INTEGRATING CARBON CAPTURE IN MINING THROUGH METALLURGY. PART 1: LEACHING AND RECLAMATION OF ASBESTOS TAILINGS: THETFORD MINES CARBON CAPTURE AND REMEDIATION PROJECT

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ABSTRACT

Planetary Hydrogen ("PH") is engaged in developing a proprietary carbon capture technology aimed to be integrated within existing and closed mining operations. The enabling metallurgical process is based on classic unit operations involving sulfuric acid leaching of magnesium contained in suitable ores and tailings, solution processing and electrolytic acid regeneration with simultaneous magnesium hydroxide precipitation. The resulting hydroxide precipitate is used for either Ocean Air Capture ("OAC") or Direct land-based (DC) carbon capture or a combination thereof. Column-simulated heap leaching results to date on a representative Thetford Mines asbestos tailings sample produced recoveries of 84%, 90% and 75% for magnesium, nickel and cobalt, respectively, after 86 days of leaching. Average asbestos conversion to silica was 83%, with complete conversion (~0% asbestos) within the top layer. Vat leaching results produced comparable metallurgical performance after 29 days of leaching. Optimization test-work is underway at the time of writing the paper. The OAC capture potential of the magnesium hydroxide produced is estimated at 1.65 t dry tailings-feed per ton of CO_2. Mass and energy balances of full-scale operation predict specific energy consumption is 9.5 MWh/t captured CO_2, translating into a CO_2 carbon-footprint ratio of 4.4:1 as tons captured vs. tons generated. The capex of the full-scale operation with 1,000 ktpa CO_2 removal nameplate in the form of magnesium hydroxide at plant-discharge (FOB) is tentatively estimated to USD$ 1,232 Bn. The annual opex was estimated to USD$ 0.364 Bn pointing to a pre-tax annual ROI of 48% with 7.1 years capital-amortization.

KEYWORDS

Ocean Alkalinity Enhancement, Magnesium hydroxide, Heap Leaching, Carbonation.

INTRODUCTION

Mine tailings with a high magnesium content present an ideal setting to observe and promote mineral carbonation due to the presence of reactive magnesium bearing silicates such as Brucite ($Mg(OH)_2$) and serpentine polymorphs ($Mg_3Si_2O_5(OH)_4$) [1-3]. Ore processing techniques such as milling and crushing further enhance the mineral reactive surface area to promote passive carbonation [4 – 6]. The global CO_2 sequestration potential of the ultramafic mine tailings (asbestos, talc, etc) is estimated to be about 175 Mt CO_2/y [6]. Although the rates of passive carbonation have shown to offset approximately 11% of the CO_2 emissions, accelerating the observed rates requires geochemical treatments or changes [7]. One such geochemical treatment involves the acid leaching of magnesium-bearing silicates to accelerate the dissolution of magnesium and other metals from host minerals followed by their sequential precipitation.

Planetary Technologies is developing a proprietary process flowsheet that integrates acid leaching and subsequent solution treatment with electrochemical salt splitting in order to recover various pay-metal-intermediates along with magnesium hydroxide from amenable feedstocks. A simplified process schematic is shown in Figure 1. The tailings are leached with a dilute stream of sulfuric acid produced by the magnesium sulfate electrolysis circuit. The full-scale commercial leaching operation will be conducted in heap configuration, however investigation of vat-leaching as a temporary or back-up option is also being conducted. The Pregnant Leach Solution (PLS) from either leaching circuit is directed to the Iron removal circuit, wherein iron precipitation is conducted within a narrow pH window of 4.4-4.6 by the addition of a controlled amount of slaked lime. Oxygen from the electrowinning circuit is injected to significantly improve the reaction kinetics. Other metals such as aluminum, manganese and chromium co-precipitate with iron to various degrees. The resulting first-barren solution is directed to the Nickel - Cobalt Mixed Hydroxide Product (MHP) circuit. Nickel and cobalt are precipitated by controlled addition of slaked lime at a pH of 8-8.3. The resulting second-barren solution is directed to the electrolysis circuit that produces the sulfuric acid that is being redirect to the leaching circuit, and the final magnesium hydroxide salient product intended for carbon-capture capture. Carbon capture is realized by either scrubbing the carbon dioxide from the atmosphere (land-carbonation) or dispersing in sea water (ocean alkalinity enhancement).

The present work describes the results of the bench-scale proof of concept testwork conducted on a representative asbestos tailing sample originating from the Thetford mines, located in the province of Quebec, Canada. The amenability of the sample to heap and vat leaching was established by conducting a set of bottle roll tests under ambient conditions at ambient temperature. The responses to vat and heap leaching were investigated using laboratory-scale column experiments. The solution processing and electrochemical responses were investigated through base-line bench-top testworks.

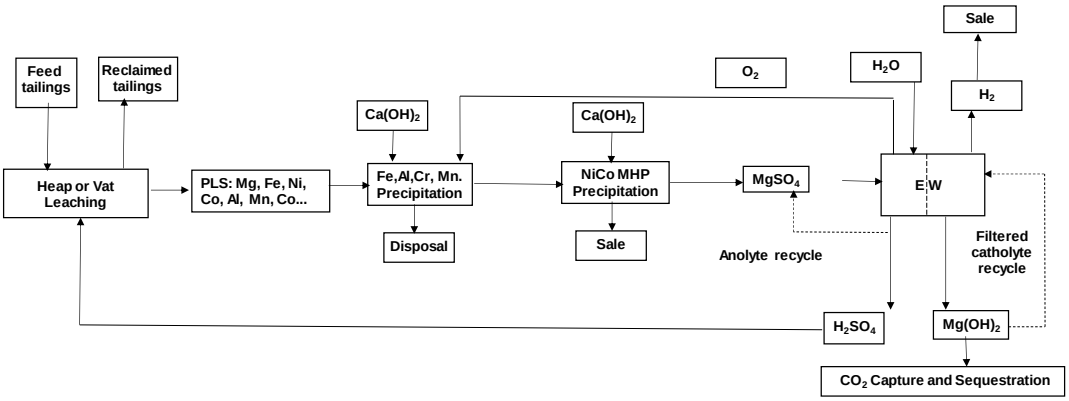

Fig. 1. Simplified process schematic

MATERIALS AND METHODS

Tailings Mineralogy and Chemical Composition

The mineral feed considered for the process described herein consists of the Thetford Asbestos Tailings. The asbestos mine tailings piles consist of Normandie, Bell, National, Lac d'Amiante, British Canadian I & II and the King Beaver resources. Cumulatively, they are estimated to contain 246,286,000 metric tons of measured, indicated, and inferred resources [8]. The tailings consist primarily of Fe, Ni, Si, and Mg along with minor quantities of Ca, Al, Ti, and Mn. The magnesium silicates include chrysotile and serpentine as the major constituents, along with other silicate-rich minerals such as olivine, lizardite, and orthopyroxene. About 90% of the nickel is present in a soluble oxidized form. Insoluble nickel is primarily deported to Heazlewoodite (Ni_3S_2) - a highly refractory nickel sulfide, Awaruite (Ni_3Fe) - a naturally occurring alloy of Ni and Fe, and Garnierite ($NiO.MgO(SiO_2).xH_2O$) - a hydrated metasilicate in which the nickel substitutes for some of the magnesium in the serpentine crystal lattice. Due to the absence of any iron sulfides, Fe is primarily found in the tri-valent state in the minerals hematite (Fe_2O_3) or magnetite (Fe_3O_4). The Normandie tailings comprise a mix of mainly sand-to-pebble sized ultramafic to mafic host rock material, some chrysotile and serpentine fibers, and some powdered rock. Some magnetite and brucite are known to be collectively associated with the chrysotile in veins.

The chemical composition of a crushed and pulverized Thetford tailings head-sample was determined by XRF (X-ray fluorescence) and ICP (Inductively Couple Plasma spectrometry). Key analysis are summarized in Table 1. The tailings-sample predominantly contained Mg (22.7%), Si (18.7%) and Fe (5.1%) with some Ni (0.17%), and Co (0.01%). The asbestos content in the head sample was estimated at 3 wt% according to the Polarized Light Microscopy ("PLM") method.

Table 1 — Chemical composition (wt%) of the Thetford Tailings

Elemental Analyses, %								
Mg	Si	Al	Ni	Co	Ca	Fe	Cr	Na
22.7	18.7	0.48	0.17	0.01	0.19	5.11	0.24	0.05
Cu	CO_3^{2-}	Cl^-	Mn	Zn	V	Ti	P	Asbestos
0.002	0.77	0.01	0.08	<0.004	<0.010	0.01	0.004	3

Metallurgical Thesis

The known challenges with any fibrous feed, including asbestos containing magnesium silicate tailings relate physically to operability [9]. This is because of the flow-adverse process response impacted by their fibrous structure. The flowability (rheology) of a fibrous-leaching-slurry prevents mixing at the required shear rates [10].

In addition, chemically, the elevated levels of acidity and overall ionic content in conjunction with the high silica content further challenge the traditional metallurgical approach. Silica-gel formation tends to commonly generate additional operability issues during the conventional-agitated leaching and subsequent separation and processing steps [11].

The metallurgical thesis proposed by Planetary Technologies relies upon changing the type of leaching from agitated-mixing to heap or vat leaching. These techniques offer certain advantages in that they actually take advantage of the fibrous nature of the tailings. This physical reality promotes in turn a radically different, process-friendly flow behavior. The key underlying rheological improvement is due to the fact that it is only the leach-solution that needs to flow-freely through the feed, instead of creating slurry and forcing it to flow by mixing.

The difference between the two methods is the nature of the flow of the leaching solution, also known as "lixiviant". Heap leaching is based on gravity-based irrigation-flow of the lixiviant between the

mineral particles that are not submersed in said solution. Vat leaching is realized by forced percolation-flow of the lixiviant through the minerals fully immersed in it. Heap leaching is realized by stacking the feed material in “heaps” and installing the required irrigation system and drainage ponds. Vat leaching is realized in large tanks fitted with a solution circuiting and storage system. This difference allows for the possibility of significantly larger scale heap operations compared to vat operations.

Additional advantages of heap and vat leaching methods include the use of dilute solutions, relative insensitivity to the actual pay-metal grade of the feed material, as well as lower capital and operating expenses.

Project deployment outline

The overall objective of the metallurgical-component of the project is to demonstrate the feasibility of the electrochemically-enabled heap and vat leaching routes including the required downstream processing steps for the Thetford asbestos tailings deposit.

The project development is conducted on a staged-gated sequence aimed on continuous due diligence in all relevant aspects [12 - 19]. Key risk areas being mitigated include technical, health-safety-environmental, economic, financial, permitting, geopolitical, marketing, community relations, etc.

Technically, the methodology applied meets or exceeds the CIM Best Practice Guidelines for Mineral Processing (BPGMP) [19]. They supplement the Principles of Process Support for Mineral Resources/Mineral Reserves Estimation for the purposes of the NI 43-101 Technical Report (“NI 43-101 TR”).

The testwork involves the following main phases:

- Laboratory (“Bench”) scale, non-integrated: Amenability – bottle roll leaching, small scale column-simulated heap leaching - single lift, Iron and impurities removal, Ni-Co MHP precipitation, Magnesium sulphate electrolysis, Carbonation of the magnesium hydroxide;
- Pilot testwork: medium to large scale column-simulated heap leaching, partially-integrated, including Electro-cell prototype, Continuous processing including carbonation;
- Demonstration plant testwork - fully integrated modular processing capability for heap and processing sections.

Process and economic models are generated upfront and updated in tandem with the progress of the testwork progress during and at the end of each phase.

Due diligence is performed continuously on aspects including technical (metallurgy, electro, handling, storage, delivery logistics), gaps-flagging, environmental (permitting, closure, remediation, fatal flaws (all of the above), as well as monitoring of classic risk factors and uncertainties: financial, geopolitical, environmental, permitting, marketing, social, etc.

TESTWORK CONDITIONS AND RESULTS SUMMARY

Column-simulated heap leaching conditions and results

The setup used for the column used to simulate heap leaching consisted of a polyvinyl chloride (PVC) column of 15 cm diameter and 1.8 m height provided with a diffuser-membrane tubing at the top and a perforated bottom fitted with a geotextile cloth (Figure 2). A tailings-sample charge of about 36 kg was loaded into the column. Irrigation was realized by pumping the lixiviant solution containing 7.3 wt% H_2SO_4 and 4% wt. Na_2SO_4 onto the top of the column at a flowrate of 3.5 mL/min corresponding to 0.2 L/min.m^2 irrigation rate. Fresh lixiviant was fed until the pH reached a value of about 2.5. At this point it became "Pregnant Leach Solution” and it was collected continuously in a separate storage vessel. The test continued in recirculation mode in order to maintain the leaching kinetics until the reaction kept progressing at an increasing cumulative rate. The column-simulated heap leaching was continued until metal extractions

plateaued after 86 days of leaching. The column was washed with DI water until a sample of the discharge wash water reached a pH value of about 4. The volumetric inflow and outflow from the column were similar and stable, predictive of a stable heap leach operation under the conditions as tested.

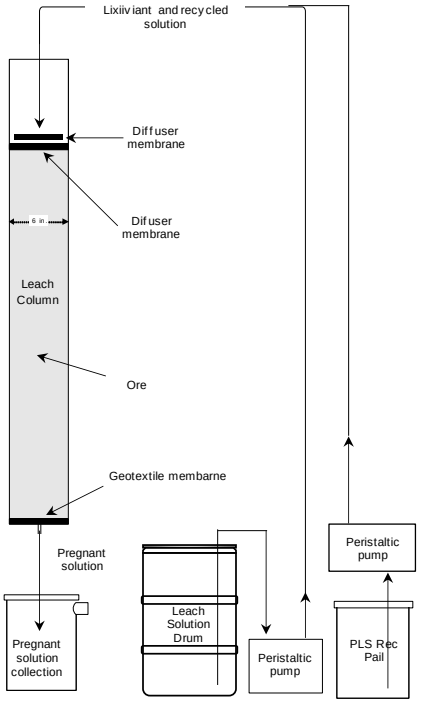

Figure 2 - Experimental setup for the simulated column heap leaching

The extractions for magnesium, iron, nickel and cobalt were 84%, 53%, 90% and 74%, respectively. The metallurgical balance indicated complete asbestos removal in the solid samples withdrawn from the top of the column. The asbestos content in the solid sample collected from the overall residue was 1 wt% versus 3 wt% in the head sample, determined by PLM. This corresponded to 81 wt% asbestos reduction for a magnesium dissolution extent of 84%. The results are summarized in Table 2.

A TCLP (Toxicity Characteristics Leaching Procedure) test was carried out on a “wet” composite sample retrieved from the heap leach column. The results indicated the dissolved concentrations of deleterious elements were well below the schedule limits (Table 3).

Table 2- Column simulated heap leaching results summary

Stream	Mg	Si	Al	Ni	Co	Ca	Fe	Asbestos
Leaching, analyses in units as shown								
Feed, %	22.7	18.7	0.48	0.17	0.01	0.19	5.11	3
PLS, mg/L	18100	143	161	174	8	85	2400	-
Wash, mg/L	2020	63.2	13.5	22.7	1.2	10.1	178	-
Residue, %	6.75	32.9	0.55	0.037	0.002	0.16	3.87	1
Leaching, extractions, % by method as indicated								
Calc Head	84	1	35	90	74	42	53	-
Direct Head	88	1	36	114	83	41	50	-
Feed vs. Residue	83	-2	33	87	86	53	56	81
Accountability	105	103	103	127	97	89	94	19

Table 3 - Concentrations of dissolved elements (mg/L) as determined by a TCLP test on a wet composite sample from the heap leach test-work

TCLP Scan, mg/L							
Elements	Hg	As	Ag	Ba	B	Co	Cd
Schedule Limits, mg/L	0.1	2.5	5	100	500		0.5
Sample	<0.00001	<0.002	<0.0005	0.163	0.14	0.0123	0.00035
Elements	Cr	Mg	Na	Ni	Pb	Se	U
Schedule Limits	5				5	1	10
Sample	0.0081	8.04	1480	0.166	0.00367	0.0016	<0.00002

Column-simulated vat leaching conditions and results

The tests column configuration was changed from heap-leach to vat-leach simulation by relocating the membrane material at the bottom which allowed flow of lixiviant through while preventing solids to pass. The lixiviant was pumped into the bottom of the column from the lixiviant solution drum The amount of sample was the same as for the heap-leach simulation test, and the composition of the lixiviant was identical as well.

Percolation was realized by pumping the lixiviant onto the bottom of the column at a flowrate of about 16 mL/min corresponding to about 1 L/min.m^2 percolation rate. The column was flooded throughout the entire test. The addition of fresh and recycled lixiviant was managed similarly to the heap-column and with the same pH target of 2.5. The column-simulated vat leaching was continued until metal extractions plateaued after 29 days of leaching. The column was washed until the wash water reached a pH value of about 4.

The results are summarized in Table 4.

The metallurgical balance returned recoveries of 79%, 88% and 66% for magnesium, nickel and cobalt, respectively. The PLM-determined asbestos content in the “top cut” and “composite samples” were “trace” <1% wt. and 4 wt%, respectively. The volumetric inflow and outflow from the column were similar and stable, predictive of a stable vat leach operation under the conditions as tested.

Table 4 - Column simulated vat leaching results summary

Stream	Mg	Si	Al	Ni	Co	Ca	Fe	Asbestos
Analyses, units as shown								
Feed, %	22.7	18.7	0.48	0.17	0.01	0.19	5.11	3
PLS, mg/L	11700	110	105	123	6	68	1750	
Wash, mg/L	1770	59.5	23.5	10.3	0.6	6.8	712	
Residue, %	9.89	29.7	0.56	0.048	0.003	0.19	4.53	4
Extractions, %								
Calc Head	79	2	39	88	66	41	60	-
Direct Head	93	1	42	122	83	48	76	-
Feed vs. Residue	75	10	33	84	82	43	50	24
Accountability	118	92	109	138	101	105	126	76

Iron and Impurities Removal by Precipitation

A series of four base-line iron and impurities removal testwork was conducted on test-samples of about 2 L pregnant leach solution produced by the heap leach column simulation test. Under the pre-optimized conditions, oxygen was sparged at an average volume flow rate of 1200 NmL/min into the agitated reactor. The pH was maintained continuously at 4.6 by controlled additions of 25% wt. calcium hydroxide slurry. The oxidation-potential was maintained at 244 mV versus the silver/silver chloride reference electrode during the oxygen addition. The reaction temperature was maintained at 80 °C during the 3-hour test. Nickel losses corresponding to 95% and 100% iron removal are 15% and 25%, respectively. The composition of the precipitated residue is summarized in Table 5.

The results were not as expected, based on previous experience with previous results produced by comparable systems. It was postulated that the increased level of sodium in the lixiviant triggered excessive basic-salt formation. In addition, the well-known knowledge of very low oxygen transfer efficiency in gas-liquid boundaries was substantiated by the excess oxygen required to maximize the redox potential. Optimization testwork is planned using PLS generated by the sodium-free lixiviant generated electrolytically.

Nickel and Cobalt Precipitation

Two ambient-temperature bench-scale precipitation tests were conducted at two stoichiometry excess additions of calcium hydroxide dispensed as 25% wt. slurry. The tests lasted 1.1 hours and 2.35 hours, respectively, during which the pH was maintained within the 8.3 to 9.1 range. Nickel and cobalt precipitation at 1.98 stoichiometry excess ranged from 80% and 88%. The composition of the precipitates is summarized in Table 5. Analogous to the iron and impurities removal, the increased level of sodium in the lixiviant triggered excessive basic-salt formation. Most likely to even a greater extent given the increased equilibrium pH level. This process stage will be optimized by upcoming testwork, in integration with the preceding iron and impurities removal stage.

Table 5 - Composition of the iron-impurity removal and mixed hydroxide precipitates

Stream	Mg	Si	Al	Ni	Co	Ca	Fe
Iron and impurities	1.58	0.67	0.93	0.22	0.01	16.3	12.3
Ni/Co MHP product	2.89	-	0.22	6.20	0.39	12.9	14.3

Magnesium Sulphate Electrolysis

Base-line testwork was conducted to investigate the electrochemical production of the magnesium hydroxide concurrently with the regeneration of the diluted sulfuric acid to be used for the heap or vat leaching.

The electrochemical unit consisted of a two-compartment cell allowing for the continuous withdrawal of the catholyte-slurry product containing the magnesium hydroxide produced at the cathode and of the anolyte of concentrated sulfuric acid produced at the anode.

The electrolysis was conducted using a low-permeability diaphragm. The catholyte contained 80 g/L $MgSO_4$ for the two typical tests exemplified.

The anolyte contained 50 g/L H_2SO_4 in test Mg7 and 70 g/L H_2SO_4 in test Mg10. The test-temperature averaged 30°C for both tests. The current density was 381 A/m^2 for test Mg7 and 907 A/m^2 for tests Mg 10.

The current efficiencies estimated based on the 88% purity of the magnesium hydroxide produced in both tests were 44% and 66% for tests Mg 7 and Mg10, respectively.

The results indicated that at comparable specific energy consumption values, practically near the margin of error, the amount of magnesium hydroxide produced increased by 188% from test Mg 7 to Mg10.

The results are summarized in Table 6. Optimization testing is underway at the time of submitting this paper.

Based on these results, combined with the full-scale operation mass and energy balances, the predicted specific energy consumption was 9.5 MWh/t captured CO_2, translating into a CO_2 carbon-footprint ratio of 4.4:1 as tons captured vs. tons generated [20].

Table 6: Comparative example of electrolysis tests results

Test	Current			Grams produced, pure equivalents of				Energy consumption	
ID	A	V	A/m^2	H_2	O_2	H_2SO_4	$Mg(OH)_2$	kWh	MWh/t OH^-
Mg 7	8.0	8.1	381	1.5	23.9	54.5	19.1	0.3	*29*
Mg 10	19.1	13.2	907	2.9	45.7	88.0	54.8	1.0	*32*

BASE LINE PROCESS ECONOMICS

The bench-scale data package was used to generate tentative economic model predictions.

The capital and operating costs ("capex" and "opex", respectively), were calculated based on generally accepted industry practices [19, 21 - 29]. The predicted full-scale process economics are summarized in Table 7. Accordingly, the capex of the full-scale operation with 1,000 ktpa CO_2 removal nameplate was estimated to USD$ 1,232 Bn. The annual opex is estimated to USD$ 0.364 Bn pointing to a pre-tax annual ROI of 48% with 7.1 years capital-amortization.

The overall level of projections-accuracy at this stage of the project is tentatively estimated to ±60% for the capex and ±40% for the opex. The immediate goal is achieving the accuracy levels required by the guidelines (BPGMP - NI 43-101) for the Preliminary Economic Assessment (Capex ±25 to ±50% and Opex: ±25 to ±35%) by the end of 2022.

Form a project development viewpoint, the demonstration plant will create the possibility of advancing the project to feasibility.

Table 7: Tentative full-scale process economics summary

Nameplate, Capex, Opex		
Annual capture, CO_2 tpa	1,000,000	
Daily capture, CO_2 tpd	3,221	
Lifetime capture, CO_2 t/deposit	140,389,519	
Installed EW Power, MW	1,536	
Total installed Power, MW	1,799	
Annual throughput, "as is" tpy	1,754,305	
Daily throughput, "as is" tpd	5,651	
Operation Lifetime, years	140	
Capex	$1,231,961,959	
Opex - per year	$363,580,705	
Additional credits, tpy		
Green Hydrogen	40,854	
Oxygen	648,493	
Ni	2,335	
Co	110.2	
Site remediation	1,754,305	
Revenues	USD$ /yr	Rev, %
Carbon credit	$250,000,000	44
Green Hydrogen	$189,971,733	34
Oxygen	$0	0
Ni	$50,783,282	9.0
Co	$4,547,097	0.8
Site remediation - residue only	$70,172,190	12.4
Sub-total annual	$565,474,302	100
Admin	$28,273,715	
Annual EBTA	$173,619,883	
Annual Pre-ROI, %	48	
Amortization ex-tax, years	7.1	
Inflation / deflation and price fluctuations ignored.		

SUMMARY AND LOOK FORWARD

- Column-simulated heap leaching test produced extractions of 84%, 90% and 74%, for magnesium, nickel and cobalt, respectively in 86 days. The asbestos reduction was 81% overall, and complete removal at the top section of the simulated heap;
- Column-simulated vat leaching test produced extractions of 78%, 88% and 66%, for magnesium, nickel and cobalt, respectively in 29 days;
- Baseline iron and impurities removal testwork results produced from 95% to 100% iron removal with 15% to 25% nickel losses, respectively;
- Baseline nickel and cobalt precipitation tests recovered from 80 to 88% of the nickel and cobalt contained in the iron and impurities removal discharge barren solution;
- The lower-than-expected precipitation performance in both precipitation-based unit operations was attributed to basic salt formation due to the presence of elevated levels of sodium in the lixiviant;
- Preliminary electrolysis testwork demonstrated that it was possible to produce a sodium-free lixiviant for leaching along with magnesium hydroxide for carbon capture;
- Based on the results to date, the mass and energy balances of the full-scale operation predicted specific energy consumption was 9.5 MWh/t captured CO_2, translating into a CO_2 carbon-footprint ratio of 4.4:1 as tons captured vs. tons generated;
- The capex of the full-scale operation with 1,000 ktpa CO_2 removal nameplate was tentatively estimated to USD$ 1,232 Bn. The annual opex is estimated to USD$ 0.364 Bn pointing to a pre-tax annual ROI of 48% with 7.1 years capital-amortization.

Subject to successful financing and permitting, the project is envisioned to be "shovel-ready" in 2026. Following the targeted 2027 successful commissioning and ramp-up, the required magnesium hydroxide production level for 1,000 ktpa CO_2 nameplate capture capacity will be achieved in 2028. Incremental extension will be possible due to the nature of the heap leach operation. On that basis, the nameplate capacity will be doubled to 2,000 ktpa CO_2 starting in 2032 (Table 8).

Table 8: High level project development schedule and forecasting

Year completed	2022	2023	2024	2025	2026	2027	2028	2030	2032
Stage	Pilot	Demo	Feasibility, ECPM and Permitting		Construction	*C&R	Expansion		
Annual capture, CO_2 ktpa	Low	1.2				300	1,000	1,500	2,000
Cumulative capture, kt CO_2		1.2				301	1,301	2,801	4,801
Lifetime capture, CO_2 t/deposit	140,390	140,388				140,088	139,088	137,588	135,588
Annual feed throughput, ktpa	Low	2.1				526	1,754	2,631	3,509
Feed reserves, kt	246,286	246,284				245,758	244,003	241,372	237,863
Operation Lifetime, years	140	n/a					139	92	68

*C&R: Commissioning and ramp

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