the purity of the extracted solution, simplifying downstream processing. Environmentally, the process eliminates the need for strong acids or harsh chemicals, reducing both environmental impact and operational hazards. Operating under mild conditions at ambient or slightly elevated temperatures, water leaching consumes less energy than more aggressive hydrometallurgical methods. It is also cost-effective, requiring simple equipment and minimising material losses through efficient resource utilisation. Scalable for industrial applications, this method is well-suited for large-scale vanadium extraction and enables the recovery of valuable byproducts like titanium, improving economic viability. Additionally, its selective nature reduces impurities in the vanadium solution, leading to high-quality final products with improved metallurgical performance

In review the research and industry papers, the effect of not only the particle size distribution, leaching time affect the vanadium extraction, but also the pulp density of the feed into the leaching process can improve the vanadium recovery, (Goso, 2017 and Muthukumar, 2020). It is recommended further testing of these variables is undertaken to optimise the leaching process of the TTR concentrate.

De-Silication Precipitation

The precipitation of silicates from a water-based leachate within a stirred precipitation tank will be a critical step in the TTR process. During leaching, silicate minerals will dissolve alongside the vanadium. Precipitating the silicates serves to purify the solution, preventing interference in subsequent processing steps such as metal recovery or precipitation. This process will involve adjusting the pH, temperature, and introducing a specific reagent to promote selective silicate precipitation while minimising the loss of Vanadium.

Silicate Removal

After silicates are precipitated through controlled pH adjustment and reagent addition, the resulting solid precipitates will be separated from the liquid using a filter press. This equipment works by forcing the slurry through a series of filter plates, which trap the solid precipitates while allowing the clarified leachate to pass through. The filter press provides a reliable and efficient method for handling large volumes of slurry, producing a clear filtrate and compact filter cake that can be easily removed and disposed of or further processed. By effectively removing silicates, the filter press prevents contamination, scaling, or clogging in subsequent processing stages, ensuring the vanadium-rich solution remains suitable for precipitation or extraction steps. This approach is particularly advantageous for its operational simplicity, scalability, and ability to handle high-solids content.

Ammonium Metavanadate (AMV) Precipitation

The formation of AMV begins with the treatment of the vanadium-rich leachate solution within a stirred precipitation tank. The addition of ammonium salts, commonly ammonium sulphate or ammonium chloride will induce a chemical reaction that results in the precipitation of ammonium metavanadate.

This process is highly selective and efficient, enabling the separation of vanadium from other impurities in the leachate. The precipitated AMV is then collected, filtered, and subjected to further processing steps, such as calcination, to produce high-purity vanadium pentoxide or other specialized vanadium compounds. AMV's significance extends beyond its role in the production chain; its controlled precipitation also ensures high recovery rates and contributes to the economic viability of vanadium extraction and refinement operations.

AMV Removal

The AMV precipitate will be separated from the leachate using a filter belt, which continuously processes the slurry by feeding it onto a moving porous belt. As the slurry moves along the belt, vacuum or pressure filtration removes the liquid, leaving behind a filter cake of AMV. The filter belt system is particularly advantageous for its ability to handle high-throughput operations and maintain continuous processing. The collected AMV filter cake will be washed to remove residual impurities. This efficient and scalable approach ensures high recovery rates, minimises losses, and supports the production of high-purity vanadium compounds.

De-ammonia kiln calcination

During this thermal decomposition, the recovered and cleaned AMV is subjected to precisely controlled kiln conditions, including optimal temperatures and residence times, to ensure complete breakdown of ammonium compounds while preserving the purity and desired crystalline structure of the resulting V_2O_5.

A key feature of the calcination process is the recovery of ammonia gas released during decomposition. The installed system will capture and recycle this ammonia, minimising emissions and reducing the environmental footprint of the operation. This closed-loop approach not only aligns with sustainability goals but also enhances overall process efficiency by converting what would otherwise be a waste product into a reusable input. By combining precision control, product quality, and environmental stewardship, de-ammonia kiln calcination ensures the production of high-grade vanadium pentoxide while supporting a more sustainable industrial process.

The direct extraction method of vanadium from vanadium-titanium magnetite (VTM) is typically performed using a sodium salt roasting-water leaching process. In this method, VTM is roasted in a rotary kiln under oxidizing conditions with sodium salts, followed by wet grinding and water leaching of the roasted calcine. The vanadium-bearing solution is purified by adding ammonium sulphate ($(NH_4)_2SO_4$) or ammonium chloride (NH_4Cl) to precipitate ammonium metavanadate (AMV) and ammonium polyvanadate (APV). This method has been successfully applied in countries like South Africa and Brazil, enabling economic extraction of vanadium from VTM concentrate. Based on typical industry indicators, vanadium pentoxide can be obtained with a purity of 99.5% to 99.8% by sodium roasting-water leaching, with the proposed process the vanadium leaching efficiency and the total recovery process are 97% and 71.41% to 78% respectively. (Nasimifar, 2022)

In review of the industrial vanadium extraction processes, sodium salt roasting followed by water leaching remains the dominant process for extracting vanadium from VTM, owing to its high efficiency, low operational cost, and simplicity. With increasingly stringent environmental regulations, the focus must shift toward innovative processes that emphasize comprehensive resource utilization and pollution reduction at the source. These advancements represent the future of the industry and warrant ongoing research and development. (Li, 2018).

Process Flow Sheet - Dry Basis Mass Balance

The following is a table showing the high-level dry mass balance of the titanomagnetite, based on a 1000 tph pilot plant. The basis of this mass flow sheet is taken from the UC/Callaghan Innovation test results for the recovery of a representative titanomagnetite sand sample. This has the following assumptions

- There is a 99% LIMS recovery rate
- Roasting feed of Sodium Carbonate of 20%
- Roasting produces approximately 12% mass emissions (based on Trinh, 2021- Efficient Recovery of Vanadium and Titanium from Domestic Titanomagnetite Concentrate Using Molten Salt Roasting and Water Leaching)
- High recovery of solids - 95% (based on UC/Callaghan Innovation testing)

Process Stage	Mass (Kg)	Fe	Mn	Ti	Ca	K	P	Si	Al	Mg	Na	V
Ball Mill Feed	1000.0	589.59	4.84	47.68	3.63	0.43	0.20	10.08	20.08	17.13	0.51	3.35
LIMS Feed	990.00	589.59	4.84	47.68	3.63	0.43	0.20	10.08	20.08	17.13	0.51	3.35
Roasting Feed	1188.00	278.16	4.60	47.68	3.63	0.43	0.20	10.08	20.08	17.13	103.46	3.35
Leach Tanks Feed	1045.44	278.16	4.60	47.68	3.63	0.43	0.20	10.08	20.08	17.13	103.46	3.35
TiFe Solids	982.71	476.86	3.86	33.40	4.57	3.86	0.09	19.54	14.56	12.38	47.22	1.39
Leachate	58.96	0.43	0.01	0.10	0.00	0.00	1.86	0.00	17.47	0.26	49.49	2.63
Vanadium Recovery												78%

Table 4: The dry mass balance of the University of Canterbury laboratory testing taken from a representative sand sample with water leaching.

The dry mass balance conducted during the UC/Callaghan Innovation testing provides an initial overview of the material flow and vanadium recovery potential and does not include the de-silication (removal of the alumino-silicates) and AMV processes which uplift the purification of the vanadium recovered. Further testing and analysis will be required to refine these results. Additional work is needed to validate the distribution of vanadium across the individual process streams, assess losses more accurately, and determine the impact of process variables on recovery efficiency. This will ensure a more comprehensive understanding of the system and support the optimisation of processing parameters for scalable production. Future testing should also address any discrepancies observed and incorporate a broader range of input materials to enhance the reliability of the mass balance findings.

Preliminary Economic Evaluation: Pilot Plant

The estimation of capital expenses (CAPEX) for the Pilot Plant is a conceptual high-order assessment aimed at providing a preliminary understanding of potential costs. This includes the initial capital investment for infrastructure such as roasting kilns, leaching tanks, separation units, and essential support systems like waste and water management facilities. While a full operating expenses (OPEX) assessment is not included, a high-level evaluation highlights cost-sensitive elements of operating the pilot plant, specifically the costs of labour and chemical reagents such as sodium salts for roasting. These estimates are based on generalised assumptions about process parameters, feed grade, and scale of operations, offering a foundational economic perspective to guide further detailed feasibility studies.

It is recommended that the pilot plant be constructed in New Zealand.

Building the plant locally will support the retention of intellectual property (IP) by maintaining close control over innovative processes and technologies developed during the demonstration phase. Additionally, operating the plant in New Zealand allows for the collection of critical data and insights that will inform key decisions about the final location of the full-scale operational plant.

Factors such as logistical challenges, supply chain considerations, and environmental impacts can be evaluated more effectively, enabling the identification of an optimal site for the commercial facility while ensuring the pilot plant phase contributes maximum value to the project's overall success. The Pilot plant would be housed within a regular large-scale steel shed/warehouse and should not prove problematic to locate.

Capital Expenditure (CAPEX)

The capital cost assessment for this project has been prepared on a factorial basis and has been estimated to an accuracy of -25% to +50% in accordance with a typical Class 5 estimate as defined by the AACE standards. Basic flow sheets have been prepared and equipment sized. The equipment pieces have been priced and specialised factors have been used to account for the rest of the costs associated with construction of the plant.

The CAPEX estimate is a Monte Carlo-based capital expenditure (CAPEX) estimate and provides a probabilistic estimate, enabling the robust evaluation of uncertainties. In this case, the P80 value—representing the cost level that is expected to be exceeded only 20% of the time—has been adopted as the base price. This level reflects a reasonably confident yet realistic cost expectation. To account for contingencies, an allowance of 15% has been included. This methodology balances risk tolerance and financial planning, supporting informed decision-making .

CAPEX Assumptions

- New equipment (used equipment items will be considered if readily available)
- No government taxes or charges
- No owners cost
- No future currency variation, a fixed price has been assumed on the selected currency reference date.

Estimation Criteria

- Concentrate feed is delivered to the Pilot Plant at a cost of USD 25/tonne
- Concentrate feed throughput of 1 tonne per hour (tph)
- Project contingency set at 15%
- Estimated equipment pricing based on budget pricing from various sources.

Currency Basis (24/01/2025)

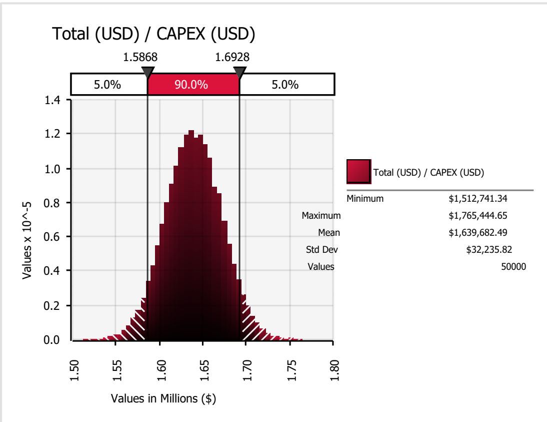
- 1.75 NZD: 1 USD
- 1.58 AUD: 1 USD
- 0.96 EUR: 1 USD

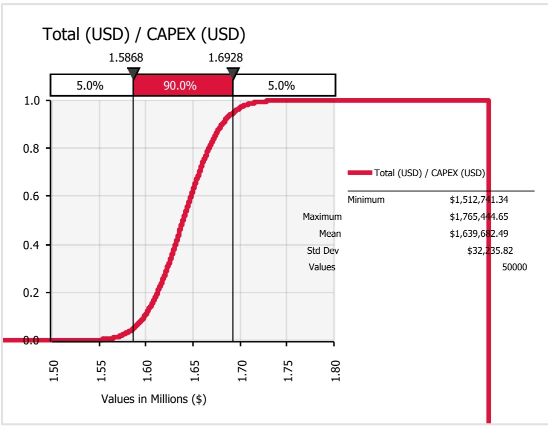
CAPEX

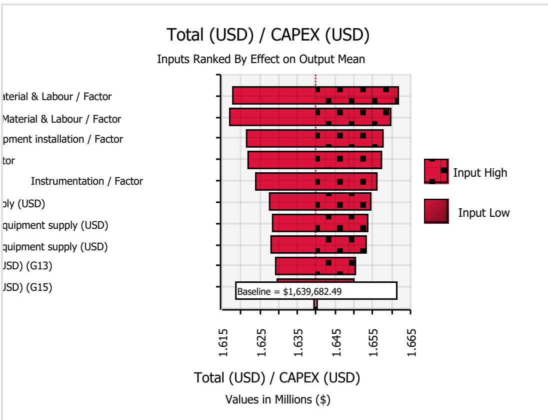
P80	USD 1,667,121.00 (NZD 2,917,462.00)
Contingency	USD 250,070.00 (NZD 437,500.00)
Total CAPEX Estimate	**USD 1,917,191.00 (NZD 3,355,085.00)**

@RISK Output Report for Total (USD) / CAPEX (USD)

Performed By: Siecap NZ
Date: 24 January 2025 10:41:12







Simulation Summary Information	
Workbook Name	TTR 1 tph Pilot Plant
Number of Simulations	1
Number of Iterations	50000
Number of Inputs	22
Number of Outputs	1
Sampling Type	Latin Hypercube
Simulation Start Time	23/01/2025 11:37
Simulation Duration	00:01:03
Random # Generator	Mersenne Twister
Random Seed	682966582

Summary Statistics for Total (USD) / CAPEX (USD)				
Statistics			**Percentile**	
Minimum	$	1,512,741.34	**5%**	$ 1,586,798.07
Maximum	$	1,765,444.65	**10%**	$ 1,598,205.07
Mean	$	1,639,682.49	**15%**	$ 1,605,957.71
Std Dev	$	32,235.82	**20%**	$ 1,612,219.25
Variance		1039148337	**25%**	$ 1,617,625.31
Skewness		0.014868746	**30%**	$ 1,622,576.80
Kurtosis		2.933770451	**35%**	$ 1,627,080.11
Median	$	1,639,574.73	**40%**	$ 1,631,378.29
Mode	$	1,633,415.72	**45%**	$ 1,635,461.97
Left X	$	1,586,798.07	**50%**	$ 1,639,574.73
Left P		5%	**55%**	$ 1,643,838.14
Right X	$	1,692,785.63	**60%**	$ 1,647,986.88
Right P		95%	**65%**	$ 1,652,286.87
Diff X	$	105,987.56	**70%**	$ 1,656,651.56
Diff P		90%	**75%**	$ 1,661,520.11
#Errors		0	**80%**	$ 1,667,120.64
Filter Min		Off	**85%**	$ 1,673,326.57
Filter Max		Off	**90%**	$ 1,681,103.56
#Filtered		0	**95%**	$ 1,692,785.63

Change in Output Statistic for Total (USD) / CAPEX (USD)				
Rank	**Name**	**Lower**		**Upper**
1	Electrical Material & Labo	$	1,618,029.44	$ 1,661,681.52
2	Piping Material & Labour	$	1,616,959.94	$ 1,659,631.98
3	Equipment installation /	$	1,621,417.26	$ 1,657,565.74
4	Process building	$	1,622,105.72	$ 1,657,373.53
5	Instrumentation / Factor	$	1,624,043.79	$ 1,655,946.21
6	Rotary kiln / Equipment s	$	1,627,655.24	$ 1,654,420.83
7	1000C 90 Minutes / Equ	$	1,628,302.30	$ 1,653,667.04
8	500C 120 Minutes / Equ	$	1,627,961.90	$ 1,653,263.39
9	Equipment supply (USD	$	1,629,177.91	$ 1,650,400.31
10	Equipment supply (USD	$	1,629,800.66	$ 1,649,826.57

Figure 9 - @Risk CAPEX Report

Operational Expenses (OPEX)

A high-level evaluation underscores the critical cost-sensitive elements of operating the pilot plant, focusing on labour and chemical reagents as primary operational expenses.

Labour costs are anticipated to be a significant component, reflecting the need for skilled personnel to oversee process monitoring, operate complex equipment, and perform routine and preventive maintenance. The availability, training, and retention of such personnel will directly impact operational efficiency and overall costs.

Chemical reagents, particularly sodium salts used in the roasting process, represent another key expense[7]. These consumables are fundamental to the plant's operations, and their cost sensitivity arises from variations in market prices, supply chain logistics, and the specific quantities required for achieving desired process outcomes.

Understanding and managing these cost drivers will be essential for optimising operational efficiency and ensuring the financial viability of the pilot plant.

The Challenge of OPEX Estimation for a Pilot Plant

Developing a full operating expense (OPEX) estimate for a pilot plant is impractical as they are designed to test process feasibility and scalability rather than achieve optimised, steady-state operations.

Variability in process parameters, feed grades, scale of operations, and equipment performance introduces significant unpredictability in operating costs. Furthermore, the plant's purpose—to validate, and refine processes—means operational conditions will change frequently, making it challenging to establish reliable cost baselines. As a result, high-level evaluations focusing on key cost drivers, like labour and chemical reagents, will provide a more meaningful and actionable framework for decision-making and planning at this early stage.

Enabling Improved OPEX Through the Pilot Plant

The pilot plant will serve as a pivotal step toward reducing long-term operational expenses (OPEX) by providing a controlled environment to test and refine processes.

By simulating full-scale operations, it will allow for the identification and mitigation of inefficiencies in labour allocation, reagent consumption, and energy usage. Key insights gained from the pilot plant phase—such as optimising chemical dosing rates, improving equipment uptime, and streamlining operational workflows—will directly translate into reduced costs at commercial scale.

Additionally, the data collected during the pilot plant phase will support informed decision-making for process adjustments and technology upgrades, ensuring a smoother transition to full-scale operations with lower OPEX.

[7] Soda Ash - Price - Chart - Historical Data - News states January 2025 sodium carbonate at NZ$366 / tonne
https://businessanalytiq.com/procurementanalytics/index/sodium-chloride-price-index/#google_vignette

Environmental Considerations

The salt roasting and water leaching process for vanadium extraction involves several steps that may impact the environment. To ensure sustainable and responsible operations, it is critical to identify, assess, and mitigate potential environmental challenges. Below are key considerations:

Emissions from Salt Roasting

- Carbon Dioxide (CO_2) Emissions: The high-temperature roasting process will release CO_2.
- Volatile Organic Compounds (VOCs): The roasting process will release minor quantities of VOCs depending on feedstock impurities.
- Particulate Matter (PM): Dust and fine particles generated during processing

Sodium Salt Usage and Residue Management

- Sodium Carbonate Residues: The roasting process generates residues containing unreacted sodium salts and other by-products.
- Effluent Control: Sodium-rich effluents from water leaching can contribute to salinity issues.

Wastewater and Solid Waste

- Water Leaching Effluents: Wastewater from the leaching stage may contain dissolved salts, trace metals, and other impurities.
- Solid Waste from Residue: Post-leach residues must be safely managed.

Energy Intensity

- Energy Consumption: The roasting process is energy-intensive due to the high temperatures required. To reduce environmental impact, options such as waste heat recovery, process optimisation, or shifting to lower-carbon energy sources (e.g., biomass or solar thermal energy) should be explored.

Resource Efficiency

- Water Usage: Water demand for leaching must be managed. Recycling and reuse systems can help reduce freshwater dependency.
- Material Recycling: Reagents used in the process can potentially be recovered and reused, reducing raw material consumption and associated environmental impacts.

Mitigation Strategies

To address these considerations, an integrated environmental management approach is recommended:

1. Implement advanced emissions control systems to minimise air pollution.
2. Adopt closed-loop water management systems to reduce water usage and effluent discharge.
3. Recover and reuse reagents to enhance resource efficiency.
4. Optimise energy use through process innovations and renewable energy integration.
5. Develop comprehensive waste management plans to safely handle solid and liquid residues.

By proactively addressing these environmental considerations, the salt roasting and water leaching process can be developed into a more sustainable and environmentally responsible method for vanadium extraction.

Next Steps

To achieve the full potential of Vanadium recovery from TTR sand, Siecap recommends that the next steps focus on refining key processes and confirming the process flow diagram. These efforts will aim to improve efficiency, enhance recovery rates, and align operations with sustainability goals. By optimising roasting parameters, advancing leaching techniques, and validating processes at scale, TTR can pave the way for a more economically and environmentally viable recovery pathway.

Optimisation of Roasting Parameters for TTR Sand:

- Investigate adjustments to key roasting variables, such as temperature, duration, and sodium carbonate concentration, to improve efficiency.
- Conduct experimental trials to determine the ideal conditions for maximising vanadium recovery from TTR sand.

Enhanced Leaching Techniques:

- Explore varying concentrations, liquid-to-solid ratios (pulp densities), and leaching times to identify conditions that enhance vanadium extraction.
- Explore the particle size distribution effect on vanadium extraction, with water leaching.

Precipitation Testing:

- Undertake precipitation testing to optimise the TTR titanomagnetite V_2O_5 purity.
- To achieve a product of acceptable purity and physical properties, further testing and optimisation of batch and continuous precipitation processes will be essential. Testing should also ensure a vanadium precipitation efficiency of 98% and evaluate the efficacy of recycling residual vanadium in the filtrate. Comprehensive analysis of these parameters will provide valuable insights into refining operational efficiency and maintaining product quality.

Characterisation of TTR Sand:

- Perform detailed mineralogical and physical analyses to better understand the factors limiting vanadium recovery.
- Use the findings to inform targeted modifications to the roasting and leaching processes.

Scalability and Process Validation:

- Validate the PFD processes under pilot-scale conditions to ensure feasibility and effectiveness for industrial applications.
- Assess the economic implications of process improvements to balance recovery efficiency with cost-effectiveness.

Sustainability Considerations:

- Evaluate the environmental impact of sodium carbonate roasting and leaching processes, including emissions, recycling and waste management.
- Identify potential process modifications that align with sustainability goals, such as reducing energy consumption or waste production.

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