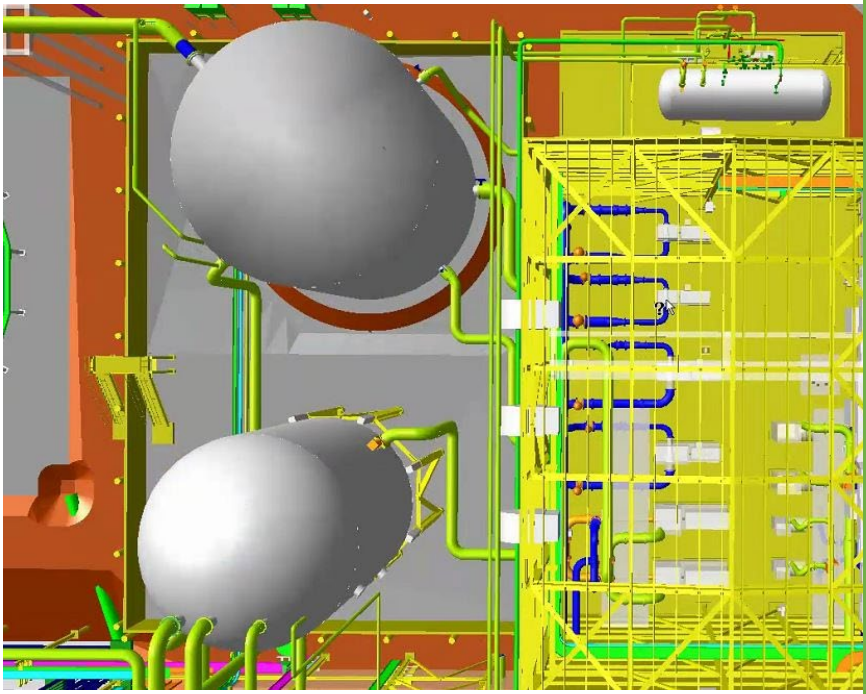
Demonstration of CVW™ Sustainable Technology at Canadian Natural Horizon

Emissions Reduction Alberta

Project F0161057

Non-Confidential Project Report

May 9, 2025



CVW CleanTech Inc.

Executive Summary

CVW CleanTech's Creating Value from Waste (CVW™) process was evaluated for potential implementation for the first time at a commercial scale at Canadian Natural Resources Limited's (Canadian Natural) Horizon site north of Fort McKay in Northern Alberta. This process, comprised of a hydrocarbon recovery facility (Concentrator Plant) and a minerals production facility (Mineral Separation Plant) recovers residual bitumen and solvent, extract valuable critical mineral products from froth treatment tailings (FTT) stream and provide meaningful environmental benefits, including significant fugitive methane emissions and VOC emissions reductions. Solvent refers to any hydrocarbon that is utilized as a hydrocarbon diluent (diluent) and solvates bitumen or a portion of bitumen; these include naphtha and paraffin hydrocarbons. In this CVW™ project, the solvent used was naphtha.

Building from a 2019 FEED study on CVW implementation at Horizon, this project completed Validation and Optimization engineering evaluation that was co-financed by CVW CleanTech, Canadian Natural, Natural Resources Canada's Clean Growth Program, Sustainable Development Technology Canada (SDTC) and Emissions Reduction Alberta (ERA). The objective of the project was to optimize the facility design based, in part, on recommendations from the 2019 FEED study and develop an optimized project to an AACE Class 3 level of project definition. The engineering of the Concentrator Plant (CP) was led by Canadian Natural. The Concentrator Plant (CP) is responsible for hydrocarbon recovery and minerals stream conditioning and is comprised of conventional oil sands technologies, including cyclones, flotation, solvent extraction and distillation. The Minerals Separation Plant (MSP) was designed by FWS Group (FWS) and IHC-Robbins. The Mineral Separation Plant produces valuable minerals products, including concentrates of zircon and titanium-bearing minerals through the utilization of conventional minerals dressing equipment. All technologies have been uniquely designed and configured for oil sands FTT processing and have been validated through extensive piloting.

The optimized technical design of the CP was completed between January and December 2020, with the MSP optimization and validated capital cost estimate developed in the first quarter of 2021. Key areas of optimization within the Concentrator Plant included containment of process gasses and vapours in a vapour recovery unit and some modification to equipment to improve reliability and reduce costs. The Mineral Separation Plant was re-designed to produce a second mineral product enriched in titanium-bearing minerals to complement the primary zircon concentrate product. Associated mineral facilities were re-engineered to support the new minerals process design and a material handling 'transload' facility was developed to manage transfer of mineral products from trucks to rail cars for transport to international markets.

A number of studies were conducted throughout project period, including the culmination of a multi-year tailings sampling campaign to evaluate the concentration of valuable minerals in froth treatment tailings. Additional technical studies focused on design of the project's Tailings Distillation Units and hydrocarbon vapour emissions within the MSP. Independent verification and quantification of the environmental benefits accruing to the CVW™ project was commissioned to The Delphi Group in accordance with SDTC requirements. The validated project details all key tie-ins such as produced diluted bitumen and cleaned tailings.

The CVW™ project would recover hydrocarbons, bitumen and naphtha, from FTT. It is CVW CleanTech's view that CVW™-processed tailings may demonstrate enhanced settling and flocculation behaviours that lead to efficiencies in tailings management performance. An optimized thickener system has been designed to transition CVW™ tailings across the project battery limit to tie into existing facilities at the host oil sands mine.

CVW™ technology has the potential to deliver significant GHG emission reductions upon implementation at an oil sands facility. These CVW™ project emissions have been estimated by The Delphi Group and include, tailings pond methanogenic emissions avoidance as well as upstream avoidances from bitumen mining, napththa production and mineral separation, and are net of CVW™

process emissions. A stoichiometric model developed by Alberta Environment and Protected Areas, has been adopted to assess methane and carbon dioxide emissions avoidance from ponds due to reduced naphtha deposition from froth treatment tailings afforded by CVW™ implementation. The resulting GHG emissions profile (annual tonnes CO_2e), with comparison to the 2019 FEED study emission report by Stantec:

GHG Emissions Abatement Benefit	Delphi Group (2021)	Stantec (2019)
TP Methanogenesis	643,989	642,787
Bitumen Production FE	109,810	93,168
Naphtha Production FE	61,831	-
Minerals Production FE	37,095	-
CVW™ Process	-220,337	-163,665
subtotal	**632,388**	**572,290**
Heat Integration	0	0
Net Benefit	**632,388**	**572,290**
% site-wide emissions	10.69	8.35

Implementation of CVW™ can result in a net reduction and avoidance of GHG emissions of up to 632,000 tonnes CO_2e annually and this finding compares well to the earlier Stantec study. CVW CleanTech believes that CVW™ technology has the potential to reduce GHG emissions by 5-10% on a site wide basis. Other air quality benefits, including volatile organic compound emissions reductions and abatement of secondary organic aerosols, may also be realized.

A conditioned AACE Class 3 capital cost estimate has been developed for the optimized CVW™ Horizon project. This cost has been developed from budgetary costs of tagged equipment with vetted build-ups to estimate other direct and indirect costs. The cost estimate was developed to ascertain the cost of a CVW™ facility at a host oil sands mine. The cost estimate has been reviewed by independent 3rd Party estimation experts and the associated P50 contingency was developed by independent consultants.

CVW CleanTech, with collaboration from Canadian Natural, Natural Resources Canada, SDTC and Emissions Reduction Alberta (ERA), have successfully completed the optimization and validation engineering evaluation for potential implementation of CVW™ technology at a host oil sands mine.

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Project Description

CVW CleanTech's CVW™ Project represents a first-of-kind sustainable technology designed to create value through resource recovery while remediating oil sands froth treatment tailings (FTT). Creating Value from Waste™ (CVW™) is a clean technology that processes FTT, recovering contained hydrocarbons and preventing their release into tailings ponds and the atmosphere. The release of these hydrocarbons into ponds causes methane formation, a major source of fugitive emissions in the oil sands industry. The recovery of naphtha, an upgraded product from bitumen processing, from FTT reduces fugitive methane formation from tailings ponds and provide environmental enhancements including enhanced tailings management with associated water-use and land-use benefits. Additional benefits include critical minerals recovery (zircon and titanium-bearing mineral concentrates) creating a new minerals industry and significant economic diversification beyond bitumen and export markets for Alberta. This phase of the CVW™ Project encompassed the validation and optimization engineering for potential implementation at an oil sands mine.

CVW CleanTech and Canadian Natural led the validation and optimization engineering with support from various contractors and vendors with specific expertise in facilities and mineral process engineering. Optimization involves incorporating the learnings from a previous FEED study (ERA project F0160140) and advancing select activities for enhanced functionality. Validation provides further technology and project de-risking and asserts a revised AACE Class 3 capital cost estimate for CVW™. The process reduces the volume of hydrocarbons rejected to tailings ponds and related fugitive methane emissions to support targeted reduction of methane in Alberta and Canada. In parallel, the process also creates an FFT stream that is more amenable to existing tailings deposition technologies.

In addition to the one million dollar support from Emissions Reduction Alberta, Natural Resources Canada provided a grant of two million dollars through its Clean Growth Program and Sustainable Development Technology Canada (SDTC) provided a one million dollar in grant funding towards the validation and optimization engineering for CVW™. The balance of project funding was provided by CVW CleanTech and Canadian Natural.

The optimization and validation engineering has been completed, providing technical validation and cost estimates for development of an optimized CVW™ project. The project has experienced schedule delays due to execution challenges during COVID-19 pandemic, associated oil price collapse, industry capital constraints and deployment priorities. This project will benefit future engineering project engineering definitions and installations of CVW™ at other oil sands sites. The CVW™ process is standardized to retrofit at brown-field sites and several of the integration points will be similar for all sites. Both factors reduce the cost and increase the efficiency of the future CVW™ installations and accelerate the proliferation of this sustainable technology for the benefit of all stakeholders and the environment.

Introduction & Background

CVW CleanTech's froth treatment tailings technology has successfully completed 14 years of progressive R&D, including over three years of demonstration piloting at significant scale at CanmetENERGY's world class oil sands technology demonstration facility in Devon, Alberta for a consortium of oil sands operators and Alberta and Federal government agencies. Further, complementary marketing work and engagement with the Alberta government on important matters including the fiscal and regulatory regimes assist with the options of a CVW project installation.

In the 2004-2006 period, the Company developed a preliminary minerals process at the Saskatchewan Research Council, part of which was pilot tested at the Syncrude's Mildred Lake oil sands site. Following this early work, R&D was conducted on hydrocarbons recovery from froth treatment tailings in 2007-2008 with the support of Alberta Energy. These early works represented a **TRL of 3-4**, leading with a validated technology suite identified to recover both minerals and hydrocarbons from froth treatment tailings. In 2009, Alberta Energy-sponsored R&D work progressed to continuous mini-pilots on the hydrocarbons side (SGS Lakefield, GTI) and further advancements on the minerals processing flowsheet that included full scale testing of some units. This work entailed the prototype developments of what would become the full CVW™ process (**TRL 5-6**). In 2010-2014, CVW™ technology piloting was at significantly larger scale than normal CanmetENERGY scale for similar technologies (e.g. froth treatment production technologies and solvent recovery technologies piloted at CanmetENERGY by oil sands operators). This is considered an oil sands industry platform scale for froth treatment operations - following CanmetENERGY scale piloting, previous piloted oil sands technologies have successfully proceeded to commercial scale on-site implementation. During the same period, the Company's minerals separation process was demonstrated on bulk samples of cleaned sands produced at the CanmetENERGY pilot; this work was done on full scale equipment by IHC Robbins in Brisbane, Australia. As such, the CanmetENERGY/IHC Robbins pilots constitute a field and/or demonstration of the CVW CleanTech process, representing **TRL 7**.

CVW™ demonstration piloting results have been verified by independent firms, oil sands operators and government agencies. Piloting results confirm hydrocarbon recoveries of over 85% (bitumen and solvent), recovery of commercial quantities of valuable heavy minerals (titanium-bearing and zircon), improved tailings remediation and improved quality water[1]. In the Canadian Oil Sands Innovation Alliance (COSIA) 2012 Tailings Technology Roadmap[2], an initiative supported by Alberta Innovates – Energy and Environment Solutions (AI-EES), the Company's CVW™ process was identified as a 'prioritized' technology, ranking number 16 out of over 600 technologies reviewed. CVW™ was the only technology identified that provides value-added resource returns while delivering important environmental improvements. The Council of Canadian Academies, in a 2015 study for Natural Resources Canada, recognized the importance of dedicated remediation of oil sands FTT, citing CVW™ as the lone identified solution[3]. CVW™ potential for co-production of valuable heavy minerals in addition to significant environmental benefits was emphasized. Full lifecycle carbon accounting has been conducted by independent experts[4, 5, 6,] verifying the significant net GHG emissions reductions potential through commercial implementation of the technology. In 2016, the CVW™ technology won the Global Petroleum Environmental Show Environmental Innovation Award, was an award finalist at the World Heavy Oil Congress. Both COSIA and Canadian Natural have concluded that CVW™ technology is fully validated and demonstrated and is now ready for commercial demonstration.

Following this extensive $80 million R&D program, CVW CleanTech, in collaboration with Canadian Natural, then completed a $10.2 million ERA-supported FEED engineering for potential implementation at Horizon[7], which provided initial AACE Class 3 engineering scoping for the first prototype installation and validated the environmental benefits, particularly methane reduction[8]. This effort advanced the technology and project to **TRL 8**. The work described in this report advances optimization opportunities and validation engineering for the CVW™ Horizon project.

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[1] Moran, K. (2013). "Sustainable Remediation of Oil Sands Froth Treatment Tailings: SDTC Project 1449 Final Report", Titanium, 117 pp.
[2] Sobkowicz, J. (2012). "Oil Sands Tailings Technology Deployment Roadmaps. Project Report – Volume 1", Thurber Engineering, 243 pp.
[3] Newell, E. and S. Vaughn (2015). "Technological Prospects for Reducing the Environmental Footprint of Canadian Oil Sands: The Expert Panel on the Potential for New and Emerging Technologies to Reduce the Environmental Impacts of Oil Sands Development", Council of Canadian Academies, 252 pp.
[4] Flint, L. (2011). "Oil Sands Mining Emissions Reduction Potential in Conjunction with Minerals Recovery", Lenef Consulting, 28 pp.
[5] Conestoga-Rovers & Associates (2011). "Updated SMART Report: Prepared for Sustainable Development Technology Canada", 38 pp.
[6] Keesom, B., D. O'Brien and J. Blieszner (2013). "Impact of the CVW™ Process on WTW GHG Emissions and VOCs from Mined Bitumen", Jacobs Consultancy, 30 pp.
[7] CVW CleanTech (2019), "Reducing Methane Emissions and other Environmental Impacts from Oil Sands Tailings and Ponds – Deployment of Sustainable Technology", ERA Non-Confidential Project Report, ERA Project No. O160140, 34 pp.
[8] Stantec Consulting (2019), "Study Report on Potential GHG Emissions Resulting from CVW™ Project", Document No. SK-25-RPT-PR-001 Rev. B, Project No. 110903262, 19 pp.

Technology Description

CVW™ technologies remediate oil sands FTT, recovering lost hydrocarbons (bitumen and solvents including naphtha) and reducing their release into tailings ponds and the atmosphere. Solvent refers to any hydrocarbon that is utilized as a hydrocarbon diluent (diluent) that solvates bitumen or a portion of bitumen; these include naphtha and paraffin hydrocarbons. In the current project, the solvent utilized was naphtha. Reducing the release of these hydrocarbons diminishes methane formation in tailings ponds, an issue reported in numerous science-based studies by researchers, government scientists and industry operators. Implementation of CVW™ also reduces emissions of Volatile Organic Compounds (VOCs) and Secondary Organic Aerosols (SOAs).

In addition to the recovery of lost bitumen and solvents, CVW™ recovers valuable mineral products from oil sands tailings, creating a new minerals industry for Alberta. Recovery of these valuable commodities creates economic growth, jobs, royalties and taxes while delivering significant environmental benefits for Alberta and Canada. CVW™ has been extensively piloted for industry operators, Alberta and Federal oversight agencies.

CVW™ is designed to be co-located and integrated with an oil sands mining operation (**Figure 1**). An oil sands mining operation utilizes trucks and shovels (Area 1) to collect and deliver oil sands ore containing bitumen and critical minerals, to a hydrotransport system (Area 2), where the ore is mixed with water and transported as a slurry to the extraction plant (Area 3). The extraction plant uses warm water separation processes involving gravity settling and flotation to produce a bitumen-enriched froth; this froth contains the plurality of critical minerals that were extant in the ore. Resulting 'extraction' tailings are transported to the tailings pond. The bitumen froth contains water and solids (including critical minerals) that must be removed before upgrading to synthetic crude oil (SCO; Area 5). This is achieved in the froth treatment plant (Area 4), in which a lighter hydrocarbon solvent (naphtha, paraffin, hydrocarbon diluent) is utilized to reject water and solids to FTT. These tailings contain a relatively higher composition (compared to extraction tailings) of bitumen and associated solvent as well as the critical minerals. Currently, FTT tailings are deposited into tailings ponds, where the contained solvent then serves as a substrate for methanogenic biotic activity resulting in fugitive methane releases.

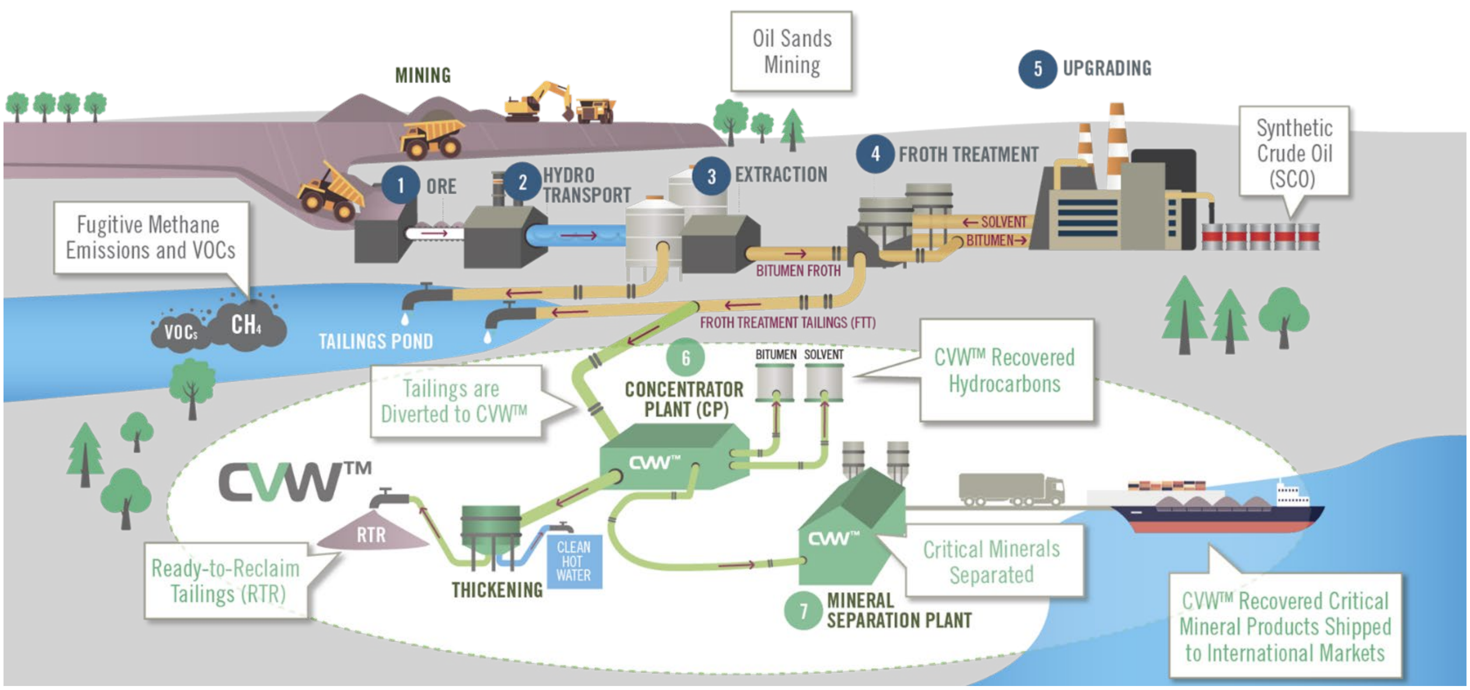

Figure 1. Integration of CVW technology, including the Concentrator Plant (Area 6) and Mineral Separation Plant (Area 7) at an oil sands mining operation (Areas 1-5).

CVW™ intercepts the FTT before deposition into the tailings pond, thereby reducing solvent deposition and subsequent biogenic methane releases. The FTT are processed in the CVW Concentrator Plant (Area 6) to recover hydrocarbons (diluted bitumen and solvent) and prepare critical mineral concentrates for subsequent processing in the Mineral Separation Plant (MSP; Area 7). The hydrocarbon products, recovered using flotation, solvent extraction and distillation, are returned to the operator of re-use and/or upgrading to SCO. The MSP utilizes conventional mineral dressing equipment to produce valuable critical mineral products that can then be exported to international markets. The clean tailings from the Concentrator Plant and the MSP are then subjected to tailings management processing (thickener) at high efficacy due to the low hydrocarbon content, supporting compliance with the Alberta Energy Regulator's Directive 85 for oil sands tailings management and providing hot water for re-use at the operator site.

The key unit operations of the CVW technology are shown in **Figure 2**. Note that in the event of phasing a project to first recover hydrocarbons potentially followed by a second phase for minerals recovery phase, only the technology indicated outside of the broken red line in **Figure 2** would be required in the initial phase.

The CVW™ process contain technologies comprised of several processing stages described below:

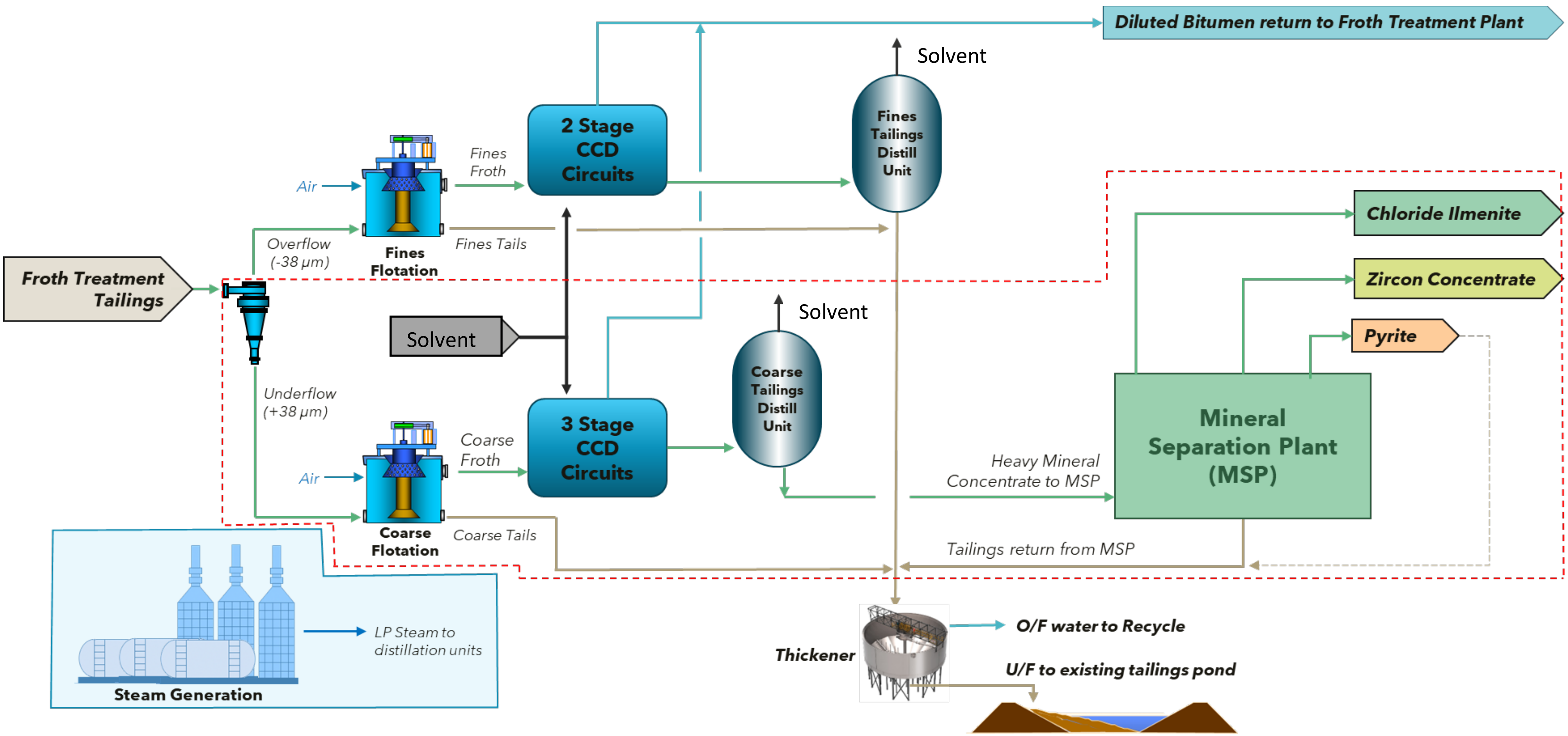

Figure 2. Generalized flowsheet of the CVW™ facilities, with emphasis on the Concentrator Plant component technologies. Note that the solvent extraction circuits are arranged in counter-current decantation (CCD) configuration. The technology components contained within the broken red lines are essential to the minerals production aspect of CVW™ technologies.

- *Bitumen Recovery*: In the Concentrator Plant, cyclones classify solids into coarse minerals (+50μ) and fines (-50μ) fractions. Bitumen is recovered from the fines fraction by flotation and solvent washing in a counter-current decantation (CCD) circuit. The cleaned tailings streams are processed to recover any lost solvent using distillation (see Solvent Recovery below). In a phased approach where hydrocarbon recovery is the focus, this area of the Concentrator Plant would be sized and designed to process whole FTT with utilities support and clean tailings reporting to a resized thickener. The HMC Production 'coarse' circuit and MSP (bounded by the broken red lines in **Figure 2**) would be deferred to a second phase.

- *HMC Production*: Also, in the Concentrator heavy mineral concentrate (HMC) is produced from the coarse fraction using selective flotation. Additional bitumen is then recovered from the mineral surfaces using multistage counter-current solvent washing. The tailings streams are then processed to recover any lost solvent using distillation. Recovered bitumen and solvent are sent to froth treatment processes while recovered HMC is sent to the Minerals Separation Plant.

- *Solvent Recovery:* The solvent recovery process is enhanced due to the removal of bitumen from FTT which alters the tailings liquid-vapour equilibrium to achieve superior performance of the distillation units and methane emissions reductions. The distilled tailings have 'below detection limits' of solvent concentration. In conjunction with other gas capture technology, residual solvent and methane releases from oil sands extraction are reduced by up to ~90%. A vapour recovery unit has been designed to capture hydrocarbons from key process units.

- *Minerals Separation:* The cleaned HMC is processed to separate valuable minerals concentrates (zircon and titanium- bearing) from non-valuable cleaned sands utilizing conventional mineral sands technologies, uniquely designed and configured for the oil sands sourced HMC suite of minerals.

- *Tailings Treatment:* CVW™ process residual tailings are then sent to tailings treatment for water recovery and tailings thickening and remediation. The thickening operation is highly efficient due to the low residual hydrocarbon values leading to efficient dewatering and treatment.

Innovative Aspects of the Project. There are numerous innovative aspects to the Project, CVW™ technology and integration at a site. Highlighted below are certain innovations relevant to reducing naphtha losses, resulting in significant avoidance of fugitive methane/GHG/VOC emissions, and enhanced tailings management.

- *Hydrocarbon vapour management:* The project features innovative designs to recover process naphtha that can be recycled. The CVW™ process tailings distillation columns exploit the immiscibility between the aqueous tailings and solvent (in the current project, the solvent was naphtha) which lowers the boiling point of the tailings and allows for enhanced recovery. Additionally, hydrocarbon vapours are managed in recirculation and recovery circuits, reducing environmental impacts.

- *Low solvent loading:* An important innovative feature of the CVW™ process solvent extraction circuits is the low solvent loading required to achieve high recovery values; loadings are ~75%+ lower than similar technologies used to recover bitumen from oil sands and process tailings. Further, the solvent extraction circuits utilize patented 'intra-phase recycle' and 'differential underflow' in their operations. These innovations prevent rag layer formations and improve the quality of the recovered diluted bitumen. In the current project, the solvent utilized was naphtha.

- *Thickener enhancements:* The tailings management thickener is introduced to achieve excellent performance at lower flocculant usage due to the low hydrocarbon values in CVW™ tailings.

Currently, the industry deposits FTT in tailings ponds. A key to CVW™ technology environmental performance is its efficacy for removal of hydrocarbons – both bitumen and solvent – from tailings, leading to abatement of fugitive GHG emissions from tailings ponds and enhanced tailings management performance. The Alberta and Federal governments in collaboration with the oil sands industry have supported the R&D, demonstration piloting and FEED phases of CVW™ development to increase resource recovery, sustainability and abate the environmental impacts of FTT. Years of collaborative development have resulted in an end-to end solution and there is a clear market need for a solution to treating FTT in industry tailings management plans that may complement efforts in regard to AER Directive 85.

Objectives

The executed objective of this project involved the validation and optimization of a potential first-of-a kind CVW™ FTT remediation and product recovery facilities at Canadian Natural's Horizon site.

Work Scope Overview

The completed project work scope was comprised of the validation/optimization engineering evaluation for a potential full-scale commercial prototype implementation of CVW™ technology at Canadian Natural's Horizon oil sands operations site to process all FTT. This project is providing critical technology and project de-risking information through progressive optimization and definition of the engineering design, including integration, layout and modularization. This engineering phase comprised technical scope as recommended from the previous engineering studies[9], including incorporation of a vapour recovery unit (VRU) to limit VOC emissions and modifications to the vapour in the CP flotation circuits. The work focused on the cost validation of the Concentrator Plant, design studies for the Thickener, Tailings Distillation Unit and CCD circuit, continuation of the tailings mineralogy sampling program and the re-profiling of the Minerals Separation Plant to produce an additional value-added product. The activities prepared the project for formal detailed engineering, which includes development technical safety deliverables, project and process deliverables for procurement and complete construction works packages.

The two milestones of the project that were completed during the grant program's eligibility window are summarized in **Table 1**. The optimization engineering was executed by Canadian Natural. This effort focused on addressing optimization opportunities, some of which were identified during the preceding FEED study[9]. In addition to study of vapour release and recovery from process units, including the flotation cells, the CVW™ process was reviewed and the heat and material balance updated to reflect the current state of integration potential. Further, the engineering design of the thickener was reviewed and revised to optimize costs and ensure integration with a host site. Work began on a re-scoping of the Mineral Separation Plant (MSP) to add a second product line consisting of a blend of titanium bearing minerals. The FTT sampling campaign was continued to assess the quality and quantity of critical minerals produced at the host site. The validation engineering exercise of Phase 2 revolved around the capital cost estimate based on the optimized project. Select studies were executed to advance the design of the integrated flotation gas and vapour recovery system, the Tailings Distillation Units the settlers in the solvent extraction circuits. The re-scoped MSP, including the transload facility (to transport mineral products from the trucks to rail cars at the Canadian National rail yard in Lynton, AB), was engineered to a Class 3 level for consistency with the optimized Concentrator Plant.

[9] Stantec Consulting (2019). CVW™ FEED Report, 25-RPT=GW-0001-00, Rev. B, 141 pp.

Table 1. Work scope, schedule and key deliverables for completed milestones for Emissions Reduction Alberta Project F0161057.

Milestone #	Milestone Description	Start Date	End Date	Key Deliverables & Tasks
1a	Optimization and Validation I	Jan 1, 2020	Dec 31, 2020	• Revised heat and material balance, PFD/PIDs for CP • Validation studies including plot plan, vapour recovery unit (VRU) and thickener • Design for flotation circuits/vapour containment • MSP equipment sizing calculations • Preliminary 3D modeling for the MSP
1b	Optimization and Validation II	Jan 1, 2021	April 30, 2021	• AACE Class III capital cost estimate • Revised heat and material balances and PFDs/PIDs for MSP • TDU design validation • Total heavy minerals content, XRF and mineralogical analysis of pipeline and core samples • Advanced MSP 3D modeling package • Transload FEED package

Benefits Overview

The removal of hydrocarbons from FTT enables significant greenhouse gas emissions reductions. By recovering the naphtha from the FTT before it is deposited into tailings ponds, the substrate for methanogenic releases is eliminated, thereby directly eliminating a significant amount of fugitive methane emissions from tailing ponds and related air quality benefits (VOC and SOA reductions) with a net benefit of up to ~632,000 tonnes CO_2e annually including functionally equivalent offsets realized through commodities recoveries, net of CVW™ process emissions[10].

This sustainable technology provides incremental recovery of bitumen and naphtha from tailings and about 180,000 tonnes annually of valuable mineral concentrates (zircon, 'HiTi'). The removal of hydrocarbons from the FTT also enables enhanced tailings management performance.

Results and Outcomes

Tailings Mineralogy

Analyses on FTT samples were conducted using the Dean-Stark Soxhlet extraction or a chromatographic test for bitumen and naphtha analyses. During the CVW CleanTech's earlier FEED study and the current CVW™ project, the resulting cleaned and dried solids from FTT were retained by CVW CleanTech for mineralogical evaluation purposes to assess the quantity and quality of valuable critical minerals extant in FTT.

[10] The Delphi Group. (2021). Creating Value from Waste (CVW™) Horizon Demonstration Project: Environmental Benefits Report - Baseline Report. The Delphi Group.

The FTT samples were obtained using two automated samplers, were collected in 1-gallon steel paint cans and shipped to Bureau Veritas labs in Edmonton. Initially, the samples were composited on a weekly basis and then monthly, using a rotary slurry sample divider, to avoid any sampling bias. The representative sub-samples were then cleaned using the Dean-Stark process and the cleaned solids were shipped to Process Mineralogical Consulting (PMC) in Vancouver for screening and heavy liquid separation using LST (lithium heteropolytungstates solution) at a density of 2.90 g/mL for the minus 250 µm plus 38 µm sand fraction. PMC then used a Tescan Integrated Mineral Analyzer (TIMA-X) for rapid quantitative mineralogy analysis on a sub-sample of the sinks, in addition to chemical analysis using XRF to ensure correlation with the TIMA results and correct analyzer calibration.

Note that these mineral assemblages are used as a basis for engineering designs for the Mineral Separation Plant and associated logistics and in economic models from a mineral production perspective. The Dean Stark analyses indicated an average of about 17.7% sands in the solids of the DTT. Of that, about 58% were coarse sands that are relevant to minerals separation and suggests the balance, less a small percentage of 'oversize' material, are fines. In mineral sands industry, the fines fraction is considered at particle size cut-off of 38 microns. The heavy liquid separation technique, used to isolate the valuable heavy minerals from the coarse sands fraction, indicated an average of 16% heavy minerals (THM – total heavy mineral) content relative to the whole solids component of FTT.

The titanium-bearing minerals in the oil sands ore FTT range from titanium dioxide to iron-titanium oxides. The column listing rutile content represents rutile and anatase with titanium dioxide content greater than 98%. Leucoxene is an iron bearing mineral with high titanium dioxide content ranging from 70% to 98%. Altered ilmenite is a weathered ilmenite mineral in which the iron is partially leached to result in titanium dioxide content ranging from 55% to 70%. Ilmenite contains 40% to 55% titanium dioxide content.

Zircon sand (zircon silicate) is found at concentrations within the FTT coarse heavy fraction. Monazite, a phosphate mineral that contains rare earth elements including cerium, lanthanum and Neodymium. In addition to zircon and titanium, these rare earth elements are listed as Strategic and Critical Minerals (SCM) in Canada[11], Alberta[12] and the United States[13].

Tourmaline, a representative silicate mineral that must be removed during processing in the mineral separation plant, assayed at 5.4% over the sampling duration. Pyrite and marcasite, iron-sulphide minerals that can contribute to tailings management issues such as acid rock drainage.

The flowrates of the SCM of interest – titanium dioxide and iron-titanium oxides, zircon and monazite – have been estimated from the mineralogical assays and FTT process data. The HiTi mass flowrate, at 7.8 tonnes per hour, is comprised of throughput of rutile and leucoxene and the total ilmenite throughput, at 5 tonnes per hour, is comprised of altered ilmenite and ilmenite. The titanium-mineral product is comprised of these two streams.

In practice, the zircon would be produced from FTT into a zircon concentrate which assays at about 75% zircon and the HiTi and ilmenite products are combined into a 'chloride ilmenite' concentrate that assays about 95% valuable titanium minerals.

CVW CleanTech also evaluated and tracked the heavy minerals in the FTT of two other oil sands operators over a period of about nine years. Up to 2014, daily samples were collected and shipped on a monthly basis to the company's Regina pilot facility or the CanmetENERGY pilot facility, where the daily samples were composited on a monthly basis, wet screened on 500 µm and 45 µm to obtain a minus 500 µm plus 45 µm sand fraction for heavy liquid separation. The oversize and minus 45 µm fractions were discarded, as there are no VHM present in the oversize fraction and the minus 45 µm fraction are

[11] Zircon is listed as a Strategic and Critical Mineral in Alberta and the United States.

[12] Alberta (2021). "Renewing Alberta's Mineral Future: A Strategy to Re-Energize Alberta's Minerals Sector", 24 pp.

[13] United States Geological Survey (2022). "U.S. Geolocial Survey Releases 2022 List of Critical Minerals", [U.S. Geological Survey Releases 2022 List of Critical Minerals | U.S. Geological Survey (usgs.gov)](usgs.gov).

too fine for conventional mineral processing and not marketable. The Minerals Engineering Centre of Dalhousie University performed the heavy liquid separation using tetrabromoethane. Mineralogy determination on the sinks fraction was performed by Geochempet in Brisbane, Australia using grain-counting microscopy. Comparative chemical analyses using XRF on a sub-sample of the sinks was performed by UltraTrace (now Bureau Veritas) in Perth, Australia. Analytical results were compiled by the Company and overall average mineral assemblages are shown in **Table 2**. The solids content in FTT across the operators studied appears consistent within the 16-18 wt% range. The heavy mineral component of those tailings shows slightly more variability but are also somewhat consistent in the range of 15-19%wt. Within the heavy mineral fraction of the tailings solids, the zircon concentration was consistent across the samples collected at ~10-11%wt. For the two operators used to benchmark the programs analysis, the titanium-bearing minerals also showed some consistency. However, Operator B showed relatively higher ilmenite content and about half the rutile content. The net titanium bearing content of both these operators exceeded 40%wt. This is in contrast to the titanium mineralogy of the current program's concentrate, which showed significantly lower concentrations of the comparable assays. Further, the pyrite content of the program's concentrate was two to almost seven times higher than the comparative samples. These differences may be due to geographic variation and/or utilization alternative measurement techniques.

Table 2. Heavy mineral assemblage of select process streams. Operators A and B represent samples collected and analyzed by CVW CleanTech under ERA F0161057. Literature values are provided for additional comparison; FTT – froth treatment tailings, froth – froth treatment feedstock, beach – solids deposition at FTT pour point. SCL - Syncrude Mildred Lake, SU – Suncor Base Plant. Sources: SCL FTT A[14], SCL FTT B[15], SCL froth[16], SU beach[16].

Component	Operator A	Operator B	ERA Study	Average	SCL FTT A	SCL FFT B	SCL froth	SU beach
solids (% tailings)	16.0	15.9	17.7	**16.5**				
THM (% solids)	19.2	18.1	15.6	**17.6**		19.7	15.9	21.3
zircon (% thm)	11.0	11.1	9.1	**10.6**	16.0	15.2	14.0	12.1
Rutile (% thm)	4.2	2.1	6.1	**4.1**	7.0	4.0	23.9	26.1
Leucoxene (% thm)	19.0	22.7	6.7	**16.1**	28.0	16.6	52.2	52.0
Ilmenite (% thm)	17.3	27.9	7.7	**17.6**	29.0	25.8	0.7	0.4
Pyrite (% thm)	9.3	3.4	28.1	**11.9**		4.0	5.8	6.9

To assess the observed variation, relevant literature values are also shown in **Table 2**. Some variation is noted amongst the valuable heavy minerals, including critical zircon and titanium minerals. The literature THM content was consistent with, and the zircon content was slightly higher than, CVW CleanTech's measurements. However, the titanium minerals were more consistent with the higher values observed for samples obtained from Operator A and B, yet in some cases the literature values significantly exceeded these as well. Pyrite values reported in the literature are lower than the current program and consistent with the Company's comparative measurements. Again, these may be due to geographic variation or artefacts of the measurement techniques.

Optimization & Validation Engineering

CVW CleanTech's Creating Value from Waste (CVW™) process was under evaluation for a prototype commercial implementation at an oil sands mine site north of Fort McKay in Northern Alberta. This process recovers residual bitumen and naphtha and also extracts valuable minerals from FTT streams.

[14] Trevoy, L.W. and R. Schutte (1981), "A New Source of Heavy Minerals from Canadian Oil Sands Mining Operation", AIME Annual Meeting, Chicago, February 22-26, Society of Mining Engineers of AIME, 81-20, 9 pp.
[15] Oxenford, J., J. Coward and S. Bulatovic (2001), "Heavy Minerals from Alberta's Oil Sands", Technical Report 2001-12, SGS Mineral Services, 11 pp.
[16] Ciu, Z., Q. Liu, T.H. Estell, J. Oxenford and J. Coward (2003), "Heavy Minerals in the Athabasca Oil Sands Tailings - Potential and Recovery Processes, Can. Metal. Quarterly, Vol. 42(4), 383-392.

The optimization and validation engineering phase was co-financed by CVW CleanTech, Canadian Natural, SDTC and ERA. The engineering was completed by an integrated team at Canadian Natural, which developed the designs for the Concentrator Plant (CP) and the Mineral Separation Plant (MSP) – with the main Process and Mechanical design of the MSP plant developed by IHC Robbins of Brisbane in Australia and facilities engineering provided by FWS Engineering.

The optimization and validation engineering was completed from January 2020 to March 2021. The technical design for the Concentrator Plant was completed between January and December 2020 and that for the Mineral Separation Plant by March 2021. The capital cost estimate developed from through the first quarter of 2021 with independent validation and contingency estimate. As the CVW™ project advanced, optimization engineering exercises were conducted based, in part, on the recommendations of the 2019 FEED study. Select key outcomes are highlighted in this report, including plot layout and material balance revisions to incorporate a vapour recovery unit and modifications to contain flotation gases. Subsequent validation activities included a revised capital cost estimate and engineering studies to confirm scalability and operability of select process units.

Plot Layout

The project team conducted project efficiency reviews resulting in some changes to the orientation and configuration of process modules. The CVW™ project is described in two sections – a Coarse Circuit and a Fines Circuit. The Coarse Circuit is part of the minerals function along with the downstream Mineral Separation Plant and is primarily responsible for valuable mineral production. The Fines Circuit is largely responsible for hydrocarbon recovery and environmental benefits accruing to the technology.

<u>Concentrator Plant (CP)</u>

The Concentrator Plant process circuits layout was tuned towards process flow optimization with emphasis on minimizing the path length of tailings streams, especially those containing coarse solids, and relieving congestion in the flotation area. Further plot planning was directed at facilitating modularization. FTT are introduced in the near west area of the layout at the feed tank. The Concentrator Plant (CP) was configured around the tailings pump box, which is centrally located. The flotation circuits (Fines and Coarse) are located to the north side of the tailings pump box, with the coarse flotation tailings pipeline being located closest to PB to minimize coarse slurry transport distance. Both cyclone circuits are located in the west-central area of the plot plan, again to optimize process flow and minimize transportation of coarse material through the plant. The primary cyclone is located on the east side of Cyclone and Process Water Pumphouse. The MSP Feed cyclone is located east of the Coarse Circuit Pumphouse. A 3D model of the site layout is shown in **Figure 3** that of the Concentrator Plant proper is shown in **Figure 4**.

The solvent extraction circuits, comprised of static mixers and IPS (Fines circuit) or dynamic mixers and open vessel settlers (Coarse circuit), are found on the south side of the central pipe rack, south of their respective flotation circuits. The Tailings Distillation Units (Coarse and Fines) are found in a central location north of the flotation circuits (northeast section of quadrant). The corresponding overheads product separators (Coarse and Fines) and aerial coolers are located on the north and west side of the TDU circuits, respectively. A vapour recovery unit (VRU) is located east of the Fines settlers. The thickener and flare are at the far west end of the plot space. Aerial coolers on the east side of the TDUs are to provide cooling water to reduce the temperature of the heavy minerals concentrate slurry before transportation to the MSP. The Fines TDU overhead cooler is located to the east side of the TDUs, while the Coarse TDU cooling unit is located to the west. The MSP feed cooling water is to be provided by site. The utilities, including boiler and water treatment facilities are located north-east of the VRU. The CP E-house is located at the far east side of the CP plot . The MSP area (plus associated equipment and facilities) is located to the east of the CP.

Figure 3. Rendering from the CVW™ optimization study 3D model depicting the plot site.

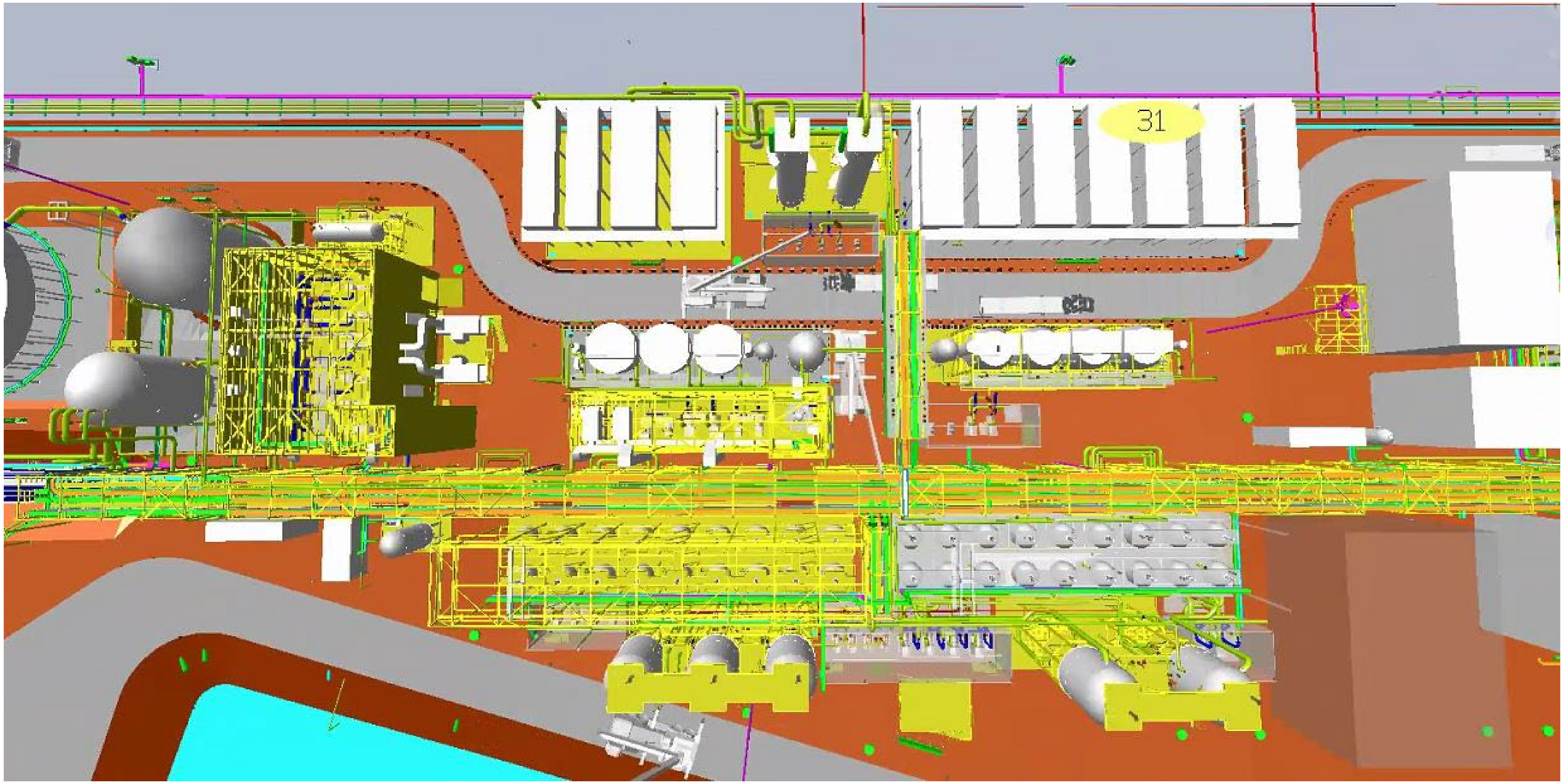

Figure 4. Rendering from the CVW™ optimization study 3D model depicting the central elements of the Concentrator Plant.

Mineral Separation Plant – Process redesign

The 2019 FEED design consisted of wet mill circuits and a large dry mill to produce three different mineral products – primary and secondary zircon sands and a titanium (Hi-Ti) sand. The capital costs for this configuration were significant and an optimization was required and completed at the end of FEED project. The mineral separation plant was modified to eliminate the dry mill side representing a significant portion of the facility and it a more feasible process focused on the production of a zircon concentrate. Subsequently, CVW CleanTech discovered a market for an Ilmenite product in addition to the zircon concentrate. IHC Robbins were retained to modify the process design to include a small dry mill section to the plant to produce the ilmenite. This work involved re-sizing the wet mill circuits, adding a second belt filter and fluid bed drier, and adding two dry mill circuits and an additional product bin. IHCR produced modified PFDs, H&M balance, P&IDs, 3-D model including piping, mechanical equipment lists, and associated MTOs. A block flow diagram shows the modified plant flow (**Figure 5**).

A heavy mineral concentrate (HMC) feed, produced in the Coarse circuit of the Concentrator Plant and characterized by heavy mineral content in excess of 50% and bitumen concentrations less than about 0.5 wt% (dry sands), is introduced into Area 15. This Gravity Upgrade Circuit (GUP) area is comprised of gravity spirals which reject lighter, generally siliceous, trash minerals. The GUP concentrate is then processed in Area 50 in a flotation operation to remove pyrite. The flotation operation is supported by Area 51, which is utilized to prepare flotation reagents. The concentrate from Area 50 is then passed through a Magnetic Separation Circuit (MSC) in Area 20. The MSC utilizes low intensity magnets and wet high intensity magnetic separators to produce a titanium-enriched magnetic concentrate and a zircon-enriched non-magnetic concentrate (NMC). The magnetic concentrate is then processed in a dry mill (Area 45), comprised of electrostatic separator circuits, to produce an ilmenite (titanium) product that is stored in Area 65 for transport offsite. The NMC is then processed in Area 25, which is comprised of gravity spirals and wet shaker tables that are utilized to reject additional light mineral trash. The upgraded NMC is then sent to a dry mill (Area 30), where it is processed through electrostatic separators. The primary product from this stream is zircon concentrate that reports to Product Handling and Loading (Area 65). A secondary product is a titanium-bearing mineral (Hi-Ti) product that is stored in Area 65 and blended with the ilmenite product from Area 45 before loading onto trucks for offsite transport. The process is supported by Area 85 for process water supply and tailings transport.

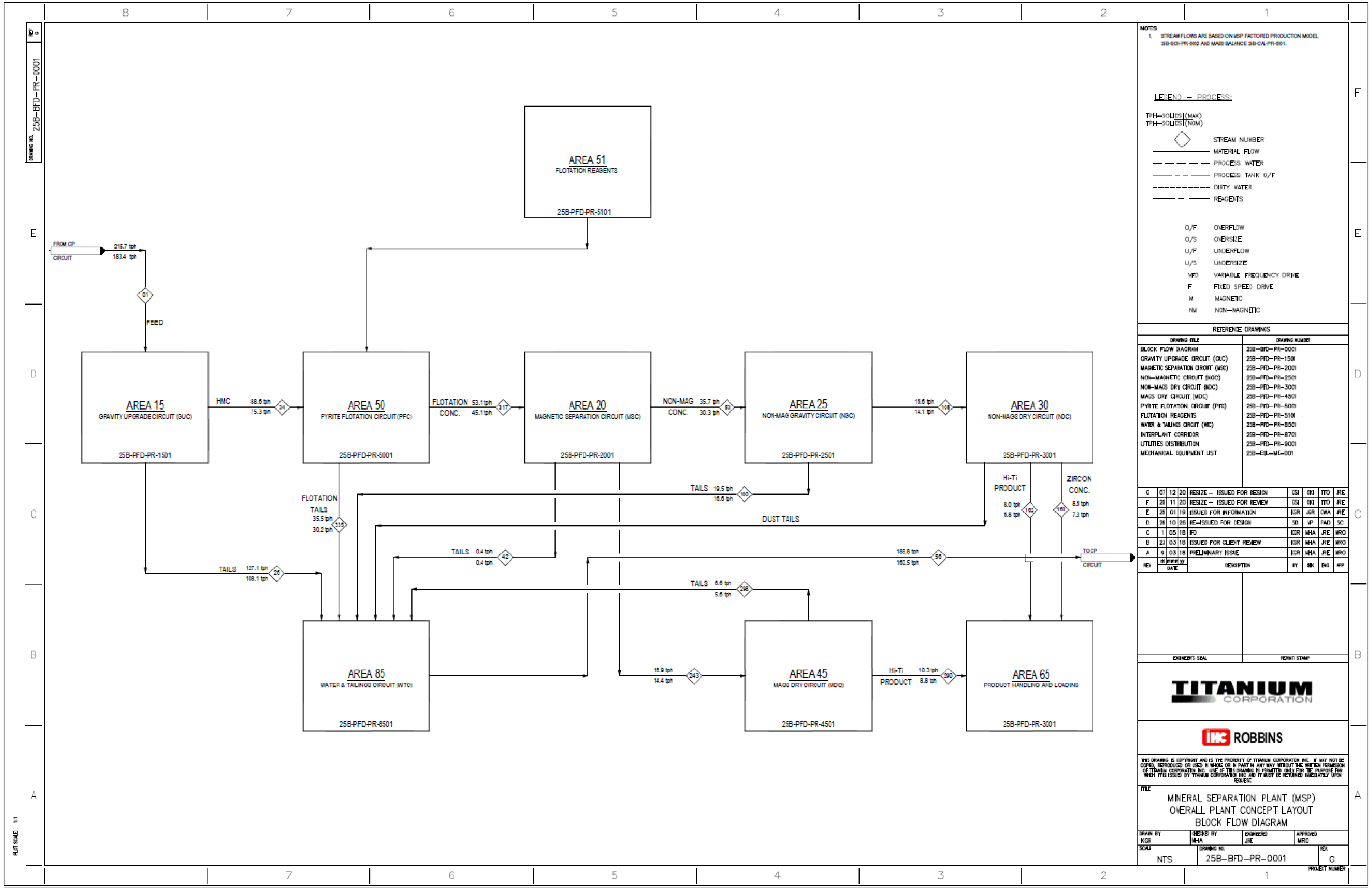

Figure 5. Block flow diagram of optimized CVW™ minerals separation process.

Mineral Separation Plant – Facilities Engineering

FWS engineering was retained to develop the facilities engineering for the optimized mineral separation process, including structural, electrical, instrumentation, and utilities aspects of the MSP. They produced the structural design, electrical single line diagrams, load list, electrical equipment list, instrument index and major equipment list, utilities PFDs and P&IDs, 3-D model, and associated MTOs. The reduced electrical load relative to the 2019 FEED meant that the electrical e-house and the remote instrument building could be combined into one modular building, saving cost. A 3D rendering of the mineral processing facility is shown in **Figure 6**. The wet plant represents the front end of the process and includes gravity spirals, shaker tables, wet magnets, flotation (Areas 15, 50/51, 20, 25 in **Figure 5**) as well as back-end tailings slurry management (Area 85 in **Figure 5**) for transport back to the Concentrator Plant's thickener. The dry plant processes magnetic and non-magnetic streams from the wet plant via electrostatic separators (Areas 45 and 30 in **Figure 5**) to produce an ilmenite concentrate and a zircon concentrate that report to dedicated product bins for truck transport to the transload facility (Area 65 in **Figure 5**).

Mineral Technologies (MT) was invited to perform a quality review of the MSP process and facility designs to assess and identify obvious maintainability, operability, and constructability issues as well as to make recommendations on potential design and layout improvements. Participants included minerals process, construction, mechanical and design expertise from Mineral Technologies Australian and United States offices, along with representatives from CVW CleanTech and FWS. The outcomes of this review provides value to CVW CleanTech prior to entering detailed design.

Minerals Transport – Transload Facility

CVW CleanTech engaged FWS to provide FEED services and advance the basic design of the Transload Facility in Lynton, AB. Specifically, FWS developed final plant layouts and general arrangements, develop the accurate project scope of work and estimate project budgets and execution schedules. The project was executed on a Design-Build basis, which is reflected in the budget and schedule creation.

The transload facility is required to transfer mineral products from trucks to rail cars as part of the transportation logistics. The project scope includes the complete design, supply and installation scope to turnkey Design-Build the Transload Facility with associated infrastructure at Lynton, Alberta. From a bulk material handling perspective, the scope includes the Truck Unloading, Rail Car Loading, Unloading Conveyor, Loading Conveyor with Hopper, Ventilation, and a Dust Management System. A drawing of one of the engineered options for the facility is shown in **Figure 7**.

The transload facility was designed to meet the key performance parameters including total products throughput of 169,000 tonnes per annum, with a facility life of 65 years. Truck unloading capacity is set to about 28 20-tonne trucks per day, with stockpiling capacity of 3,800 m^3 in covered structures, representing two weeks of storage capacity. The rail loadout capacity is designed for 280 tonnes per hour, with 42 rail cars (91 tonne, low cube covered hopper) expected weekly.

The transload facility layout was developed throughout the validation study, and the cost was based on the selected layout option (three options were developed). It should be noted that the layout has been developed not for a specific location within the Lynton facility, as the final site is not known at this stage. After the final site/siding position has been selected, further optimization is expected that may affect the conveyor lengths.

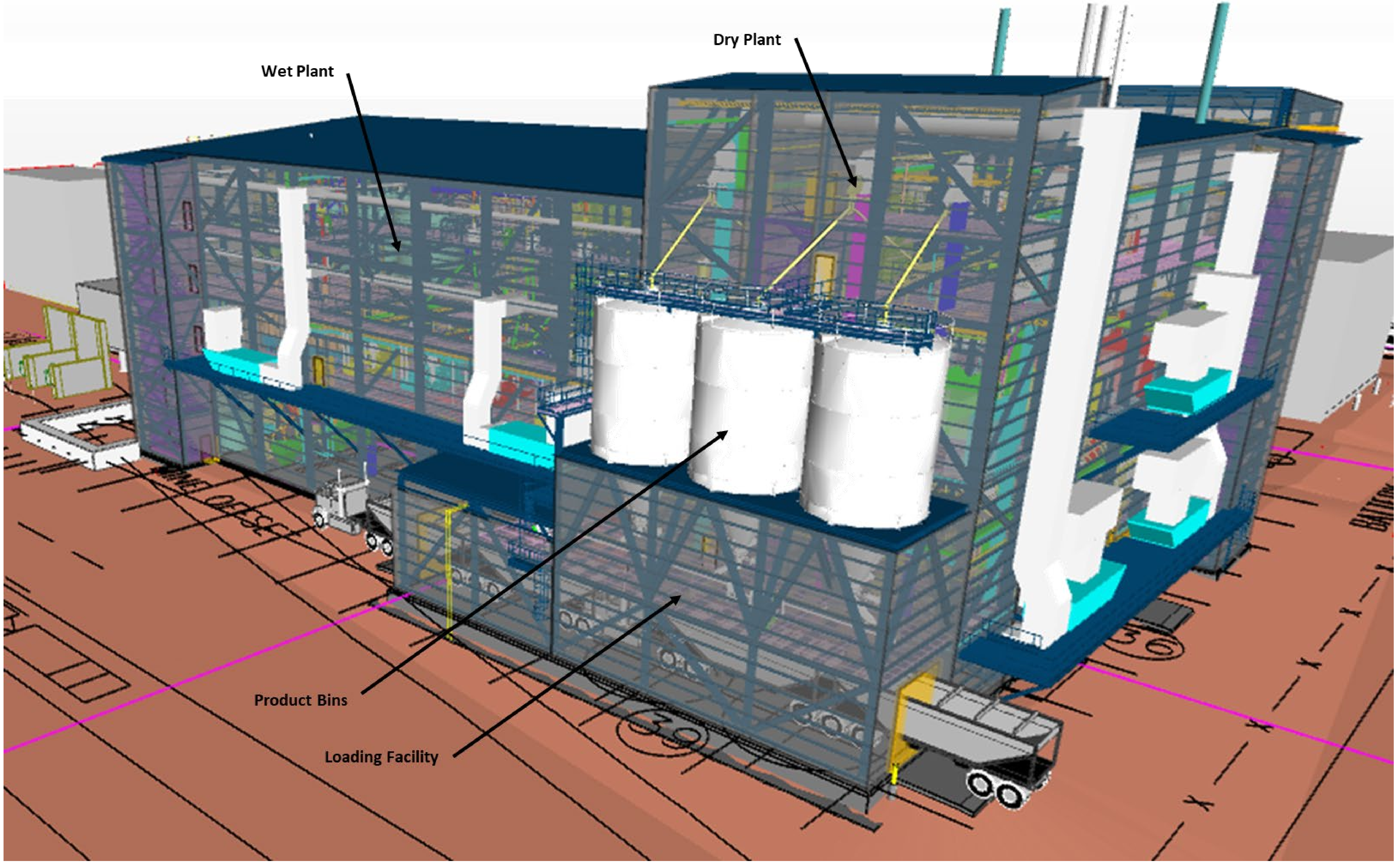

Figure 6. Rendering from 3D model of Mineral Process Facility of the Mineral Separation Plant, view from the south east.

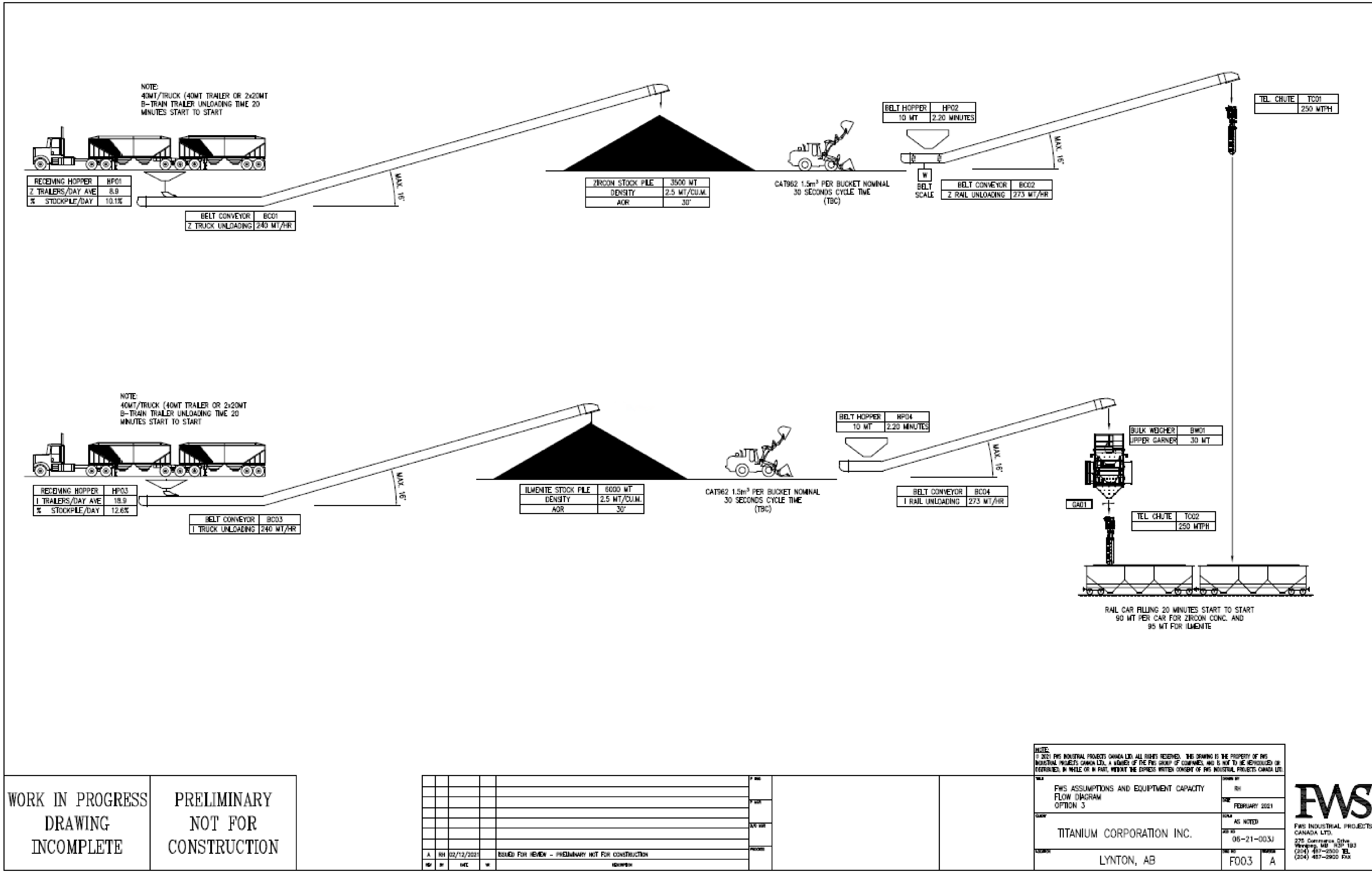

Figure 7. Configuration of a CVW™ transload facility option.

Heat & Material Balance

The heat and material balance developed during the FEED study was reviewed and revised based on the optimization activities executed during the 2020-2021 period. Two formal revisions of the HMB were developed, along with a number of intermediate iterations and some following the validation period intended to achieve acceptable closures for environmental benefits estimates. The Concentrator Plant balance were integrated with that of the Mineral Separation Plant for a unified CVW™ process balance. Some of the key advancements/modifications included:

- Increase to the feedstock (FTT) temperature from 70˚C to 80˚C.
- Revisions to the flotation system in which the spent flotation gases are recycled to avoid hydrocarbon losses to the atmosphere.
- Integration of a vapour recovery system that captures hydrocarbon vapours from the blanket gas system, including a small fraction of air from the flotation circuits.
- Adjustments to the steam requirements of the process (relative to the 2019 FEED study) to account for the higher operating temperature and specific loading at the TDU.
- Significant redesign of the minerals process to produce two concentrates.
- Outside battery limit re-sourcing of the cooling water for heavy mineral concentrate slurries

A generalized block flow diagram (**Figure 8**) is provided for context of the revised material balance.

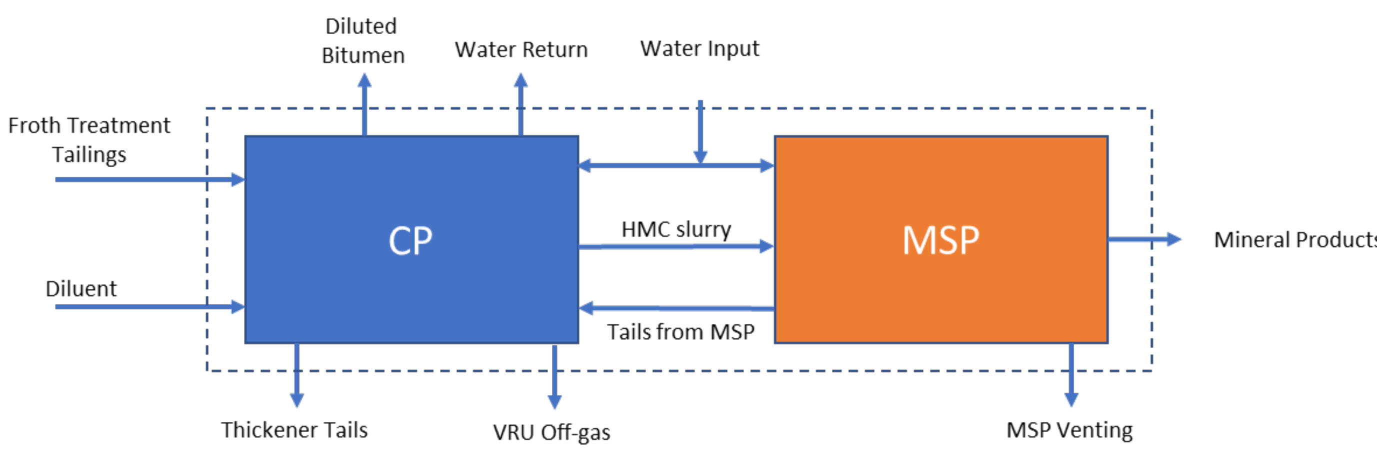

Figure 8. Generalized block flow diagram showing CVW™ flows across the battery limit (broken line enclosure) and interconnections between the CP and MSP. The diluent used in the project was naphtha.

Note that the mineral products include a zircon concentrate and an ilmenite concentrate at a ratio of 1:1.5. The unified balance shows excellent closure on total mass and on each constituent. The largest deviation with respect to material closure is observed with water, with a net deviation of about 1.6%. Water imports include cooling water for the MSP feed (HMC slurry) as well as raw water for MSP process applications. The return water is generated at the thickener overflow and is net of internal re-use water for steam generation and other CVW applications. The naphtha (labelled as 'diluent' in ***Figure 8***) in the thickened tailings represents the residual lost to tailings ponds against which baseline performance is estimated. Further, the naphtha in VRU off-gas represents residual VOC emissions, again, against which baseline performance is measured.

Cost Estimating Methodology

The costing exercise for this project is a Class 3 Capital Cost Estimate in compliance with AACE (Association for the Advancement of Cost Engineering) requirements. This was confirmed and/or adjusted with the results of the Risk Analysis, which was developed by an independent expert in Risk management (Conquest Consulting) with Canadian Natural project staff attending. The estimate was completed to the level of accuracy in accordance with AACE International Recommended practice No. 18R-97 Cost Estimate Classification System Guidelines. This estimate reflects an expected accuracy range of +30%/-20% with confidence level @ P50.

For the Concentrator Plant (CP), the work covers the entire scope from flowsheet, heat and mass balance development, equipment sizing, P&ID development, Electrical and I&C design, Civil Structural and Architectural design, etc. right through to the development of MTOs and the Class 3 estimate. Disciplines involved in this part of the work are Process, Mechanical, HVAC, Piping, Electrical, Instrumentation & Controls, Civil / Structural / Architectural, Environmental and Technical Safety. For MSP, FWS Engineering was responsible for checking that the MSP Process, designed by IHC-Robbins, and Mechanical deliverables meet all Canadian and applicable standards. AACE Class 3 estimates for the Concentrator Plant (CP) including thickener system, associated utilities and buildings, the Minerals Separation Plant (MSP) including the laboratory and the Office & Control Room, as well as general plant infrastructure were prepared.

The cost estimate includes all direct and indirect field costs. Other indirect costs include engineering and construction management costs and owners costs. Project direct costs were developed based on material take-offs (MTO) provided developed by the engineering disciplines, vendor quotations, budget quotes, subcontract rates from in-house data, and productivity factors and wage rates. Direct costs are assembled by discipline based on direct labour, shop/module labour, material, tagged equipment, module and subcontractor costs. Subcontractor unit costs covers supply and installation costs. Subcontractor unit pricing is inclusive of overhead and profit and excludes living out allowance (LOA), travel costs and travel time costs, which are captured separately in the indirect costs of the estimate. Construction indirect cost is based on the construction execution plan, contracting strategy and preliminary schedule of the project. It was primarily bottoms-up to align with construction contracting strategy where applicable, in consultation with CVW CleanTech, and rest was based on historical factored allowances. The contingency was determined by an independent third party to be just under 12% of the project costs.

CVW CleanTech endeavored to provide functional direction on capital cost estimates by examining the project on a recovered resources basis. The hydrocarbon function is comprised of the ‘Fines’ circuit of the Concentrator Plant and delivers the hydrocarbon recovery benefit and the majority of the environmental benefit. The minerals function is comprised of the ‘Coarse’ circuit of the Concentrator Plant plus the Mineral Separation Plant and delivers the mineral recovery benefit and a fraction of the environmental benefit. The environmental benefits accruing to CVW™ include GHG emissions abatement, Critical Air Contaminants (CAC) abatement, including volatile organic compounds (VOC) as well as water-use and land-use benefits; these benefits are described in a subsequent section. Using a factorized approach against the Class 3 estimate for the CVW™ project, a contingency of 20% and CPI inflation of 11.3%, CVW CleanTech has reprofiled a CVW™ project on functional units[17].

Construction would be implemented in three phases, beginning with Early Works that involves site preparation, underground installations and placement of pilings for facility and process structures. Early works of the facility construction would be planned to commence during spring thaw, when detailed engineering would be approximately 50-80% complete. The main construction phase would begin with the installation of the centralized pipe rack. Concurrently, process modules which have been fabricated off-site and delivered to the project site, would be installed in a sequence that follows the process flow.

[17] CVW CleanTech (2023). Process and Technology Overview. https://wp-cvwcleantechnology-2024.s3.ca-central-1.amazonaws.com/media/2023/08/12135955/CVW-Process-and-Technology-Overview.pdf,CVW CleanTech, 112 pp..

The Mineral Separation Plant construction would be timed such that it is completed as the Concentrator Plant reaches completion. Finishing Works comprise the remaining 20-30% effort to satisfy 90% completion certificates. The project engineering and construction effort is scheduled to occur over a 48 month period followed by commissioning (**Figure 9**).

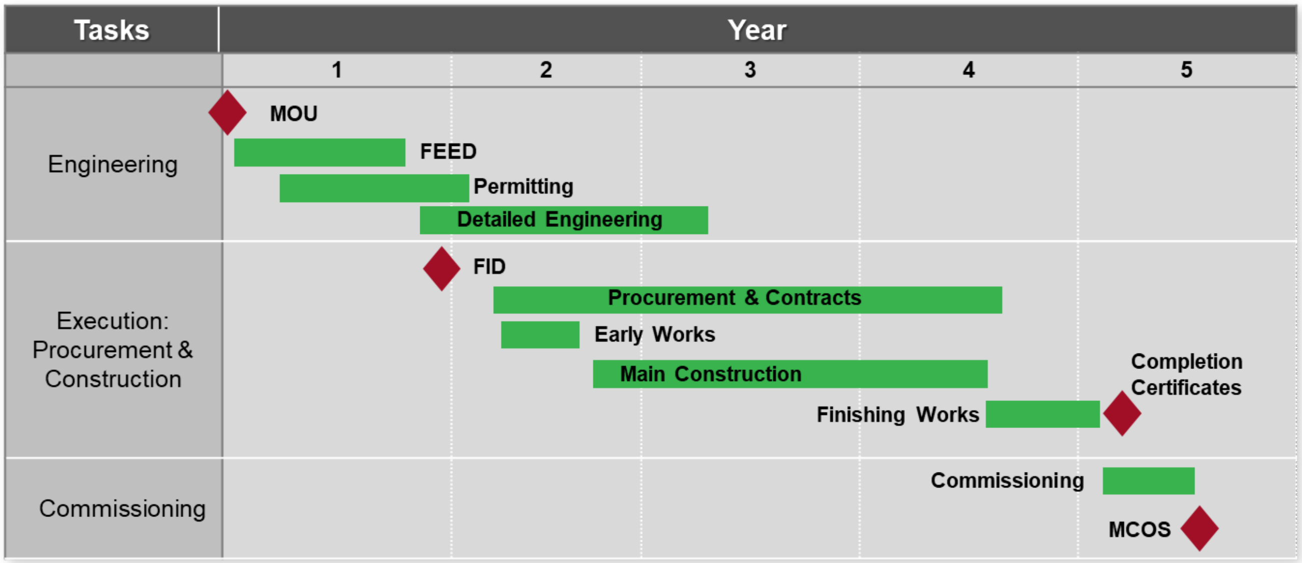

Figure 9. Project Gantt chart indicating engineering, construction and commissioning phases of a CVW project.

Studies

The project team engaged in and executed a number of studies in support of the optimization and validation exercises. In addition to the tailings mineralogy work described above, a thickener redesign for optimal integration and cost efficiency was conducted. Another set of studies address the scalability of the CVW™ Tailings Distillation Units. These involved computational fluid dynamic modelling executed by Coanda Research and Development Corporation (Coanda) and Hatch Engineering. Physical testing and process modeling work on the impact of spent flotation gas recycling and integration into a vapour recovery unit was executed to integrate this safety and VOC capture technology into the design. Finally, an independent study by Conquest Consulting was completed on environmental benefits accruing to a CVW™ installation confirming the material carbon abatement potential and other critical air quality, land and water use benefits.

Thickener

In the 2019 FEED study, there was a requirement to maximize the thickener underflow solid content >50%. However, that posed an issue regarding the pumpability of the stream. A shear thinning loop, that included pump and associated piping and instrumentation, was added to address the issue. The thickener underflow solids content has been set to 48% based on testing by SNF executed during the FEED study. Further, the project team has considered injection of carbon dioxide in the thickener system to control pH and improve water clarity. A cover has been added to limit vapour cloud formation.

During the optimization period, the thickener overflow pump system was deleted and thickener overflow transport was achieved by gravity flow. The existing water pumps have been replaced by slurry pumps. Further, the off-specification/thickener by-pass pumping system was been deleted. Hydraulic calculations had indicated that a set of booster pumps would be required for pumping the thickener underflow.

Tailings Distillation Unit Modelling

Over ten years of CVW CleanTech's research and development has culminated in a novel steam distillation process to recover over 98% of process solvent from CVW™ tailings slurries, enabling oil sands operations to lower the solvent loss intensity to less than 0.5 bbl/kbbl (barrels of solvent per thousand barrels of bitumen produced) and reducing fugitive methane emissions by up to 90%. Early phase research involved thermodynamic phase behaviour experimentation and conceptual designs of the prototype distillation unit at the bench scale. Testing continued into a second phase of large-scale pilot testing that integrated CVW CleanTech's Tailings Distillation Unit (TDU) into the complete suite of CVW™ technologies.

The overall scope of work contracted to Hatch Engineering of Calgary ("Hatch") was executed as two packages. Task 1 involved an independent review of the current design. This review was completed to comment on its design, installation, and constructability. It utilized Hatch's previous experience with similar applications to make any recommendations for improvement. Task 2 contemplated computational fluid dynamics (CFD) analysis of the design to predict overall steam/slurry hydrodynamics and heat transfer inside the distillation column slurry pool. Simulation outputs include detailed velocity, pressure, and temperature distribution throughout the modelled domain. The model also output steam mass and temperature distribution to indicate heat transfer efficiency. CFD analysis was completed using ANSYS Fluent for the CVW™'s current design and two additional design improvements/alternatives.

The technical review indicated that the current design likely provides the most effective at heat transfer of the geometries considered, but consideration must be given to constructability and operability. Hatch's CFD modelling concluded that the TDUs operate in a turbulent regime, which benefits interfacial heat and mass transfer. Sufficient residence time should be allowed to avoid any short circuiting related to transport phenomena. CVW CleanTech's conducted supporting calculations indicating that heat transfer and mass are completed efficiently in accordance with modelling, providing two orders of magnitude factor on liquid pool residence time.

CVW CleanTech contracted with Coanda Research and Development Corporation (Coanda) to provide a CFD analysis of the TDU design. The work built upon the findings from the conceptual design tested in a previous modeling project. The study, conducted during the optimization and validation engineering phase of the CVW™ project, was expected to address (a) steam distribution, hydrodynamics within, and heat transfer to, the liquid pool and (b) operational performance criteria including slurry velocities at the vessel wall, mass transfer and phase change inferences, and an assessment of the mechanical stability with respect to steam hammer.

Multiphase multispecies simulations of the proposed TDU vessel were performed using the commercial software ANSYS Fluent™. Two phases were considered in the modeling: the vapour/steam phase and a lumped slurry phase that is comprised of water, diluted bitumen and solids. Further, bubble coalescence and break-up were not consider in lieu of a constant bubble size. These measures were undertaken to reduce the complexity and stiffness of the transport equations being modeled. Condensation and evaporation were accounted for in the simulation via the Lee model.

The pressure profile throughout the vessel was monitored at specific locations along the vessel wall. It was found that the frequency of observed pressure fluctuations was very low and will not create any mechanical issues for the vessel or sparger.

The key conclusions from the multiphase flow and heat transfer simulation in the Coanda study include:

- High degree of mixing observed in liquid pool
- Excellent heat transfer observed in close proximity to designed internals
- Pressure field fluctuations indicate system frequency of ~1 Hz; should not create any issues with mechanical stability of vessel

- No high wear regions observed at vessel walls
- Steam may channel to vessel core – consider reorienting internals

The results of both the Hatch and Coanda studies are consistent and suggest the current TDU effectively delivers the energy required to drive the desired naphtha recovery without material operability or maintenance issues.

Flotation Vapour Study and Vapour Recovery Unit

During the 2019 FEED, naphtha vapour emissions with spent flotation gas were identified as a potential safety issue and a recommendation was made to address this in subsequent engineering effort. Two options to manage flotation gas vapours were considered, including recycling of the flotation gas (air) in a closed system integrated into the vapour recovery unit. An alternative option that was also examined was the implementation of a closed vapour system in which hydrocarbon vapours would be used as the flotation gas. This concept was supported by a physical testing campaign that looked at the use of various light hydrocarbon gases in a homologous series, including propane, octane and decane, on flotation performance. The air-based approach was ultimately adopted and simulations were developed to assess the quality of flotation vent gases produced by the CVW™ process from a safety perspective. The models were based on physical 'pool' naphtha analytical data and, to simulate the 'tailings' naphtha observed in the FTT, a Naphtha Recovery Unit was simulated in front of the CVW™ process to provide a cut residual naphtha stream that is representative of NRU 'tailings' naphtha.

At higher flotation temperatures heavier naphtha components are driven into the produced gas phase albeit at lower concentrations. This trend also is demonstrated with aeration rates. These observances are enhanced in the Coarse flotation circuit due to the use of 'pool' naphtha as a scavenging process aid. While the present results generally agree with the modelling utilized by the project team, in that the produced vent gases are comprised of hydrocarbons in the range of one mole percent and are likely close to the LEL or within the explosive range at design conditions. Certainly, all hydrocarbon gas phase concentrations are above the safety design standard of 20% of the LEL, necessitating the containment and/or management of these gas streams. This modelling indicates the potential hydrocarbon vapour release from the flotation circuits, necessitating containment in a vapour recovery system.

The use of recycled air in the flotation system is seen as a way to minimize both emissions and treatment requirements for this stream. Bench testing in 2020 established that there may be minimal material performance difference between the use of fresh air and recycled air (with hydrocarbon contamination). Some spent flotation gas, enriched with hydrocarbon vapour, passes to the CCD solvent extraction circuit with the froth product and some make-up air would be required. In concert with the flotation study described above, it was determined that a vapour recovery system would be implemented to capture to process vapours from the flotation, solvent extraction and distillation units in a single vapour recovery unit (VRU).

The naphtha vapours reporting to the VRU were sourced from the flotation circuits, diluted bitumen product system and the Tailings Distillation Unit overheads. The vapour pressures of naphtha, CVW™ diluted bitumen and NRU tailings diluted bitumen was first assessed as a function of the analytical composition of the pool naphtha and resultant fractions following NRU treatment. CVW CleanTech's Hysys model sizing the VRU (in support of the optimization study) at a flotation gas recycle rate of 99% and incorporating a methane blanket over the diluted bitumen product stream and Tailings Distillation Unit overheads. This analysis supports optimization findings in that hydrocarbon vapours will be adequately contained.

MSP Process Releases of Naphtha and Water Vapour to Environment

The Mineral Separation Plant (MSP) receives heavy mineral concentrate prepared in the upstream Concentrator Plant (CP). The HMC slurry contains trace amounts of naphtha in diluted bitumen, and the project raised concerns about potential safety issues due to naphtha evaporation into the MSP process building. This potential evaporation could occur at open slurry surfaces in process units such as gravity spirals, flotation cells and pump boxes. The MSP building is equipped with air handling units to move up to three volumes per hour and gas detection instrumentation is installed to detect hydrocarbon vapour in the MSP slurry before it exits the CP.

Naphtha mass transfer rates were calculated for winter and summer design conditions within the MSP plant. The rates were found to result in relatively low absolute evaporation of naphtha. Under design conditions, the rate of naphtha evaporation is less than 1 kg per hour. This evaporation rate may rise to above 10 kg per hour with higher than anticipated naphtha concentrations in the MSP feed slurry due to, for example, underperformance of the TDU. Regardless, corresponding values of naphtha in the plant environment are significantly below the lower explosive limit for naphtha (at ~0.8 volume %) and the generally accepted safety standard adopted by the industry that recognizes the maximum allowable hydrocarbon concentration to be less than 20% of the LEL, typically below 0.01 volume percent.

Environmental Benefits

CVW™ technology is designed to remediate oil sands FTT, recovering lost hydrocarbons, preventing their release into tailings ponds and the atmosphere. Once deposited into mature tailings pond, solvent serves as a substrate for biogenic methanogenesis which results in fugitive methane release from ponds to the atmosphere, which is a serious issue reported in numerous science-based studies. (In the current project, the solvent utilized was naphtha.) Further, bitumen resides as 'mats' that rest on the surface of the fluid fine tailings (FFT) layer in ponds and, due to biogenic gas production within the FFT), are a source for hydrocarbon contamination at the surface of the pond[18]. As oil sands operations mature, methane emissions from ponds increase, with individual ponds reporting annual methane emission levels as high as one megatonne carbon dioxide equivalents[19]. In recovering hydrocarbons, CVW™ provides functionally equivalent emissions offsets through incremental hydrocarbon recovery, delivers critical air contaminant benefits as well as land-use and water-use benefits that are consistent with the industry's tailings management mandates. Waste heat recovery from thickened tailings overflow have the potential to contribute to project environmental benefits but were not incorporated into the CVW™ project. Project benefits are net of CVW™ process emissions. The CVW™ process supports the Federal government Clean Fuel Standard in reducing the intensity of produced synthetic crude oils at oil sands sites by 5-10%. CVW CleanTech commissioned The Delphi Group to conduct an independent review of the project environmental benefits under its agreement with SDTC, which is summarized in **Table 3**. This table compares the Delphi Group analysis with an earlier analysis done by Stantec Consulting during the 2019 FEED Study and CVW CleanTech's estimates.

[18] Syncrude Canada (2022). "2022 Pit Lake Monitoring and Research Report, Base Mine Lake Demonstration Summary: 2012-2021.
[19] Kong et al. (2019), "Second-generation Stoichiometric Mathematical Model to Predict Methane Emissions from Oil Sands Tailings", Science of the Total Environment, **604**, 133646.

Table 3. Summary of GHG emissions abatement benefits accruing to the CVW™ project from independent reviews by The Delphi Group[20] and Stantec Consulting[8]. Calculations captured in the Natural Resources Canada's Clean Growth Project (NRCan 2023; CGP-17-0897) are also shown. CVW™ impact relative to site-wide emissions are based on 2019 emissions intensities[21] and the design project production rate. Emissions abatement is reflected as annual tonnes of carbon dioxide equivalents.

GHG Emissions Abatement Benefit	Delphi Group (2021)	Stantec (2019)	NRCan GHG Study (2023)
TP Methanogenesis	643,989	642,787	667,003
Bitumen Production FE	109,810	93,168	53,873
Naphtha Production FE	61,831	-	67,638
Minerals Production FE	37,095	-	41,888
CVW™ Process	-220,337	-163,665	-157,622
subtotal	**632,388**	**572,290**	**672,780**
Heat Integration	0	0	104,385
Net Benefit	**632,388**	**572,290**	**777,165**
% site-wide emissions	10.69	8.35	11.35

The CVW™ process addresses methane emissions in Alberta by reducing hydrocarbons from entering tailings ponds and the atmosphere, reducing methane/GHG emissions resulting from their microbial metabolization into methane. The GHG emissions reductions achieved with CVW CleanTech's process are a result of the reduced volume of hydrocarbons discharged to an oil sands tailings pond and the atmosphere. Extensive scientific studies[22] and modelling[23] have established that once released into a tailings impoundment, light hydrocarbons, such as naphtha and other solvents, are metabolized by microbes and release GHGs, primarily methane. Functional equivalencies are based on incremental commodities (bitumen, naphtha and mineral concentrates) production that offset emissions required to produce equivalent volumes using the accepted commercial practices. CVW™ process emissions are based on emissions factors for natural gas and electricity consumption required to operate the Concentrator Plant and Mineral Separation Plant. The differences amongst the CVW™ project emissions studies shown in **Table 3** result from some variation in the emissions factors used, base case emissions assumptions and minor product variations as the project developed.

Implementation of CVW™ technologies also reduces harmful Critical Air Contaminant (CAC) emissions of Volatile Organic Compounds (VOC) and Secondary Organic Aerosols (SOA). The direct recovery of process solvent from hot FTT prior to deposition in tailings impoundments prevents emissions of volatile organic compounds (VOC) which are harmful to human and wildlife health. In mining oil sands operations, FTT are deposited into tailings ponds, where a significant fraction of the solvent mass can volatize into the atmosphere as VOCs, depending on temperature and other atmospheric conditions. The Delphi Group[10] estimated the reduction of VOC emissions resulting from the implementation of

[20] The Delphi Group (2021), "Creating Value from Waste Horizon Demonstration Project. Environmental Benefits Report - Baseline Report, 58 pp.
[21] Alberta (2021), "Alberta Oil Sands Greenhouse Gas Emission Intensity Analysis for the period of 2011-2019", Alberta Oil Sands Greenhouse Gas Emission Intensity Analysis - Open Government.
[22] Siddique et al. (2007), "Metabolism of BTEX and Naphtha Compounds to Methane in Oil sands Tailings", Environmental Science and Technology, **41**, 2350.
[23] Burkus, (2014), "GHG Emissions from Oil Sands Tailings Ponds: Overview and Modelling Based on Fermentable Substrates. Part II: Modeling of GHG Emissions from Tailings Ponds Based on Fermentable Substrates", Alberta Environment and Sustainable Resource Development, 63 pp.

CVW™ technologies to be up to 4,000 tonnes per year. Secondary Organic Aerosols (SOA) related to FTT have been identified by Environment Canada as an emerging public health concern[24]. SOAs are related to their light hydrocarbon precursors, including naphtha components from FTT, and are emitted at a rate ranging from 16,000-30,000 tonnes annually in the oil sands region.

Land-use benefits are realized through reduced mining and tailings pond footprints and fresh water use intensity is reduced on a functional equivalent basis largely due to efficiencies in tailings management and mineral production water consumption. The Delphi Group estimated the annual land-use and water-use benefits from CVW™ project implementation at 46 Ha and 2.8Mm^3, respectively. The CVW™ process may support advanced tailings management activities and reduce potential acid rock drainage issues at an oil sands site through partial recovery and concentration of pyrite, which can then be actively managed to avoid sub-aerial deposition and potential oxidation. Further, CVW™ integration and production of valuable mineral products may positively impact the host tailings reclamation efforts through reduced radioactive element depositions.

Conclusions

CVW CleanTech's Creating Value from Waste (CVW™) process was evaluated for potential first-of-kind commercial implementation at an oil sands mine site north of Fort McKay in Northern Alberta. The CVW™ process recovers residual bitumen and naphtha, extract valuable minerals from FTT streams and provide meaningful environmental benefits, including significant fugitive methane emissions avoidance.

The Optimization and Validation engineering phase was co-financed by CVW CleanTech, Canadian Natural, Natural Resources Canada's Clean Growth Program, SDTC and Emissions Reduction Alberta. The engineering was completed by an integrated team, which developed the designs for both the Concentrator Plant (CP) and the Mineral Separation Plant (MSP).

The optimization and validation phase was completed from January 2020 to April 2021. The main conclusions of the CVW™ FEED study include:

- An optimized integration design for implementation of CVW™ technology has been developed. This details all key tie-ins such as produced diluted bitumen and cleaned tailings. Notable additions to the process technology include modifications to the flotation gas phase circuitry, reduction of rotating equipment, modification to the thickener system and the addition of a vapour recovery unit to limit potential release of hydrocarbons including VOCs. The optimized process development was informed by several technical studies, including vapour management and computational fluid dynamic studies of the Tailings Distillation Units.
- Implementation of CVW™ can result in a net reduction of GHG emissions of up to 632,000 tonnes CO_2e annually through abatement of fugitive tailings pond methane emissions, functionally equivalent benefits through incremental commodities recoveries including bitumen, sovlent and mineral concentrates.
- Tailings sampling indicated that valuable minerals are extant within FTT in attractive volumes. While some variability was observed, the mineralogy was reasonably consistent with that of other oil sands mining operations in the Wood Buffalo region.
- An AACE Class 3 capital cost estimate has been developed for the optimized CVW™ project. This cost has been developed from budgetary costs of tagged equipment with vetted build-ups to estimate other direct and indirect costs. This cost estimate will serve as a base for potential commercial deployments of CVW™.

[24] Liggio et al. (2016), "Oil Sands Operations as a Large Source of Secondary Organic Aerosols", Nature, 534, 16.