

# **B.C. Montney Produced Water to Saleable Salt Technology Pilot Test**

**Geoscience BC Report 2022-11**

**March 31, 2022**

**Saltworks Technologies Inc.**



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# 1 EXECUTIVE SUMMARY & INTRODUCTION

This pilot project explored Montney unconventional co-produced water treatment innovations that would reduce the reliance on disposal wells while ensuring no harmful substances are released into the environment. This project completion report outlines the findings and cost projections resulting from an off-site pilot study.

The work focused on treatment of British Columbian Montney Formation produced waters with air humidification-dehumidification (“HDH”) evaporation technology. This enables use of moderate grade waste heat (80-90° C) available at gas production facilities to evaporate and treat saline water. Propane was used in the pilot plant to replicate the waste heat that is used at full scale. In past projects, waste heat is typically generated by engine jacket or compressor jacket cooling water.

The treated water met all BC Aquatic Life Water Quality Guidelines (“BC ALGs”). There are two pathways to discharge the treated water:

- A) As liquid water, returned to the environment, requiring a water discharge permit, slightly higher cost.
- B) As water vapour, released to the atmosphere through use in the system’s cooling tower circuit, requiring a cooling tower permit, slightly lower cost. Work has been focused on this pathway given its lower cost and greater applicability to jurisdictions outside BC. It is important to note that there is no direct contact of un-treated produced water with atmosphere during evaporation: a practice thus far prohibited in BC. Only condensed distilled water that has undergone post treatment for volatile organic compounds (“VOCs”) enters the cooling tower circuit. The cooling tower circuit includes saline drift elimination technology that exceeds the United States Environmental Protection Agency (“USA EPA”) guidance on cooling tower drift control. Most jurisdictions rely on the USA EPA method.

This project explored and pilot tested equipment modifications with the goal of achieving zero liquid discharge (“ZLD”). The goal included production of solid salt fit for safe industrial re-use as road salt. This meant removing the remaining 60-70% water captured in the brine reject and producing solid salt free from deleterious contaminants, thereby reducing the need for liquid brine disposal, or landfilling of salt.

Industry Montney operators provided truck-transported volumes of Montney Formation produced water to the pilot test site at Richmond B.C. These water samples, delivered over the course of several months, with volumes of 2 m<sup>3</sup>, were used to test the HDH process, particularly for the suitability and scalability of the equipment for scaled-up volumes of produced water.

The overall project objective was to gain knowledge of the reliability and economics of the HDH pilot process, while ensuring no harmful by-products were released to the environment.

## 1.1 RESULTS:

- **Clean Water:** treated liquid water met BC ALGs, with slight traces of metals introduced during the post treatment tests. This report includes details, data, and discussion.

- **NORMs Management:** Naturally occurring radioactive material (“NORMs”) pre-treatment was successfully implemented. This involved dosing sulphate to precipitate barium sulphate at a stoichiometric ratio of 1.2 to 1.8 (varies with Sr and Ca levels), leveraging the well-known phenomena that radium (key NORM in question) co-precipitates with barium sulphate.
- **Industrial Salt Production:** Solid salt produced for two of the three water samples met Transport Canada’s road salt specification as defined by ASTM International (“ASTM”): >95% calcium-sodium chloride without ‘deleterious’ substances. Trace levels of NORMs were detected in the solid salt, however additional processing may be able to prevent this. The third produced water sample was sulphate rich, barium weak. Owing to elevated sulphates, this produced water could not meet the Transport Canada road salt specification. Only produced water chemistries with raw calcium-sodium chloride proportions greater than 95% are a candidate for road salt re-use. The other primary industrial re-use applications of salt in British Columbia are in the pulp and paper sector: caustic soda, chlorine gas, and bleach production. These processes also require low sulphate input salts, drawn from the same inventory as road salt. In summary, sulphate rich produced waters are a poor candidate for industrial salt production and re-use.
- **Industrial Salt Market Size:** The British Columbian solid salt market is estimated at 200,000 tonnes per year of consumption. This translates into ~2 million m<sup>3</sup> per year of produced water, or ~5,500 m<sup>3</sup>/day of produced water. Specific to north-eastern British Columbia (“NE BC”), the road salt demand is ~40,000 tonnes per year, which equates to ~1,375 m<sup>3</sup>/day of produced water. In short, the salt produced from one mid-sized Montney operator site would provide all the road salt needed within ~400 km of the surrounding region. To manage the volume of produced water generated in NE BC, alternative salt market or disposal mechanisms would need to be developed. Road salting contractors in the area have expressed interest to pick-up the salt free of charge and accept custody so long as specifications are met, and supply does not exceed demand.
- **Technology Fit:** Although the pilot technology achieved the solid salt production goals, HDH technology is not recommended for widespread implementation as a ZLD technology at this time. HDH technology can be used as a robust concentrator of produced water, that can reliably produce a brine reject of 30-40% salt solution without significant operator intervention. However, when producing solid salt, a notable amount of operator attentiveness and continuous tuning of wash cycles is required to prevent scaling and crusting the evaporation module packing. This is not sustainable in the oil field and an alternative technology pathway should be pursued.
- **ZLD Technology Fit:** For Montney produced water in NE BC, it is recommended to use forced circulation vacuum (~30 kPa absolute) steam-based evaporators in ZLD applications. For example, mechanical vapour recompression (“MVR”) cycle, or a single effect evaporator-condenser system can be used to evaporate saline water at ~75-80°C.
- **ZLD Cost:** An all-in service cost estimate to treat produced water, based on an MVR (not HDH) ZLD platform, is \$40/m<sup>3</sup> CAD. This assumes a 200 m<sup>3</sup>/day plant, 5-year contract, produced water that is equivalent to samples used in this pilot, free removal of solid salt by a road salting contractor, electrical energy at \$0.08/kWh, and 85°C waste heat thermal energy at no cost other than \$200,000 CAD for integration of the waste heat transmission system. The cost range varies with

location and site preparation conditions. In comparison, HDH technology operating as a produced water concentrator will cost in the \$20-30/m<sup>3</sup> CAD range.

## **1.2 RECOMMENDATIONS:**

1. Operators with produced water should consider HDH waste-heat-driven technology as an economic and viable contender for produced water volume reduction producing a concentrated brine, but not for ZLD applications. This should include further investigation of impacts to water disposal wells related to injecting highly concentrated brines (i.e., 350,000 mg/L total dissolved solids) generated by a produced water volume reduction plant.
2. Operators should consider forced circulation vacuum evaporative crystallizer technologies a sound contender for ZLD production of salt for industrial re-use. However, the cost of produced water disposal will need to rise considerably before solid salt production is commercially attractive as an alternative to water disposal. Consider researching additional markets or uses for the solid salt, as the British Columbian salt market could be rapidly over-supplied with solid salt produced from a small number of Montney sites where ZLD technology is applied.

## 2 PILOT DESCRIPTION

### 2.1 PILOT TECHNOLOGY

The evaporator used during this pilot project is based on air humidification-dehumidification technology (“HDH”). HDH offers two interlinked benefits: (1) the ability to evaporate water from a saline solution at temperatures below 85°C without vacuum conditions, and (2) the use of engineered plastics that are corrosion resistant in place of expensive metallurgies (i.e., CPVC pipework and glass reinforced vessels).

The plant is a single-effect, thermally-driven, low-temperature evaporator that can produce high quality freshwater for surface discharge. The plant was developed to concentrate saline waters close to saturation, not as a crystallizer for solid salt production, however this pilot would test the ability of the plant to generate solid salt.

### 2.2 PROJECT OBJECTIVE

The project objectives were to:

- Assess if the HDH technology could be extended to act as crystallizer, reliably producing solid salt.
- Confirm no releases of deleterious produced water by-products to the environment, either in the treated water produced or solid salt destined for industrial re-use.
- Understand the reliability and economics of the complete system tested.

### 2.3 PROCESS FLOW DIAGRAM (PFD)

A Process Flow Diagram is included in **Error! Reference source not found.** below.

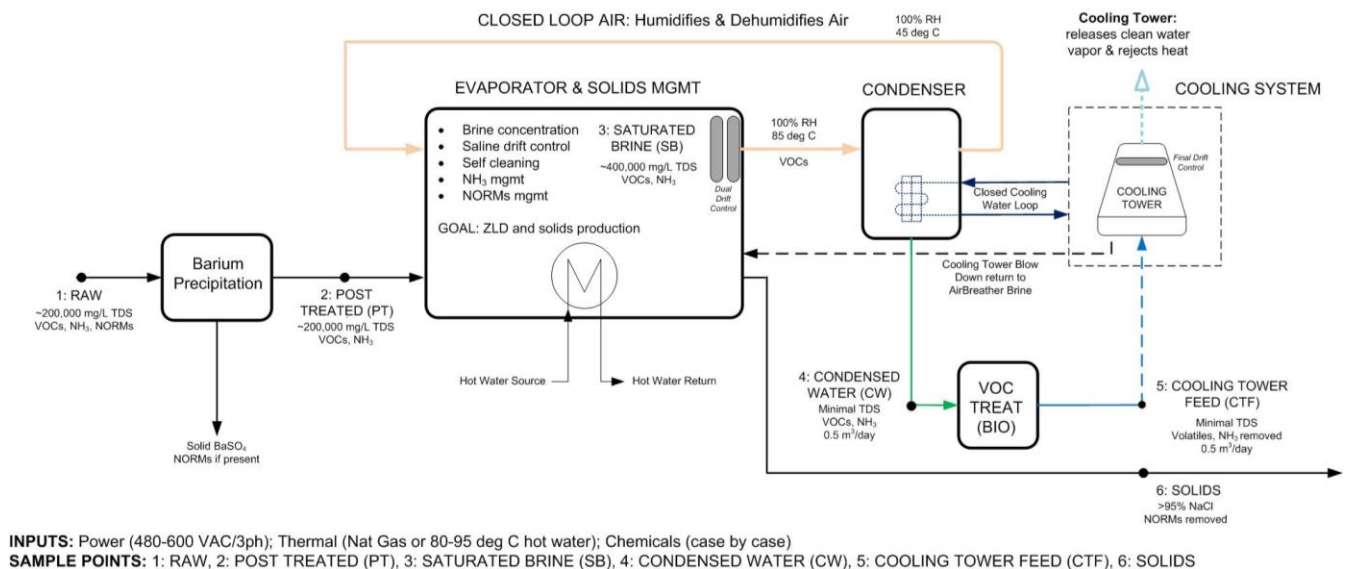


Figure 1: Pilot System High Level PFD

## **2.4 PILOT PLANT DESCRIPTION**

The pilot plant used was built and field tested in the Marcellus shale. This plant was successful at reducing produced water volumes by 50% without release of any harmful compounds present in the produced water. A full-scale permit was issued for use in Pennsylvania, and this pilot plant was updated to enable zero liquid discharge (“ZLD”) solid salt production.

### 3 PRODUCED WATER SAMPLES & PROCESSING

Three participating oil and gas operators each provided 2 m<sup>3</sup> of produced water samples. All samples were extracted from operating sites within a 50 km radius of Ft. St. John, BC. All sites practice water sharing within their area and therefore produced waters come in and out over time. The 6 m<sup>3</sup> total sample size was sufficient for the test program as the small-scale pilot could be operated at reduced capacity, and with ~18% of the sample mass as salt.

The primary treatment objectives were to:

1. Remove naturally occurring radioactive material (“NORMs”) to non-detect levels if present, with NORMs testing completed by the Saskatchewan Research Council (“SRC”).
2. Generate treated water that met the BC Aquatic Life Guidelines (“BC ALGs”) for discharge<sup>1</sup>.
3. Generate solid salt that met Transport Canada’s road salt standard, which references ASTM D632-12(2020)e1 Standard Specification for Sodium Chloride<sup>2</sup>. In summary, the specification is: >95% sodium-calcium chloride without ‘deleterious compounds’ (undefined by Transport Canada, assumed to be NORMs and heavy metals). Solid salt quality was measured by dissolving the solid salt sample in distilled water and completing independent third-party full water chemistry analysis. This is the same procedure followed when solids are submitted directly to a lab.

#### 3.1 PRODUCED WATER SAMPLE TECHNICAL BRIEFING

Two of the produced water samples were remarkably similar in composition: both in total dissolved solids (“TDS”) and individual ion make-up. Both waters were ‘high barium, low sulphate,’ which have a greater likelihood of containing NORMs due to their low sulphate content. This is because NORMs will co-precipitate with barium sulphate, and barium sulphate has extremely low solubility. If sulphate was present, it would almost immediately precipitate barium sulphate and NORMs. After effective NORMs removal, these produced waters were both identified as candidates for solid salt production that would meet Transport Canada’s >95% sodium-calcium chloride road salt specification.

The third produced water was different from the other two. The producer of this water communicated to the Project Team that they were shutting-in operations indefinitely in the area where the sample was taken for internal confidential reasons. They provided the water sample to complete their project commitments but did not expect the need for produced water treatment in that area for the foreseeable future. However, this water was processed through the pilot plant with the steps appropriate to its chemical makeup. Two steps were not applicable: pre-treatment and salt production. Pre-treatment was not applicable owing to its high sulphate content while barium was near equilibrium with sulphate. This

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<sup>1</sup>[https://www2.gov.bc.ca/assets/gov/environment/air-land-water/water/waterquality/water-quality-guidelines/approved-wqgs/wqg\\_summary\\_aquaticlife\\_wildlife\\_agri.pdf](https://www2.gov.bc.ca/assets/gov/environment/air-land-water/water/waterquality/water-quality-guidelines/approved-wqgs/wqg_summary_aquaticlife_wildlife_agri.pdf)

<sup>2</sup><https://www.astm.org/d0632-12r20e01.html>



meant that it likely did not contain NORMs, which results verified, and therefore NORMs pre-treatment was not required on this water. In addition, this produced water was quickly identified as a poor candidate for industrial solid salt production. This is because its high sulphate content (>5%) would prevent the ability to meet Transport Canada's >95% sodium-calcium chloride road salt specification. Therefore, coupled with reduced interest from the producer to treat this water, solid salt from this water was not produced. The other two samples were fully processed.

Solid salt composition cannot be shared due to confidentiality agreements, however the produced salt from the first two produced water samples mentioned above met the certification standards for industrial salt in British Columbia. Industrial salt is used in British Columbia for road de-icing and production of caustic soda, chlorine gas, and bleach. The same salt supply is used in both. The chemicals mentioned are used in BC's pulp and paper industry. The salt source is either residual salt from potash mines in Saskatchewan transported by rail, or sea salt from seawater evaporation ponds in Baja Mexico barged up the coast to BC.

The goal for solid salt production in this project was to meet Transport Canada's road salt standard (>95% sodium chloride by mass). Calcium in place of sodium is beneficial and accepted by road salt purchases, although it is less desirable in the chemical production industry. Legally, purchasers seek to avoid deleterious substances, such as NORMs.

### 3.2 NORMS REMOVAL

Naturally occurring radioactive material treatment in saline waters is industrially practiced in some mining and oil and gas operations. It involves dosing sodium sulphate to precipitate a barium sulphate sludge at a stoichiometric ratio of  $\text{SO}_4$ : Ba of 1.2, assuming negligible strontium. This approach leverages the well-known phenomena that radium and other NORMs co-precipitate with barium sulphate. The objective is to reduce barium in the post treated water to ~ 10 mg/L, which is used as a proxy for effective NORMs removal. The precipitated products are then filtered and disposed of at a qualified landfill. The landfill employed for disposal and the associated disposal costs will vary based on the radioactivity of the solids generated.

A water sample type-summary is included as **Error! Reference source not found.** below in Section 5. This table shows the efficacy of the NORMS removal process. Only one operator's water chemistry is shared for reasons of brevity and confidentiality.

## 4 PILOT PLANT OPERATION

### 4.1 PRE-TREATMENT

The NORMs removal steps were completed via a 1000 litre batch mixing system with sodium sulphate dosing as described above. The pilot plant includes a ceramic membrane filtration system, which removes precipitated particles and total suspended solids (“TSS”) from the produced water. The concentrated TSS and precipitants are captured in bag filters, with a filter press employed in full scale plants.

### 4.2 EVAPORATIVE CONCENTRATION

The pilot plant was capable of full capacity (200 litres/day) 24-hour operation with little intervention while acting as a produced water concentrator, however required more intervention than expected while producing solid salt.



Figure 2: Photos of the Pilot Plant



Figure 3: Solids Management Circuit

### 4.3 CRYSTALLIZATION

The pilot plant was operated continuously during day shift when crystalizing, with capacity reduced during night shift. It was not operated at full capacity during night shift because the automated wash cycles required observation until 'fully tuned.' 'Fully tuned' means that the cleaning cycles are effective at restoring performance without the need for operator observation or intervention, and the wash cycles represent less than 40% parasitic loss to capacity through downtime or wash water consumption. The pilot plant did not reach reliable fully tuned status in solid salt production and crystallization mode. Although parasitic losses (wash water consumption) were limited to 40% of total plant capacity (diminishes capacity by 40%), the evaporation module packing was at risk of detrimental scaling and plugging. The original evaporation module packing was replaced with polytetrafluoroethylene ("PTFE") packing, which reduced wash water consumption, yet salt still built-up on the leading edge of the evaporation module dehumidified air inlet and evaporation module walls. Although performance could be maintained, it was analogous to 'walking a tightrope.' Troubles encountered while under the watchful eye of trained pilot operators and system engineers taught that the technology may not be fit for reliable continuous solid salt production in remote locations.

With the evaporation modules of air HDH systems, the hypothesis is that sodium chloride salts 'crust' and build-up on surfaces when air is used as a carrier gas. As water evaporates from heat and mass transfer, sodium chloride crystals will precipitate. Although most crystals become a suspended solid in the saturated liquor, some adhere to surfaces where heat and mass transfer occur. Once they start to adhere, crystals grow over time and reach a point where a cleaning cycle is required. This cleaning cycle is initiated based on differential air pressure (air flow restriction) across the evaporation module. The PTFE packing reduces build-up on the packing itself, however the supporting structure still presents nucleation points. Although PTFE coatings are available for the supporting structure, they will wear off with abrasion over time.

In summary, employing air as the carrier gas, has its benefits as a brine concentrator by enabling use of low-grade heat without requiring a vacuum or specialized metallurgies (engineered plastics can be employed). However, in the case of solid salt production, use of a HDH cycle places the evaporation module surfaces at too great of risk of scaling and crusting with salt. The authors believe that the correct technology would be mechanical vapour recompressions ("MVR") - a forced circulation vacuum flash-based system with a high circulation rate cyclonic flash vessel with no packing inside, operated at a slight vacuum. This will require specialized metallurgies such as duplex stainless steel to withstand the chlorides. Using a greater vacuum will enable the use of a lower temperature waste heat. By way of example, 30 kPa absolute vacuums are common in such systems, which would be sufficient for use of 80°C heat sources.

### 4.4 SOLID SALT EXTRACTION

The solid salt decanter centrifuge operated as intended. It can reliably produce salt with no free moisture and passes in-house paint filter tests. If over-loaded, decanters will output salt with increased free water content. Based on the pilot results and experience from prior ZLD projects, designers should specify a

decanter that operates at <30% of its rated capacity. This will help ensure no free water in the solid salt discharged. Decanter centrifuge staging and redundancy optimization is worth consideration during detailed design of ZLD systems.

## 5 PILOT DATA - WATER

Detailed water chemistry data mapped to the sample nodes on the PFD in Figure 1 **Error! Reference source not found.** is presented in Table 1. Inorganic and VOC data is presented. The post treated condensed water at node 5 is the critical sample point. It represents either release to the environment as freshwater, or feed to the cooling tower circuit for evaporation to atmosphere. Node 5 data is compared to the BC Freshwater Aquatic Life Water Quality Guidelines. The theory is that clients who seek the return of the freshwater to the environment can do so, although these machines have a higher cost due to the need for air coolers in place of the cooling tower. If a cooling tower is employed, government regulators want to ensure there are no volatile releases to the environment, or detrimental salt drift. This would be equivalent to discharging treated water to the surface, and then withdrawing surface water to operate a cooling tower.

All node 5 water samples met the BC ALGs, with some minor exceedances that are manageable at full scale.

As expected, the condensed water at Node 4 prior to post treatment contains volatile ammonia and methanol (key VOC), originating from the produced water. Biological moving bed bioreactor (“MBBR”) post treatment effectively removed ammonia and VOCs to safe levels for discharge. However, post treatment elevated metals (Al, As, Cu, Zn) slightly. The suspected reasons are leaching from ‘dead’ biomass, and lab measurement error. The MBBR biomass has been utilized to treat a variety of waters prior to this project. Biomass can accumulate metals from the water being treated. When changing the water feed, some biomass dies as new biomass grows. It is possible that due to the small sample volume and short processing run time, the biomass did not fully adjust to the new water source, with a heavy initial leaching shock for the samples processed. At full scale, the slight exceedances are not expected. In addition, the slight exceedances are for non-volatile ions and therefore negligible. When a cooling tower system is used (lower cost), the inorganic ions will remain in the cooling tower water and not evaporate to atmosphere.

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**Table 1:** Water Chemistry from a confidential producer, water sample points are included in row 1, referenced to numbered nodes on the Process Flow Diagram of Figure 1.

Parameter	1-Raw (C)	1-Raw (D)	2-PT	3-SB	4-CW	5-CTF
Units:	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
pH	6.67	6.36	4.51	3.98	4.58	6.76
Total Dissolved Solids	256853.3	258844.4	318577.8	401333.3	91.7	317.3
Total Dissolved Solids (CALC)	0.0	0.0	225000.0	366933.3	78.5	266.2
Total Suspended Solids	262.4	72.7	165.3	149.3	<2.0	<2.0
Total Hardness (as CaCO3)	31826.7	39139.6	50744.9	206933.3	14.9	132.4
Total Organic Carbon	345.3	369.4	322.9	614.0	175.2	10.0
Alkalinity (as CaCO3)	46.67	72.80	<1.0	<1.0	3.64	33.15
Aluminum	<0.5	<0.5	0.14	<1.00	0.07	0.13
Ammonia (as N)	<10	858.7	607.6	3313.3	3.3	0.3
Antimony	<0.05	<0.05	<0.00400	<0.0400	<0.00020	0.00
Arsenic	<0.01	<0.01	<0.0100	<0.0400	<0.00050	0.01
Barium	2538.7	2773.3	2.1	<0.100	0.1	0.1
Beryllium	<0.005	<0.005	<0.00200	107.7	<0.00010	<0.00010
Bicarbonate (as CaCO3)	50.00	88.75	<1.0	<0.0200	3.41	33.15
Boron	31.80	37.65	47.99	148.27	0.18	0.18
Bromide	<500	<500	<500	<1000	<0.10	<0.10
Cadmium	0.00	<0.001	0.00	<0.00200	<0.000010	0.00
Calcium	11106.7	12800.0	13415.1	59061.3	4.8	52.3
Carbonate (as CaCO3)	<1	<1	<1.0	<1.0	<1.0	<1.0
Chloride	122266.7	118471.1	171804.4	253333.3	48.5	109.9
Chromium	<0.05	<0.05	<0.0100	0.41	<0.00050	0.00
Cobalt	0.01	0.03	<0.00200	0.09	0.00	0.00
Copper	<0.05	<0.05	<0.00800	<0.0800	0.00	0.01
Fluoride	<200	<200	<500	<1000	<0.10	0.28
Hydroxide (as CaCO3)	<1	<1	<1.0	<1.0	<1.0	<1.0
Iron	85.33	70.40	13.35	145.00	0.02	0.03
Lead	0.01	<0.005	<0.00400	<0.0400	<0.00020	0.00
Lithium	56.45	65.71	98.20	284.73	0.02	0.04
Magnesium	989.3	1075.2	1381.3	6432.0	0.6	2.6
Manganese	3.20	2.80	3.65	11.95	0.01	0.02
Mercury	<1	<1	<0.000010	<0.000010	<0.000040	0.00
Molybdenum	0.03	0.02	<0.00200	<0.0200	<0.00010	0.00
Nickel	<0.05	<0.05	0.01	1.73	0.00	0.00
Nitrate (as N)	<50	<50	<50.0	<100	<0.010	0.02
Nitrite (as N)	<50	<50	<50.0	<100	<0.010	0.01
Phosphate (as P)	24.27	16.53	<25.0	<50.0	<0.0050	12.13
Potassium	2737.8	3040.0	3275.4	14563.6	0.9	18.0
Selenium	0.54	0.49	<0.0100	<0.100	<0.00050	<0.00050
Silica, Reactive (as SiO2)	8.28	7.20	12.37	93.05	<0.40	18.02
Silver	<0.01	<0.01	<0.00100	<0.0100	<0.000050	<0.000050
Sodium	65333.3	69066.7	51900.0	56206.2	17.3	28.4
Strontium	2050.0	1932.0	1600.0	11252.6	0.6	0.0
Sulfate	<5000	<5000	268.5	90.7	<1.0	4.2
Thallium	0.098	0.089	0.094	0.430	0.000	0.000
Tin	<0.005	0.0	<0.00400	<0.0400	0.0	0.0
Titanium	0.1	0.2	<0.100	<1.00	<0.0050	<0.0050
Uranium	<0.001	<0.001	<0.000400	<0.00400	<0.000020	0.0
Vanadium	<0.1	<0.1	<0.0200	<0.200	0.0	0.0
Zinc	1.792	2.987	0.672	7.579	0.053	0.064

## **6 ZLD TECHNOLOGY FIT**

When pursuing Zero Liquid Discharge (ZLD), we recommend forced-circulation, vacuum-based, evaporative crystallizers over HDH technology. This recommended technology can be driven electrically as a mechanical vapour recompression (MVR), or thermally as a single or multiple effect plant. An MVR employs a forced-circulation design, which reduces heat exchanger scale risk by not evaporating solution on the heat transfer surface, and instead flashing the fluid to evaporate in the compressor feed vessel.

The heat exchangers are plate and frame construction with high velocity flow-scouring of plates, which further reduces heat exchange scaling risk, and allows for rapid opening and cleaning if needed.

### **6.1 DECANTER CENTRIFUGE**

A decanter centrifuge extracts crystals from the crystallizer output slurry while producing a saline brine discharge with reduced solids. The decanter centrifuge operates in continuous flow mode. This type of centrifuge is recommended because they accept process variability better than other types, operates more reliably than a pusher centrifuge on smaller particle size and remains operational with reduced slurry concentration.

The integration of the MVR and decanter centrifuge is important. Crystallizers are most reliable when operated between 1% and 10% solids, ideally with the centrifuge accepting 10% solids and returning 1% solids to the crystallizer. This reduces the risk of plugging interconnecting pipework and vessel outlets.

## 7 ECONOMICS

The cost for evaporation technology as a service is ~\$40/m<sup>3</sup> inlet volume for a 200 m<sup>3</sup>/day inlet capacity MVR system. The cost estimate includes:

- Capital equipment
- Installation in a weather-proof insulated and heated tent
- Operations and maintenance
- Chemicals

The service cost assumes:

- Reasonable site access, to be further defined.
- A 2-to-5-year contract.
- The Oil & Gas operator provides leased land on site for installation at \$1/year.
- The power sale agreement details and type of plant installed may result in adjustments to the cost above. For example, an electrically driven MVR consumes more power than a thermally driven unit.
- If thermally driven, the O&G operator provides waste heat in the form of ~85°C hot water at sufficient flow rates brought to and returned from the site.
- Salt produced is picked-up by a salt distribution contractor at no cost. A road salting contractor active in NE BC confirmed this is appropriate if road salt specifications are met since it offsets their external purchase costs.

Alternatively, if an operator sought to invest capital, the following could be assumed:

- Total cost of treatment, inclusive of capital and operating expenses, would equate to ~\$40/m<sup>3</sup> treated.
- Pay-out period and net present value will vary based on several factors, and would be considered relative to alternative disposal costs.



## 8 CONCLUSIONS & RECOMMENDATIONS

The overall project objective was to gain knowledge of the reliability and economics of the humidification-dehumidification process, while ensuring no harmful by-products were released to the environment.

The pilot project developed and tested a novel HDH zero-liquid-discharge system capable of processing highly saline produced waters typical of the Montney Formation of Northeast British Columbia, with commercial quality salt as the only by-product of the processing. The HDH technology has environmental benefits as it can be transported to water production sites, thereby reducing, or eliminating water trucking. The technology also utilizes waste heat from natural gas processing facilities, and has the option to produce clean liquid water, or evaporate the clean water to atmosphere. Further, the clean salt produced can be sold and re-used commercially.

Successful demonstration of this technology would provide Montney operators with a potentially economic and viable alternative to trucking and sub-surface disposal of produced water. To this end, several Montney operators provided field samples of highly saline Montney produced water to the HDH test site for processing and testing of the HDH technology.

The pilot project achieved the goals of upgrading a HDH plant and producing commercial quality salt, with zero liquid discharge, from the Montney operator water samples provided. The pilot study found that achieving ZLD with HDH technology required elevated operator attention to prevent salt scaling and crusting in the evaporation module, and that the HDH technology is better suited to generate reduced production water volumes, with highly concentrated brines (i.e., saturations of ~350,000 mg/L total dissolved solids) as a by-product. Further research is recommended on the impacts to water disposal wells with respect to disposal of highly concentrated brines. The pilot project also determined that sulphate-rich produced waters are a poor candidate for industrial salt production and re-use.

To achieve zero liquid discharge, this study recommends the use of forced-circulation, vacuum-based, evaporative crystallizers utilizing mechanical vapour recompression, over HDH technology, however the cost of produced water disposal will need to rise considerably before solid salt production is commercially attractive. Cost and economic input parameters of this recommended technology were provided in the Economics section of this report.

The pilot study demonstrated that clean, commercial-quality solid salt, free of deleterious contaminants, can be produced by the technology tested. British Columbia has an existing need for solid salt of this quality, for road-use and in the pulp and paper sector, however the adoption of zero liquid discharge technology at several Montney operator sites would likely quickly over-supply the salt market. Research into additional markets or uses for the solid salt would be beneficial and is recommended.