Comparison of the Behaviour of Spilled Conventional and Non-Conventional Oils through Laboratory and Meso-scale Testing: Summary Report

For:

Canadian Association of Petroleum Producers

Canadian Energy Pipeline Association
(TC Energy and TransMountain)

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Scientific Advisory Committee

The Scientific Advisory Committee (SAC) provided inputs into the development of the test procedures and initial protocols used in this project. Membership of the SAC included:

- Canada Energy Regulator
- Environment and Climate Change Canada
- Fisheries and Oceans Canada
- Natural Resources Canada
- Polaris Applied Sciences, Inc.

EXECUTIVE SUMMARY

There is a risk of spills associated with all oil product transportation systems, including pipelines. Spills are rare events with the consequences, to a large degree, determined by location, timing and environmental conditions. Knowledge about how different oils behave under different conditions is important in making the right decisions to select the most effective recovery strategies and equipment.

This study was commissioned with the goal of significantly enhancing the state of knowledge of oil properties and behaviour for spills of conventional and non-conventional oils in a range of environmental conditions: fresh and marine waters, with and without sediments in the water, and cold and warm temperatures. Data and findings from this study will improve response effectiveness by validating computer model predictions of oil fate and behaviour over time, and by enabling responders to make more informed decisions about choosing the most effective countermeasures.

This summary report reviews an extensive series of hundreds of tests conducted at different scales in a laboratory setting and detailed in the accompanying main data report (SL Ross, 2020). Results presented and discussed in brief here were chosen to represent the most likely natural environments and spill scenarios covered in the main report.

The 14 oils selected for study range from condensate to heavy oils representing a cross section of the conventional (light, medium and heavy) and non-conventional crude oil (e.g. oil sands-derived) shipped by Canadian transmission pipelines to markets in Canada and in the United States. Bunker C (Heavy Fuel Oil - HFO) and Alaska North Slope crude (ANS) were included for additional comparison, recognizing their common use and extensive knowledge base covering the characteristics of these products. This is the first time that such a broad range of Canadian oils have undergone consistent, multi-scale, rigorous analysis related to spill behaviour.

The work was divided into six main areas of research designed to study how the properties of selected oils varied over time after being released in different environments:

1. Small-scale tests using standardized protocols to determine oil physical properties relevant to oil spill response;
2. A small-scale study to evaluate different laboratory oil evaporation methods in order to confirm that physical properties measurements are largely independent of the test protocol used;
3. Small-scale tests to study oil-particle (sediment) interaction – for marine and freshwater spills;
4. Larger-scale tests performed in a recirculating flume with both fresh and marine waters to evaluate changes in oil properties under different conditions ;
5. Small-scale tests to study how the oils flow through porous media (soil / sand/ pebble); and,
6. Larger-scale tests to evaluate adhesion of oils to shorelines – focusing on the effects of wave action on stranded oil

No laboratory test can fully simulate the complexity of the natural environment. Small scale tests such as evaporating samples in a wind tunnel, provide valuable benchmarks of oil properties at a specific point of mass loss. Recirculating flume tests come closer to replicating real world conditions where oil on water is able to spread and weather in the presence of winds, currents, UV light, varying temperatures, and mixing energy (waves/currents).

The main conclusions drawn from the six different research areas are summarized here:

- A common misconception about oil sands-derived crudes is that they tend to separate into their original bitumen and diluent quickly after they spill. This is not possible because the hydrocarbons in both the diluent and bitumen are infinitely soluble in each other and do not form separate phases after mixing together.
- Oil weathering processes including spreading, evaporation, dispersion, emulsification, dissolution, photooxidation, sedimentation, and biodegradation will all impact a slick to varying degrees. Of these processes, evaporation has the highest impact at the beginning of a spill of most oils, including oil sands-derived crudes, and can result in a substantial reduction in the mass of oil remaining to be recovered from the environment. With condensates, most of the oil naturally evaporates and disperses from the water surface very soon after a spill. Light to medium oils can lose up to 40 percent of their volume due to evaporation within a few days. Heavy conventional crudes and oil sands-derived crudes experience evaporative losses in the order of 20 percent, still a significant factor in reducing the quantity of spilled oil available for recovery in the environment.
- Oil sands-derived products demonstrated changes to physical properties (viscosity and density) more rapidly due to weathering than conventional heavy crudes in the first few hours, especially at warmer temperatures. Over longer periods (days, weeks), these products ultimately weathered to densities and viscosities comparable to conventional heavy crudes.
- Many oils form water-in-oil emulsions that greatly increase the spill volume and viscosity. Data from this study showed that heavy conventional oils and oil sands-derived products are very likely to form emulsions while in a fresh state, but these oils quickly become too viscous to emulsify any further. The two lightest products tested, condensate and synthetic, were the only oils unlikely to emulsify in either a fresh or weathered state. Light to medium crudes are unlikely to begin to emulsify until they reach a moderately weathered state after a few days. Even then, they may only form entrained water or unstable emulsions.
- The oil-particle interaction study showed that at moderate levels of turbulence and moderate-to-high sediment particle concentrations in the water, a small percentage of the spill (on average) was removed from the surface of fresh water and transferred into the water column. There was no clear correlation between oil type and density, and oil mineral aggregate (OMA) formation.
- The addition of sediments during the flume tank runs did not cause bulk submergence or sinking in fresh water for the conventional heavy crude or for the oil sands-derived crude. The only oil substantially affected by the addition of sediments to the flume tank was HFO during the low water temperature run (0°C), which saw noticeable submergence by the 1-hour mark.
- Porous media tests showed that the most viscous oils (e.g. HFO) had the lowest penetration and the least viscous oils (e.g., condensate, SYN) penetrated the furthest.
- The artificial soil, with its clay and organic material, retained selected chemical compounds and showed reduced BTEX concentrations in the run-off water when compared with the sand or gravel test results.
- Shoreline adhesion tests showed that light and medium oils are more easily self-cleaned from shoreline sediments through wave action meaning they are more susceptible to remobilization. In contrast, higher viscosity oils were more persistent and likely to remain in place.

The likelihood of oil sinking after a spill is a concern in any response. Response plans are prepared using emergency response strategies and equipment that consider the potential for some oil to submerge, be over washed by wave action, entrained in the water, or possibly sink.

Results from the small-scale and recirculating flume tests (run for a minimum of five days) showed:

- All of the oils floated in marine (saltwater) experiments regardless of the degree of weathering.
- Light and Medium Oils floated in freshwater regardless of the degree of weathering.
- Conventional and non-conventional heavy oils reached densities close to or equal to neutral buoyancy in freshwater (e.g. 0.98 to 1.02) within a few hours to days in the flume tests. This makes them susceptible to temporary submergence/over washing and entrainment but not inevitably to sinking. The increased viscosity associated with weathering contributed to the formation of weathered oil mats with entrapped bubbles that were observed to remain floating for extended periods of time in the recirculating flume.
- The HFO run at low water temperature (0°C) resulted in some blobs of oil submerging and sticking to the walls of the flume tank by 6 hours into the run. By the 24 hour mark, a large portion of the oil slick was submerged. This oil remained floating in fresh water at the warm water temperature (20°C) and in tests with seawater at both tested temperatures.
- The partially upgraded oil sands product (AHS) also showed some submergence with a few blobs of oil being stuck to the walls and settling to the bottom of the tank at the 24 hours point of the flume testing in freshwater at 20°C. It remained floating in tests with fresh water at the lower temperature and tests with seawater at both tested temperatures.
- The uptake of sediments depends on a number of factors, including the mixing energy, particle types and sizes, and the pour point and viscosity of oils that might make them more conducive to mineral aggregate (OMA) formation. The potential for entrainment in the water column through an uptake of sediments is not unique to oil sands-derived crudes and can occur for many crude and fuel oils. Notably, the addition of suspended sediment in the flume tests in this study did not cause gross submergence or sinking for the conventional heavy crude, or oil sands-derived crudes.

Data generated in this project covers the full spectrum of expected behaviours for a wide range of oils. The results demonstrate that oil sands-derived crudes do not exhibit unusual characteristics that would substantially affect the applicability of current oil spill response strategies to a wide range of spill scenarios and oil types. Any heavy oil, whether conventional or oil sands-derived, can become highly viscous and increase in density as it weathers, emphasizing the importance of rapid response using proven recovery systems designed to handle very viscous products.

Industry remains committed to being prepared to respond to the full range of possible spill events originating from its facilities or transportation systems. Mitigating the consequences of oil spills is accomplished through proven and practiced emergency response plans (including remediation and restoration) mandated by regulatory agencies and required financially by law under the Pipeline Safety Act. This study is part of maintaining and strengthening that commitment to environmental protection through ongoing research.

The well-known statement that "speed is the key for oil spill response" holds for all oil spills including spills of oil sands-derived products. Industry and government understand this and work together to continuously improve response capabilities, as evidenced by programs such as the federal Canadian Multi-Partner Research Initiative (2019 ongoing) under the Oceans Protection Plan.

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1 INTRODUCTION AND BACKGROUND

Spills of crude oil during transport by pipeline across Canada are rare events. Every effort is made through engineering design, maintenance and monitoring to prevent spills from occurring. When they do happen, spills have the potential to impact lakes, rivers, wetlands, and marine waters. Environmental impacts are largely determined by the location, timing and environmental conditions. The primary focus in responding to any spill is on public and worker health and safety, environmental protection, cleanup, and long-term remediation.

The initial physical properties of an oil, and subsequent changes with exposure to the environment (known as weathering), are critically important for spill responders to understand:

1) How the oil will behave if spilled on water and terrestrial environments, for example: the likelihood and significance of submergence (temporary or ongoing) or sinking, natural dispersion, or entrainment in water, penetration into soils, and adherence to shorelines.
2) Windows-of-opportunity available to deploy specific spill countermeasures (e.g., skimming, burning, dispersants).

Oil properties data corresponding to different degrees of oil weathering is required to calibrate, validate and improve oil-spill models. Data showing how oil properties vary over time are often not gathered consistently during spill events due to the pressure of the response operation itself. The difficulty in collating relevant data from actual releases is compounded by the fact that no two spills are alike in terms of environmental factors that play a large part in determining oil behaviour and fate.

The Royal Society of Canada (RSC) expert panel report was the genesis for the current study by identifying specific research needed to address the lack of consistent real world data defining the chemical composition, physical properties and behaviour of a wide range of spilled oils including oil sands-derived crudes (Lee et al, 2015).

The RSC recommended areas of research included:

- Evaporation and how weathering processes will affect crude oil properties and spill behaviour.
- Emulsion formation, particularly of weathered diluted bitumen on fresh water.
- Effectiveness of chemical dispersants on spills of diluted bitumen (ongoing through a companion study in 2019-2021). (SL Ross, 2019-2021)
- Submerging behaviour, including interactions with suspended particulates.

The overall objective of this study was to significantly enhance the state of knowledge of oil behaviour which provides insight into response options for spills of conventional and non-conventional crude oils transported by pipeline, primarily in Canada. A series of tests were designed to focus on:

- Oil properties and how those properties change with evaporation and exposure to a range of environmental conditions.
- Spill behaviour such as emulsion formation, submergence, and interactions with suspended particulates (sediment) in the water and on shorelines.
- Differences in behaviour between non-conventional and conventional oils, and the significance for spill response.

The tests covered a broad range of simulated environmental conditions at small and meso-scale to create a database for different oils that can be used to improve the performance and accuracy of oil behaviour model predictions in the future.

2 MATERIALS AND WORK SCOPE

A Scientific Advisory Committee (SAC) was formed for this project and asked for scientific input into the design of the experiments and the protocols used during testing and to review the results prior to release of the main report. Members of the SAC were drawn from regulatory agencies and Departments of the Government of Canada (see listing in Executive Summary).

2.1 PROJECT DESCRIPTION

The project was completed as a series of many experiments at different scales.

Bench-Scale Studies	Standardized bench-scale testing of selected conventional crude oils, shale oils, and (non-conventional) diluted bitumen products of interest. Testing measured oil composition and physical properties and their changes with weathering, and the effects of interactions with suspended particulates.
Meso-Scale Studies	Meso-scale testing to measure the effects of weathering on water with the selected oils at a larger scale. Testing assessed the effects of temperature, waves, current, air flow, salinity, UV rays and suspended particulates in water, adhesion on beach sediments, and oil penetration in simulated soils.

The six laboratory investigations included the following:

1. Standardized Analysis of the physical properties of fresh and artificially weathered oils (through evaporation) to provide data needed to model oil behaviour under varying conditions consistent with Canadian environments. This analysis involved wind-tunnel evaporation weathering of each oil and measurements of their fresh and weathered physical properties.
2. Comparison of three commonly used laboratory evaporation methods utilizing controlled heat and/or wind (air movement) to accelerate evaporative losses. This was done to verify that results were independent of the test protocol used.
3. A study of oil-particle interactions in a small-scale apparatus to determine the propensity of each oil to bind with sediment and possibly sink in a standardized test.
4. Long-term Flume Weathering Tests using on-water weathering at a meso-scale to determine the change in key physical properties of the oil as it weathered over a period of days. This test series used a recirculating flume to create conditions that better simulate a dynamic natural environment, including exposure to UV light, wind shear, surface water agitation, sub-surface water movement, suspended sediments and two temperature regimes.
5. Porous Media Tests to determine the penetration characteristics of each of the oils when spilled onto three soil types: small pebbles, sand, and loamy soil.

6. Shoreline Adhesion Tests to determine the propensity of the oil to adhere to two different beach types after being subjected to an array of waves configured to impact a sloped shoreline test section.

The overall goal of this project is to better understand the characteristics of different oils in a variety of conditions, including fresh and marine water with and without sediments, and cold and warm temperatures. Information from this project will provide responders with information to develop effective response plans and make informed decisions, and modellers with data needed to better predict oil behaviour over time.

Results are summarized and discussed in Section 3. Given the space constraints of producing a concise review of hundreds of test runs, this summary focuses on the most relevant and likely conditions to present a snapshot of the full study with examples to illustrate key findings. Complete documentation and data tables from of all tests are provided in the main report (SL Ross, 2020).

2.2 TEST OILS

A total of 14 oils were included in this study (Table 2-1). These oils range from condensate to heavy oils representing a cross section of the conventional (light, medium and heavy) and non-conventional crude oil (e.g. oil sands-derived) shipped by Canadian transmission pipelines to markets in Canada and in the U.S.

The study also included U.S. Bakken crude (NDB), a very light oil, Bunker C (Heavy Fuel Oil – HFO) which has traditionally been widely used in marine shipping and Alaska North Slope (ANS) crude oil, as additional reference points of widely studied oils. HFO also represents one extreme end of the property's spectrum in terms of an oil with high initial density and viscosity that many responders are already trained and equipped to deal with.

Bitumen is produced from natural oil sands deposits by a number of processes, including direct mining and in-place extraction. The produced raw bitumen is a semi-liquid material at room temperature and is too viscous to transport through a pipeline as is. In order to move it to market by pipeline, bitumen is diluted with either condensate or synthetic crude oil to form a variety of products such as "dilbit", "synbit" and "dilsynbit" with viscosity, density and other properties engineered for pipeline transportation and use by the customer refineries. The most commonly used diluent to decrease the viscosity of natural bitumen is called condensate. Typically, dilbits consist of blends of 20 percent to 30 percent condensate and 70 percent to 80 percent bitumen. As an alternative to condensate, mixtures of synthetic crude oil and bitumen are also blended at approximately 1:1 ratio and such blends are known as synbit. AHS oil is a partially upgraded oil sands product. SYN is a synthetic sweet blend crude produced by upgrading, to transform bitumen into light oil that can be easily transported without the addition of diluents. (Environment Canada, 2013).

Table 2–1: Oils Selected for Testing

	Name	Type
1	Condensate (CRW)	Blended Condensate/Crude, Extremely Light
2	Light Sour Blend (LSB)	Crude, Very Light
3	U.S. Bakken (NDB)	Crude, Very Light
4	Mixed Sweet Blend (MSW)	Crude, Light-Medium
5	Alaska North Slope (ANS)	Crude, Light-Medium
6	Medium Sour Blend (MSB)	Crude, Medium
7	Conventional Heavy (CHV)	Crude, Heavy
8	Bunker C – Heavy Fuel Oil (HFO)	Refined, Heavy
9	Western Canadian Select (WCS)*	Dilbit
10	Access Western Blend (AWB)*	Dilbit
11	Cold Lake Blend (CLB)*	Dilbit
12	Albian Heavy Synthetic (AHS)*	Partially upgraded oil sands product
13	Synbit Blend (SYB)*	Synbit
14	Synthetic Sweet Blend (SYN)*	Synthetic

* oil sands-derived crudes

Oils commonly transported around the world are routinely classified into four general groupings according to their specific gravity (SG) at 15°C in a fresh state. The internationally recognized oil classification table displayed in the International Tanker Owners Pollution Federation Ltd's annual handbook (2019) and other publications indicates which oils fall into the different groups and implications for weathering and natural removal from the marine environment:

Group 1: SG <0.8

Condensate (#1)

- Non persistent oils that dissipate through evaporation and dispersion in a few hours
- Do not normally form emulsions

Groups 2: SG 0.8-0.85

Light to Medium crudes (#2, 3, 4, 5, 6), Synthetic (#14)

- Can lose as much as 40 percent (higher for some light oils) to evaporation and other weathering processes within a few days
- Float in fresh water and marine environments
- Tend to form emulsions when weathered

Group 3: SG 0.85-0.95

Conventional Heavy Crude (#7), Dilbits (#9, 10, 11), Partially upgraded oil sands product (#12), Synbit (#13)

- Can lose up to 25 percent by volume through evaporation and other weathering processes within a few days
- Generally float in fresh water but can reach neutral (or very close to neutral) buoyancy over time making them susceptible to possible over washing or submergence if response is delayed.
- Likely to form emulsions when fresh and partly weathered but eventually become too viscous for emulsification to continue

Group 4: SG >0.95	HFO heavy fuel oil (#8) • Persistent due to their lack of volatile compounds and initial high viscosity which precludes evaporation and natural dispersion • May be susceptible to sinking even in warm freshwater but still remain afloat for long periods in marine environments

This commonly used sorting shows that 12 of the 14 oils fall into Groups 2 or 3 and are categorized as generally floating in fresh water. These two groups include diluted bitumen products, light to medium crudes, and conventional heavy crude.

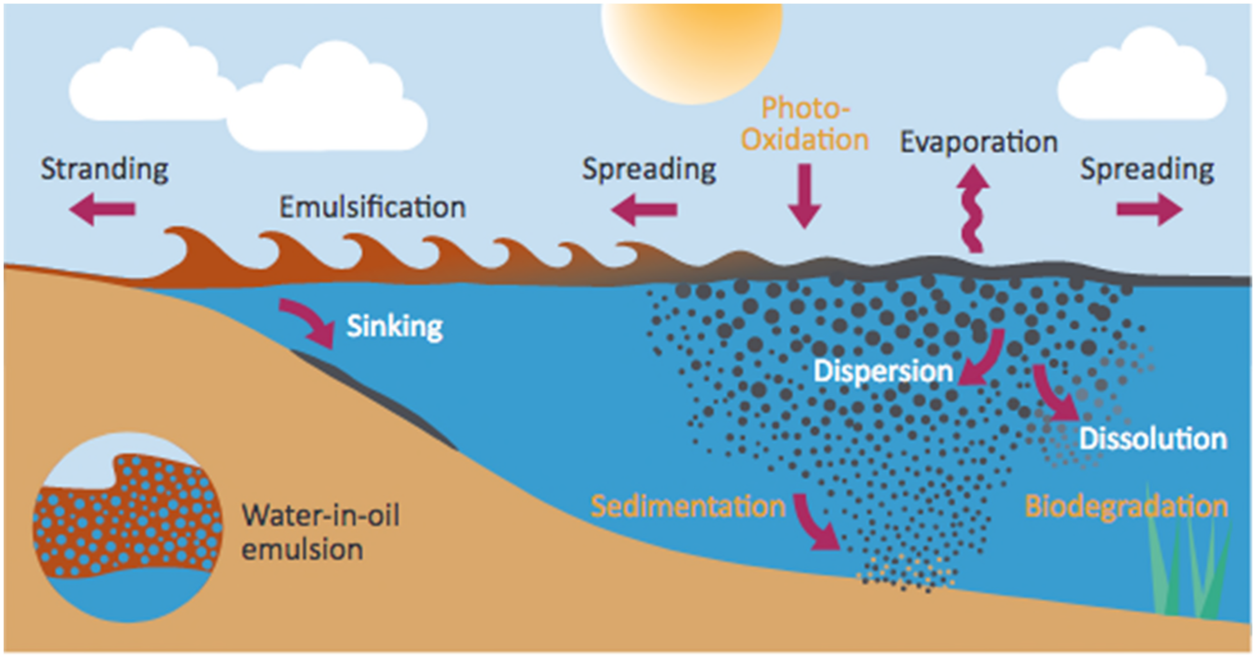
2.3 Introduction to Oil Weathering

Much of the work carried out in this project involved analyzing and interpreting the chemical and physical changes that an oil undergoes when it is spilled into a marine or terrestrial environment. The different processes that lead to these changes are collectively known as weathering and include evaporation, emulsification, dissolution, dispersion, biodegradation, oxidation and sedimentation (Figure 2-1). Key factors impacting the rate and degree of weathering include air and water temperatures, the presence of waves, currents and wind, exposure to sunlight, and the presence of natural sediments suspended in the water through turbulence.

Understanding the expected post-spill properties of weathered oils is an important component of pre-spill planning and preparedness. Physical and chemical properties of an oil will not only affect its fate and behaviour but also impact the selection of appropriate countermeasures.

Evaporation is the most rapid weathering process, resulting in the loss of the lighter, smaller-molecule and more volatile compounds in the oil. These compounds are associated with lower viscosity, lower density, and greater solubility in water. Their loss significantly affects the bulk characteristics of any remaining oil on the water or land, increasing the oil's density and viscosity.

Different oils experience very different evaporation rates depending on their chemical makeup. As an example, measurements of evaporation rates for two dilbits and an IFO 180 (intermediate fuel oil) taken in another study showed that more than 20 percent of the dilbits evaporated in 200 hours whereas only 5 percent of the IFO 180 evaporated after 200 hours. These differences are expected because the IFO 180 is a refinery product that has had many of the lighter, more volatile components already removed by distillation (Environment Canada, 2013).



Source: International Tanker Owners Pollution Federation 2019

Figure 2-1: Weathering Processes Acting on Oil at Sea

Oil on the water surface tends to incorporate water droplets and form oil-in-water emulsions, a process accelerated by mixing energy from waves. From the standpoint of spill countermeasures, emulsification negatively affects countermeasures operations by greatly increasing the volume of the oil present on the water surface (up to 5 times) and viscosity (10 to 100 times the viscosity of the parent oil).

In the natural environment, oils can emulsify at the same time as they are evaporating. Oils that have relatively high concentrations of high molecular weight asphaltenes, resins, and waxes are the most likely to form stable water-in-oil emulsions. Light to medium crudes become more likely to form emulsions as they weather and concentrations of asphaltenes, resins and waxes present increase. In contrast, heavy oils and bitumen products typically start with relatively higher concentrations of asphaltenes and/or resins and are thus likely to form emulsions when fresh, becoming much less so as they weather and become increasingly viscous. Heavy oils can quickly become too viscous to take up more water and emulsification stops. Colder temperatures generally increase viscosity, which can shift the emulsification tendency.

Changing physical properties over time defines the *Windows of Opportunity* for various spill response techniques. Key physical parameters, such as density, viscosity, pour point and emulsification, play a major role in how an oil spill will behave. As an example, once an oil reaches a density range where over washing or temporary submergence is possible or likely, specialized containment techniques and equipment become necessary. Certain types of skimmers perform best within a specific viscosity range; in-situ burning is generally difficult to initiate and sustain once stable emulsions are formed; and the use of dispersants may become less effective once the parent oil or emulsion viscosity exceeds a certain threshold for a particular oil type. Knowing the likelihood and timing of when an oil will transition to higher viscosities and/or densities can help responders select equipment and employ strategies that have the greatest chance of success.

3 METHODOLOGY, RESULTS AND DISCUSSION

The following sections represent a snapshot of methodology and results from many hundreds of test runs completed in the six different research areas outlined in Section 2. Within the space limitations of this summary report, it is not possible to cover the details of every test. The main data report contains complete documentation of all of the experimental work (SL Ross, 2020).

3.1 STANDARDIZED OIL ANALYSIS

Researchers employ a standardized set of lab tests to generate spill-related oil property information. The point of simulating oil weathering at a small-scale in the lab is to produce samples that have specified losses in oil mass through evaporation. These samples are then tested for a range of important physical properties that correspond to those mass loss points. Data derived from these tests are used as inputs into oil behaviour models (see below).

This study weathered (via evaporation) the 14 test oils in the laboratory wind tunnel for specific periods of time (Fresh; 2 days or Weathered State 1 (WS1); 2 weeks or WS2; and, 6 weeks or WS3). This was done to create multiple samples at different weathered states. These samples could then be analysed to determine physical properties useful as inputs in oil fate and behaviour computer models. Evaporation testing is performed with a target wind speed of 1.3 m/s at 22°C, and also uses toluene evaporation in parallel to help determine weathering constants for modeling purposes.

It is important to recognize that regardless of the protocol or technique used, lab weathering times using evaporation as a mechanism tend to be much longer than the expected time needed to weather the oil to an equivalent extent in the natural environment. In an actual spill situation, a combination of dynamically changing factors such as spreading, waves, winds and temperature will greatly affect and can accelerate the rate of weathering. For example, a degree of weathering via evaporation in trays of oil that takes several days in the lab may occur in a matter of hours in a real spill situation where processes like evaporation, dispersion, dissolution, emulsification, etc. are occurring simultaneously, and the oil can spread naturally without being artificially confined in a tray or a tank (creating a larger surface area – increasing the evaporation).

In an actual spill situation, responders will use spill behaviour models to predict the timing of these physical property changes (and other factors) using observed and forecast conditions at the spill site (temperature, winds, waves, etc.). Results from the standardized oil analysis are used as inputs to the oil behaviour models to improve their ability to predict weathering processes for a wide range of oil types. Flume data collected under more realistic conditions can be used to compare with model results (Section 3-4).

The test oils identified in *Table 2-1* were sampled in 2017, shipped to Ottawa, evaporated in trays in a wind tunnel to obtain specimens of multiple weathered states, and analyzed for:

Evaporation –This is an important factor in determining how much oil remains on the surface to be recovered/removed following a spill. This process along with natural dispersion into the water column can substantially reduce the volume of oil on the surface within a short time span of hours to days, from 25 to 80 percent depending on the oil type.

Density - the mass per unit volume of the oil (or emulsion) determines how buoyant the oil is in the water. Increasing with weathering and decreasing with rising temperature, density impacts:

- Sinking or temporary submergence – if the density of the oil approaches or exceeds 1 gram per millilitre (g/mL) the oil becomes subject to temporary submergence and possible sinking in fresh water (generally SG=1)
- Natural dispersion – more dense oils stay dispersed more easily in the water column
- Emulsification stability – dense oils initially form more stable emulsions (typically due to their chemical composition)

Viscosity - measure of the resistance of oil to flow, due to internal friction. The viscosity of spilled oil increases as weathering progresses and decreases with increasing temperature. Viscosity is one of the more important properties affecting spill behaviour and affects:

- Spreading – higher viscosity oils spread more slowly
- Natural and chemical dispersion – highly viscous oils are difficult to disperse
- Emulsification tendency and stability – viscous oils typically form more stable emulsions
- Recovery and transfer operations – more viscous oils are generally harder to skim and more difficult to pump

Interfacial Tension – measures surface forces between the interfaces of the water and oil, and the oil and air. Interfacial tension affects:

- Spreading – interfacial tensions determine how fast an oil will spread and whether the oil will form a sheen
- Natural and chemical dispersion – oils with high interfacial tensions are more difficult to disperse naturally (chemical dispersants work by temporarily reducing the oil/water interfacial tension)
- Emulsification rates and stability
- Mechanical recovery – oleophilic skimmers (e.g., rope-mop, belt, disk, drum skimmers) work best on oils with moderate to high interfacial tensions

Pour Point - The pour point is the lowest temperature at which crude oil will still flow. The pour point of an oil increases with weathering. Pour point affects:

- Spreading – oils at temperatures below their pour points will resist spreading on water
- Viscosity – an oil's viscosity at low shear rates increases dramatically at temperatures below its pour point
- Natural and chemical dispersion – an oil at a temperature below its pour point may be difficult to disperse
- Recovery, transfer and storage – crude oil below its pour point may not flow towards skimmers or down inclined surfaces in skimmers, and at temperatures significantly below its pour point may present storage/transfer challenges

Flash Point - the lowest temperature at which the oil produces sufficient vapours to ignite when exposed to an open flame or other ignition source. Flash point increases with increasing evaporation and is an important safety-related spill property, especially in the early stages of a spill when the oil is fresh

Emulsification – a process whereby oil on the water surface incorporates water droplets and forms oil-in-water emulsions. The tendency of crude oil to form stable water-in-oil emulsions is an important consideration for spill response in that it greatly increases the volume that needs to be recovered as well as the viscosity, while adversely affecting the recovery ability of oleophilic skimmer.

Composition – chemical analysis was performed on the oils to determine detailed hydrocarbon analysis, BTEX, Saturates, Aromatics, Resins, and Asphaltenes, metals, along with a simulated distillation.

Table 3-1 provides an overview of four key physical properties measured for each of the test oils in the small-scale tests and considered most important to responders when they are deciding on the most appropriate strategies to deal with a particular oil at a given stage in the weathering process.

- Evaporation
- Density
- Dynamic Viscosity
- Pour Point

In the overview tables, properties data corresponding to two-day, two week and six-week weathering in the laboratory wind tunnel are simply referred to as Weathered State 1 (WS1), Weathered State 2 (WS2) and Weathered State 3 (WS3) respectively. These terms reflect the fact that weathering times in the small-scale wind tunnel tests are *not* representative of exposure times for an actual spill on water in the natural environment (see earlier discussion). For example, weathering that takes days to several weeks in a wind tunnel could occur over a matter of hours to a few days exposure in a natural environment.

The tendency for oils to form emulsions and their stability at different stages of weathering is summarized separately in Table 3-2 (see following).

Additional properties such as interfacial tension, flash point, and distillation data are covered in detail in the main project data report (SL Ross, 2020)

Table 3–1: Comparison of Oil Physical Properties

Property	Weathered State	1 Condensate (CRW)	2 Light Sour Blend (LSB)	3 U.S. Bakken (NDB)	4 Mixed Sweet Blend (MSW)	5 Alaska North Slope (ANS)	6 Medium Sour Blend (MSB)	7 Conventional Heavy (CHV)	8 Bunker C – Heavy Fuel Oil (HFO)	9 Western Canadian Select (WCS)	10 Access Western Blend (AWB)	11 Cold Lake Blend (CLB)	12 Albian Heavy Synthetic (AHS)	13 Synbit Blend (SYB)	14 Synthetic Sweet Blend (SYN)
Evaporation in wind tunnel (Volume %)	Fresh	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	WS 1	71	38	41	35	30	34	13	0.4	13	14	14	16	10	20
	WS 2	77	45	51	44	38	41	21	1.7	21	23	22	21	17	29
	WS 3	80	49	56	49	42	44	25	4.2	25	27	26	24	20	34
Density (g/cm³) @ 15°C	Fresh	0.75	0.84	0.81	0.82	0.86	0.85	0.92	0.99	0.92	0.92	0.92	0.94	0.93	0.86
	WS 1	0.84	0.91	0.87	0.88	0.92	0.91	0.96	0.99	0.96	0.96	0.96	0.98	0.95	0.89
	WS 2	0.85	0.92	0.89	0.89	0.93	0.93	0.98	0.99	0.98	0.98	0.98	1.00	0.97	0.90
	WS 3	0.86	0.93	0.89	0.90	0.94	0.93	0.99	1.00	0.99	1.00	1.00	1.01	0.97	0.90
Dynamic Viscosity (cP) @ 15°C (SR = 100 s⁻¹)	Fresh	1.1*	6*	3*	5*	11*	7*	200	10,300	400	450	260	230	190	7*
	WS 1	16*	82	24*	48	241	89	2,200	10,900	2,200	6,850	3,580	6,400	1,520	22*
	WS 2	126	300	52	241	462	274	15,000	17,400	18,500	48,900	27,500	31,000	3,700	36
	WS 3	183	529	86	440	913	475	49,300	36,300	61,960	58,800	72,500	91,000	8,300	38
Pour Point (°C)	Fresh	-57	-51	-54	-24	-24	-47	-42	3	-42	-36	-39	-33	-42	-51
	WS 1	3	3	-33	12	6	-3	-15	6	-12	-12	-15	-6	-18	-27
	WS 2	12	12	-18	18	6	6	-3	12	18	3	3	0	-12	-21
	WS 3	15	15	-18	15	6	9	0	12	18	12	6	12	0	-18

Wind tunnel conditions: wind 1.3 m/s, 22°C

WS = Weathered State

SR = Shear Rate Target: 100 s^{-1}, *-higher shear rate than 100 s^{-1}, details in full report.

During the first few hours following a spill, lighter compounds in any oil will weather quickly (evaporate, dissolve, disperse, etc.) leaving lower concentrations in the remaining slick. Dilbits contain a relatively larger proportion of heavy compounds when compared to conventional heavy crudes. As lighter compounds are driven off, the compositional shift in dilbits causes initial rapid changes to physical properties such as viscosity and density of the slick versus conventional heavy crudes. As time progresses, weathering primarily due to evaporation diminishes and eventually (typically by 6-24 hours in our tests) dilbit weathering continues at rates similar to other heavy oils and the end point property (density) of these crudes can be quite similar. This behaviour was confirmed in the meso-scale recirculating flume tests at different temperatures (see Tables 3-4 and 3-5).

One common misconception about dilbits is that they tend to separate into their original bitumen and diluent quickly after they spill. This is not accurate because the hydrocarbons in both the diluent and bitumen are infinitely soluble in each other and do not form separate phases after mixing together. All crude oils, petroleum products, and oil sands-derived crudes are mixtures of hydrocarbons that will not separate as discrete liquids when spilled.

Figure 3-1 shows the trend in volume loss through evaporation for all 14 oils arranged generally from light to heavy, left to right (exception is SYN which is closer to a medium crude in terms of starting density). The oil sands-derived products are grouped to the right of Heavy Fuel Oil (HFO).

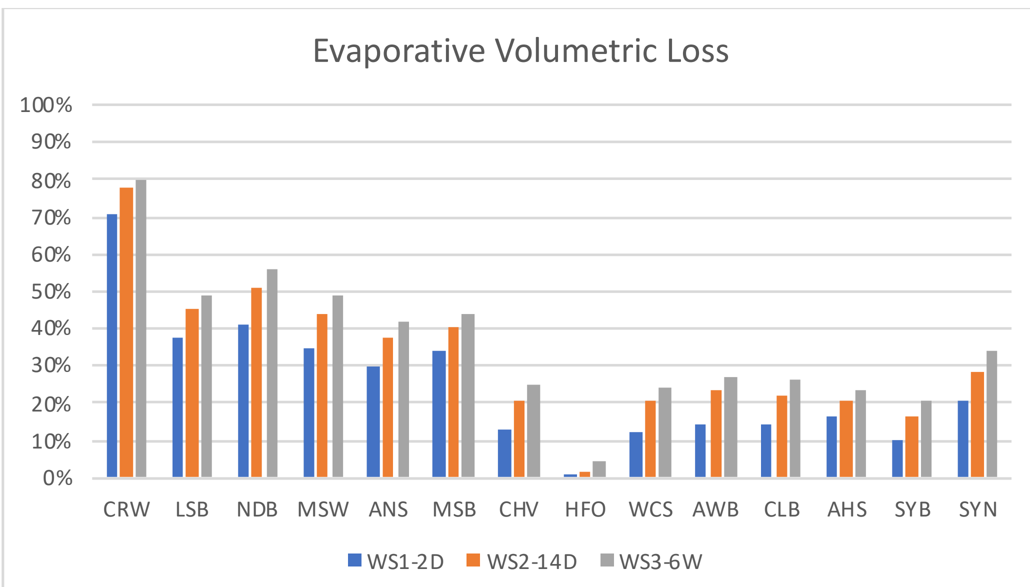


Figure 3-1: Percent Volume Loss from the Standardized Oil Analysis

Note: *WS1, WS2 and WS3 refer to the same weathered states used in Table 3-1 and discussed above.*

Figure 3-2 shows the evaporation rates for a cross section of oils sampled in this study (from light to heavy) predicted from an oil behaviour model that uses the small-scale test data as inputs. With condensates (CRW), most of the oil (80 percent or more) will naturally disappear due to evaporation from the water surface very soon after the spill, leaving little or no oil to be recovered. Light to medium oils including ANS can lose up to 50 percent of their volume within a few days in an actual spill. In contrast, heavy conventional crudes and oil sands-derived crudes experience lower percentages of ultimate evaporative loss in the order of 25 to 30 percent - still significant in terms of the overall volume or mass of oil remaining in the environment. At the extreme end of the weathering spectrum, HFO is predicted to evaporate less than 5 percent by volume, even after 5 days or more. Other processes such as natural dispersion will also affect the volume of remaining oil during an actual spill on water.

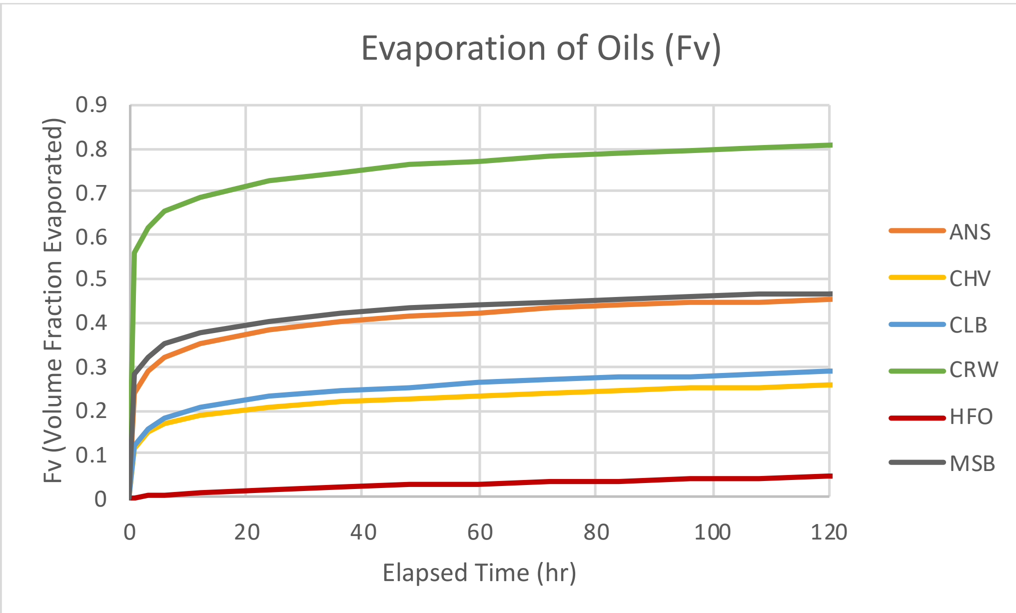


Figure 3-2: Predicted Evaporation Rates for a Range of Selected Oil Types

Note: *Curves in FIg. 3-2 are calculated for 1 mm thick slicks at 15°C in a 10-knot wind*

Density is a key factor determining the likelihood of oil temporary submergence and sinking. CHV, HFO and the oil sands-derived crudes reached maximum densities of 0.99-1.01 by Weathered State 3, corresponding to six weeks in the lab wind tunnel. These values are close or equal to neutral buoyancy, sufficient to cause temporary submergence or over washing of oil with wave action in fresh water.

It is worth noting that even oils with densities equal to or greater than freshwater were observed to remain floating for some time in the laboratory flume tank tests due to tiny entrained bubbles in the oil. This air entrapment affected the bulk density of the viscous mats of oil, which were occasionally overwashed at the waterfall feature but remained floating and/or partially adhered to the walls at the water surface during the recirculating flume tank tests.

Viscosity plays a large role in the choice of optimal skimmer or mechanical recovery system. Results from the lab weathering show that heavy oils, conventional or non-conventional, can become very viscous over a short period of time, emphasizing the need for proper planning and the selection of appropriate equipment designed to deal with oils of the target viscosity.

Pour Point can have an impact on the initial spreading of an oil, and also impact the flowing characteristics as an oil is collected because the pour point will change (increase) as the spilled oil is weathering. High viscosity and low pour point may also make weathered oil more prone to mat formation and air entrapment (noted above) which could prolong the time some weathered oil might remain afloat. Pour point limits may also impact recovery efforts if the oil is collected in tanks or temporary storage devices. If the temperature of the oil drops in these containers, the oil may resist flowing and cause logistical issues when attempting to discharge storage devices. Supplemental heating may be required.

Emulsification: Water-in-oil emulsions consist of water droplets in a continuous oil phase. The tendency of crude oil to form water-in-oil emulsions and the stability of the emulsion formed are measured by two numbers: The Emulsification Tendency Index (self-explanatory) and the Emulsion Stability assessment using four categories originally suggested by Fingas *et al.* 1998. Emulsion types are selected based on water content and the visual appearance of the emulsion after 24 hours settling. The four Stability categories are defined as:

1. Unstable – looks like original oil; water contents after 24 hours of 1 percent to 23 percent averaging 5 percent; viscosity same as oil on average. Abbreviated in Table 3-2 as (Unst)
2. Entrained Water – looks black, with large water droplets; water contents after 24 hours of 26 percent to 62 percent averaging 42 percent; emulsion viscosity 13 times greater than oil on average Abbr. in Table 3-2 as (Entr)
3. Meso-stable – brown viscous liquid; water contents after 24 hours of 35 percent to 83 percent averaging 62 percent; emulsion viscosity 45 times greater than oil on average
4. Stable – the classic "mousse", a brown gel/solid; water contents after 24 hours of 65 percent to 93 percent averaging 80 percent; emulsion viscosity 1100 times greater than oil on average

The tendency to form emulsions, and their stability once formed, vary widely between different oils. For many oils, a certain degree of weathering is necessary before emulsification becomes likely.

Table 3-2 summarizes the emulsification results from the small-scale standardized oil property tests at 15-20°C, consistent with other properties shown in Table 3-1. The two lightest products, condensate and SYN, were the only oils considered unlikely to emulsify in either a fresh or weathered state. Light to medium crudes were considered unlikely to emulsify until they reach a highly weathered state after a few days. Heavy oils and oil sands-derived crudes are very likely to form emulsions with water contents over 50 percent in a fresh state, and to form emulsions with lower water contents as they rapidly weather and become more viscous in the early stages of a spill. However, as weathering continues, these oils (including CHV and HFO) quickly become too viscous (Table 3-1) to emulsify any further.

Table 3–2: Summary of Oil Emulsion, Stability and Water Content at 15-20°C

Oil		Characteristic											
		Emulsion Tendency				Emulsion Stability				Water Content %			
		Fresh	Weathered State 1	Weathered State 2	Weathered State 3	Fresh	Weathered State 1	Weathered State 2	Weathered State 3	Fresh	Weathered State 1	Weathered State 2	Weathered State 3
1	Condensate (CRW)	Unl	Unl	Unl	Unl	Unst	Unst	Unst	Unst	0	0	0	0
2	Light Sour Blend (LSB)	Unl	Very Likely	Very Likely	Very Likely	Unst	Meso Stable	Meso Stable	Meso Stable	0	27	82	66
3	U.S. Bakken (NDB)	Unl	Unl	Unl	Unl	Unst	Unst	Unst	Unst	0	0	0	0
4	Mixed Sweet Blend (MSW)	Unl	Very Likely	Very Likely	Very Likely	Unst	Meso Stable	Meso Stable	Meso Stable	0	54	89	85
5	Alaska North Slope (ANS)	Unl	Unl	Mod	Mod	Unst	Unst	Unst	Unst	0	0	13	9
6	Medium Sour Blend (MSB)	Unl	Unl	Very Likely	Very Likely	Unst	Unst	Entr	Entr	0	0	36	42
7	Conventional Heavy (CHV)	Very Likely	Very Likely	Too Visc	Too Visc	Entr	Entr	Too Visc	Too Visc	51	28	0	0
8	Bunker C – Heavy Fuel Oil (HFO)	Very Likely	Likely	Too Visc	Too Visc	Unst	Unst	Too Visc	Too Visc	17	9	NM	NM
9	Western Canadian Select (WCS)	Very Likely	Very Likely	Very Likely	Too Visc	Meso Stable	Entr	Entr	Too Visc	60	27	0	NM
10	Access Western Blend (AWB)	Very Likely	Very Likely	Too Visc	Too Visc	Entr	Unst	Unst	Unst	31	18	NM	NM
11	Cold Lake Blend (CLB)	Very Likely	Very Likely	Too Visc	Too Visc	Entr	Entr	Too Visc	Too Visc	60	45	0	0
12	Albian Heavy Synthetic (AHS)	Very Likely	Very Likely	Too Visc	Too Visc	Stable	Meso Stable	Entr	Unst	72	26	0	0
13	Synbit Blend (SYB)	Very Likely	Very Likely	Very Likely	Very Likely	Meso Stable	Meso Stable	Entr	Entr	59	51	27	28
14	Synthetic Sweet Blend (SYN)	Unl	Unl	Unl	Unl	Unst	Unst	Unst	Unst	0	0	0	0

Key to Abbreviations: Unl = Unlikely, Entr = Entrained, Unst = Unstable, Visc = Viscous, NM =Not Measured (over 1,000,000 cP)

3.2 Comparing Different Laboratory Evaporation Methods

Researchers use several different laboratory methods to simulate evaporation of an oil spill on water when exposed to the atmosphere. There is no previous research that compares these methods to ensure that oil evaporation measurements in the laboratory are independent of the test method used. Three methods were selected for intercomparison in this study to determine if the physical properties results are significantly affected by the test procedures.

1. A tray with a "thick" (2 cm) initial layer of oil placed in a calibrated wind tunnel. The tray is frequently weighed to document the evaporation rate for defined periods.
2. A rotary evaporator procedure employed by Environment and Climate Change Canada (ECCC) to produce oil samples evaporated to specific mass losses, based upon mass loss after a maximum defined period.
3. A third technique similar to the first but using a "thin" (1.5 mm) layer of oil as a starting point.

A target was selected using the six-week lab WS3 mass loss as an end point for each of the oils. Once this data was generated from the "thick" (2 cm) layer runs, the remaining two methodologies were used to attain that target mass loss (designated endpoint). The time to reach the endpoints differed for each oil and for each methodology used, however the physical properties of oils evaporated using these different test protocols showed remarkably close agreement. Results demonstrated that the choice of evaporative test protocol made no substantial difference to the density and viscosity at a *specified mass loss endpoint*.

Figures 3-3 and 3-4 show examples of weathered densities and viscosities measured with the three different evaporative test protocols applied to CLB. Each of the three samples was measured at the four temperatures shown to determine temperature effects on the density measurements. Viscosity measurements at 0°C for the "thin" (1.5 mm) wind tunnel and rotary evaporator samples were beyond upper scale of the rheometer used to measure viscosity (in excess of 1,000,000 centipoise [cP]). Additional comparisons for all of the test oils are contained in the main data report (SL Ross, 2020).

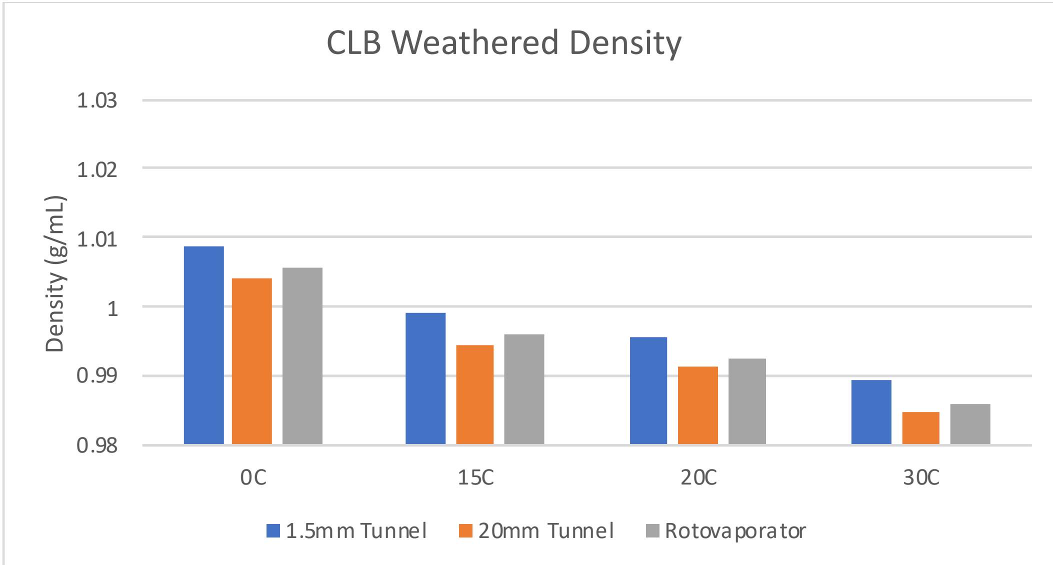


Figure 3-3: Example of Weathered Density Measured with Three Different Protocols

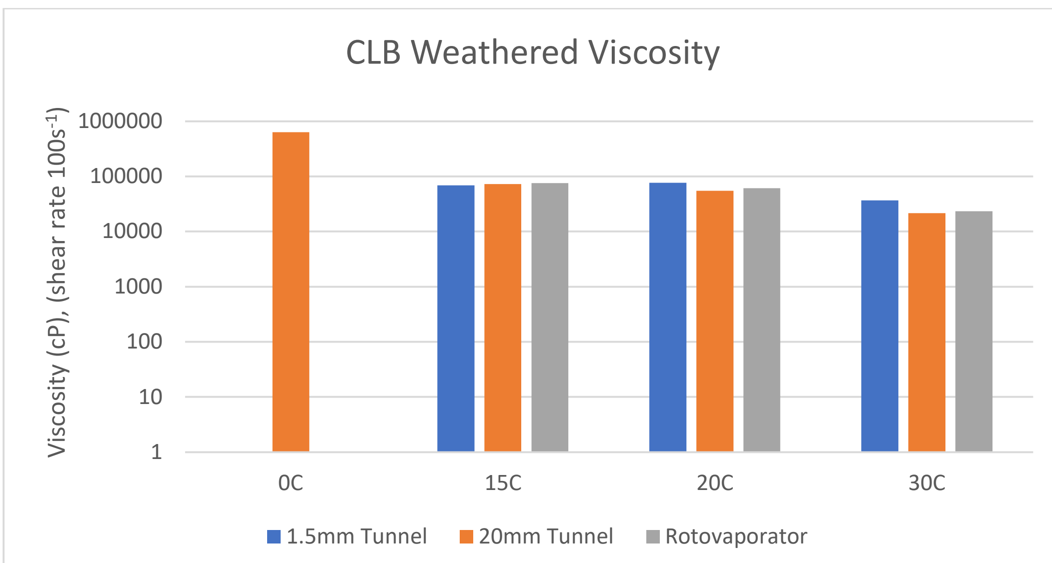


Figure 3-4: Example of Oil Weathered with Three Different Protocols – Viscosity measured at four temperatures

3.3 Oil-Particle Interactions

One of the knowledge gaps identified by the RSC 2015 report is understanding how non-conventional oils will behave when exposed to suspended particles in the water (fresh or marine). In this study, laboratory-scale tests with the project oils (Table 2-1) were performed to determine the possible effects of oil-particle interactions during a spill. Historically, this has not been a standard oil behaviour test.

Oil-particle interactions, referred to as oil-mineral aggregates (OMAs), are the formation of oil/solid agglomerates and are generally accepted as a beneficial occurrence in a *marine* environment. These small oil droplets dispersed into the water column are more readily biodegraded due to increased surface area. For example, surf-washing (oiled sediment relocation), to encourage the formation of oil-particle aggregates is an accepted technique for accelerating the natural cleaning of oiled shorelines. However; there have also been instances of spills into rivers where the interaction between the oil and suspended particles in turbulent water caused significant amounts of the oil to sink (Lee et al., 1998).

Known factors impacting oil-particle interaction include:

- **Salinity**, which can affect OMA formation. In this study, 12 oils were tested in fresh water and two in brackish water, representative of many coastal marine areas.
- **Sediment concentrations** encompassed a range of conditions from moderate to extreme sediment loadings expected in rivers in Central and Western Canada at different times of the year.
- **Sediment composition and grain size** Mineral type has been shown to affect OMA formation, but most solids will form oil/solid agglomerates.
- **Oil properties including chemical composition, density, and viscosity:**
    - Viscosity of the oil controls (in part) the formation and size of oil droplets at a given turbulence level in the water. Previous work found a significant reduction in OMA formation for oils with viscosity higher than 10,000 cP, a value reached within hours to a few days for many heavy oils, both non-conventional and conventional.
- **Turbulence:** OMA formation is complex process and simulating real world turbulence at such a small scale is very difficult. Tests used a baffled flask apparatus at two energy levels, representing moderate and very turbulent environments.

With these factors in mind, the test conditions encompassed:

- Two commonly occurring minerals in Canada: Quartz (representing sand, median particle size 10 micron, range: 0.7-37 micron), and Kaolinite (representing river clay, median particle size 1-2 micron, range: 0.2-44 micron)
- Mineral size of Quartz, median particle size 10 micron, range: 0.7-37 micron (#400 mesh)
- Mineral size of Kaolinite, median particle size 1-2 micron, range: 0.2-44 micron (#320 mesh)
- Mineral concentrations in the water: 500 and 1,500 mg/L
- Water: fresh (14 oils) and brackish 20 ppt salt (2 oils)
- Weathering: fresh and two days
- Oils with viscosities lower than 10,000 cP
- Water Temperature: 20°C

The laboratory-scale tests used the protocol reported in Lee et al., 1998. The tests were conducted in 250-mL flasks modified with a bottom spigot. An orbital shaker was used to provide mixing energy during the tests. The shaker was operated at 160 rpm for the tests with 500 mg/L minerals (moderate conditions), and 200 rpm for the test with 1,500 mg/L (high conditions), on the belief that higher suspended solids concentrations would typically be found in rivers with high levels of turbulence. Recent investigations into the energy dissipation rate in various laboratory tests determined that the apparatus used in this study produced turbulence levels in the range of moderate to very turbulent flowing streams (Kaku et al., 2005; Mukherjee, 2008).

Experiments were conducted with sediment concentrations of 500 and 1,500 mg/L in fresh water, to encompass the upper seasonal range of conditions that could be expected to be encountered in Central and Western Canada, including spring flooding (Venosa et al., 2005). For context, a river with even the "moderate" sediment loading used in these tests would appear a muddy brown. These loading rates were selected to determine if the oils tested would have a propensity to form OMAs, so that comparisons between the oils could be performed, as opposed to attempting to match a sediment concentration with a specific environmental scenario.

Given the complexity of the OMA formation process, small scale tests can never fully replicate wind and wave conditions expected in a real lake, river or ocean. In a real-world spill, OMAs could continue to form over an extended period of time, gradually removing more oil from the surface. However, the small-scale tests used in this study can highlight any significant differences between oil types as well as indicating the relative effects of turbulence, increased sediment concentrations and evaporation.

Figure 3-5 shows the calculated percentage of oil removed based upon a sample of water pulled from the bottom of a baffled flask through an incorporated spigot at the end of the agitation and settling period of each test. Free oil floating from the pulled sample was separated, then the pulled water sample was subjected to an extraction process to determine a remaining oil concentration. This result was used to calculate oil losses from the original oil slick attributed to oil particle interaction. Tests used a representative Kaolinite (clay) particle concentration of 500 mg/L at a moderate turbulence level of 160 rpm (Venosa 2005) (related results for Quartz at the same concentration and energy generally showed lower oil removal rates). Complete results are listed in the main report (SL Ross 2020).

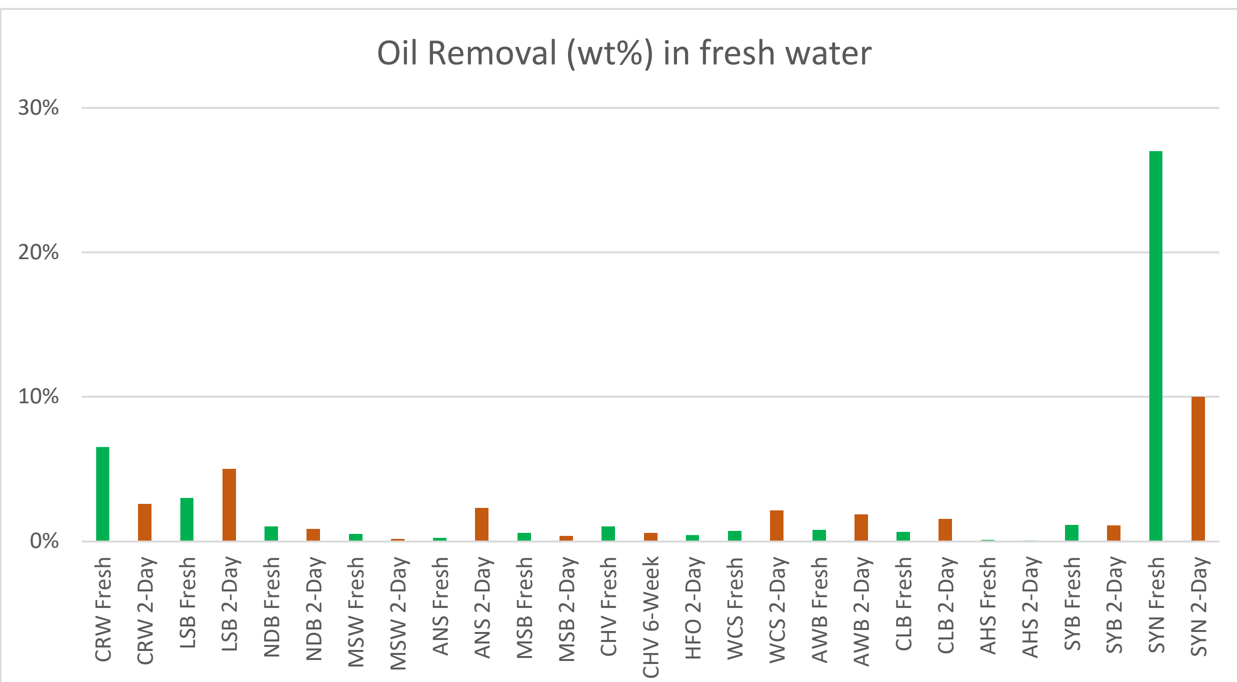


Figure 3-5: Results of Oil-Particle Interaction Tests with Kaolinite (500mg/L, 160rpm)

***Note:** Oils are generally arranged from light conventional to oil sands-derived- bitumen products, then synthetic oils reading left to right. Test data represents moderate turbulence and a Kaolinite (Clay) particle concentration of 500 mg/L.*

The key point to draw from these results is that with the exception of fresh condensate, the presence of sediments in the water in a range of commonly expected concentrations (up to 500 mg/L) removed only a few percent of the oil by weight from the surface, regardless of oil type, with the exception of higher removal by SYN. There was no clear pattern in oil removal related to oil density. Weathering tended to increase the sediment uptake slightly for a number of oils such as ANS, AWB, CLB, and WCS but the percent increase in oil removal was not significant. The opposite trend was found for CRW and SYN with a decrease in measured oil removal as the oil weathered.

All test conditions resulted in the formation of some neutral or negatively buoyant oil-particle aggregates (OMAs) with an average oil removal rate from the surface of the flask being 6 percent by weight when considering both minerals, and the two concentrations of the minerals used in testing. A few tests using the highest concentration of particulates resulted in oil removal rates between 20 and 60 percent as shown in Figure 3-6. One test involving weathered ANS crude with Quartz saw 90 percent removal, while weathered SYN with Kaolinite produced results of 92 percent removal. Not surprisingly, higher suspended solids concentrations resulted in higher oil loadings in the water column, also reflecting the higher turbulence energy applied in these tests.

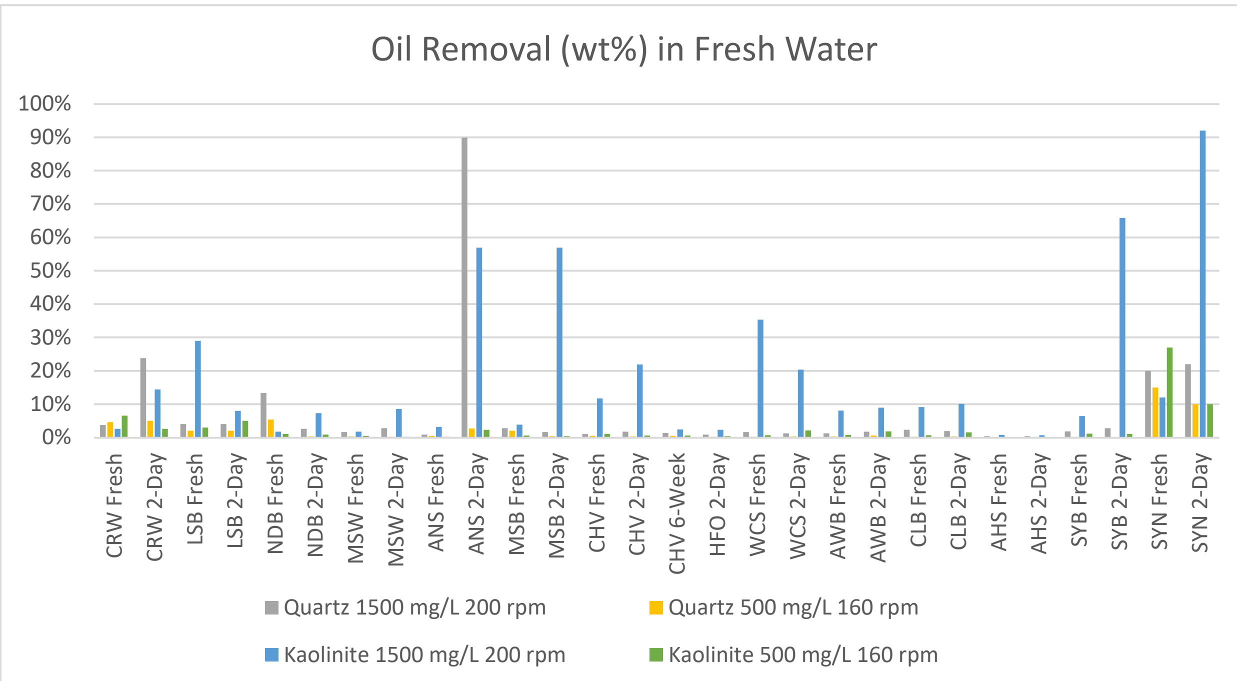


Figure 3-6: Summary Results of All Oil-Particle Interaction Tests

Oil removal rates were significantly higher for the only two oils tested with brackish water (AWB and ANS) compared to results with the same two oils in freshwater. For example, the average oil removal rate for the two test oils was 11 percent across all in fresh water vs. 21 percent in brackish water. Similarly, oil loading (measured as the ratio of the weight of oil to the weight of solid sediment in the OMA) was significantly higher in tests with brackish water (0.54 vs. 0.25 in freshwater). These results are expected because sediment particles coalesce more readily in seawater.

In terms of oil type, AHS and HFO had the lowest oil loadings of all the oils tested, averaging 0.01 and 0.03 mg oil/mg solids, respectively. The two-day weathered ANS (crude oil) had the highest consistent oil loadings, averaging 0.82 mg oil/mg solid. Several other test runs had very high oil loading (0.5 to almost 2.0 mg oil/mg solid), but there is no apparent pattern based on oil type or properties.

3.4 FLUME WEATHERING TESTS

Models can predict an oil's fate and behaviour over a range of environmental conditions with reasonable accuracy in the initial stages of a spill. This accuracy typically declines over time. After about five days, confidence in the model results diminishes rapidly. One step towards validating and improving the accuracy of model predictions over time as the oil weathers is to perform larger-scale testing in a flume that comes closer to replicating real world conditions. In the flume tank, oil on water is able to spread and weather more naturally in the presence of winds, currents, UV daylight, varying water temperatures, and surface energy (waves). Model predictions of oil fate and behaviour under these controlled conditions could be compared with the test data to improve the model performance.

Motivated by a desire to test under more realistic conditions, a full series of additional weathering tests were performed using a recirculating flume tank to augment the data from wind-tunnel weathering of small-scale samples (Section 3.1). Tests were conducted for each of the fourteen oils at two target water temperatures: 20°C and 0°C (actual temperature of colder run was between 0°C to +1°C, no ice). Fresh water was used for the majority of the tests. Some runs incorporated a concentration of sediment (1000 ppm of kaolinite), salt (35 ppt – to simulate a marine environment), or a combination of the two. In all, the flume test series encompassed over 50 runs.

There are still physical constraints in flume testing, regardless of the scale of the basin. Flume tests can only simulate a small set of conditions considering the large variability in environmental factors that a real spill would experience over short periods of time in different locations. For example, the oil can only spread so far before it contacts and, in some cases, coats the side walls. Turbulence levels and scales may not match an actual riverine or ocean environment. In spite of these limitations, the weathering rate in a flume is more representative of real-world conditions than oil subjected to small bench scale testing that can only simulate one mode of weathering at a time. For example, property changes that take two days in a wind tunnel at small scale, can occur within hours in the flume tank where the oil is subjected to a number of different weathering processes at the same time as would occur in nature. On a longer time horizon, changes occurring over several weeks in the small-scale tunnel tests can occur within a few days in the recirculating flume.

The SL Ross flume tank shown in Figure 3-7 consists of a working channel that is 0.50 m wide, and 1.5 m deep, operating with a water depth of one metre. The two parallel straight sections are 2.0 m long. Wind is circulated above the water using two fans mounted at the beginning of each turn in the tank. A flex hose attached to a ventilation fan extracts vapours from the air space above the water surface. Currents are generated using up to two submerged propellers mounted on one side. Ultraviolet wavelength light is directed to the tank surface at one end, illuminating approximately ¼ of the tank surface at an intensity about three times that experienced on a summer day in mid-June in Ottawa.

A cascade of water (waterfall) imparts surface energy to the circulating oil slick, helping the weathering and encouraging emulsification for susceptible oils. In this manner, the oil was repeatedly (approximately every 30 seconds) subjected to the equivalent to a breaking wave in an ocean or river setting. These tests created an energetic environment such as might be found in a turbulent stream. In terms of the likelihood of oil submergence, overwashing or sinking, these flume tank tests are considered representative of robust conditions that may be experienced in an actual spill.

After filling the flume tank, and stabilizing the water at the prescribed test temperature, the wind speed was set at approximately 2.0 m/s (4.0 knots) and water velocity at approximately 0.25 m/s (0.5 knots). This generated consistent movement of oil around the tank surface, while minimizing the possibility of entrainment of the oil into the water column. At the beginning of a test, a 5L sample of oil was released into the tank and circulated around the flume via surface wind shear and water currents.

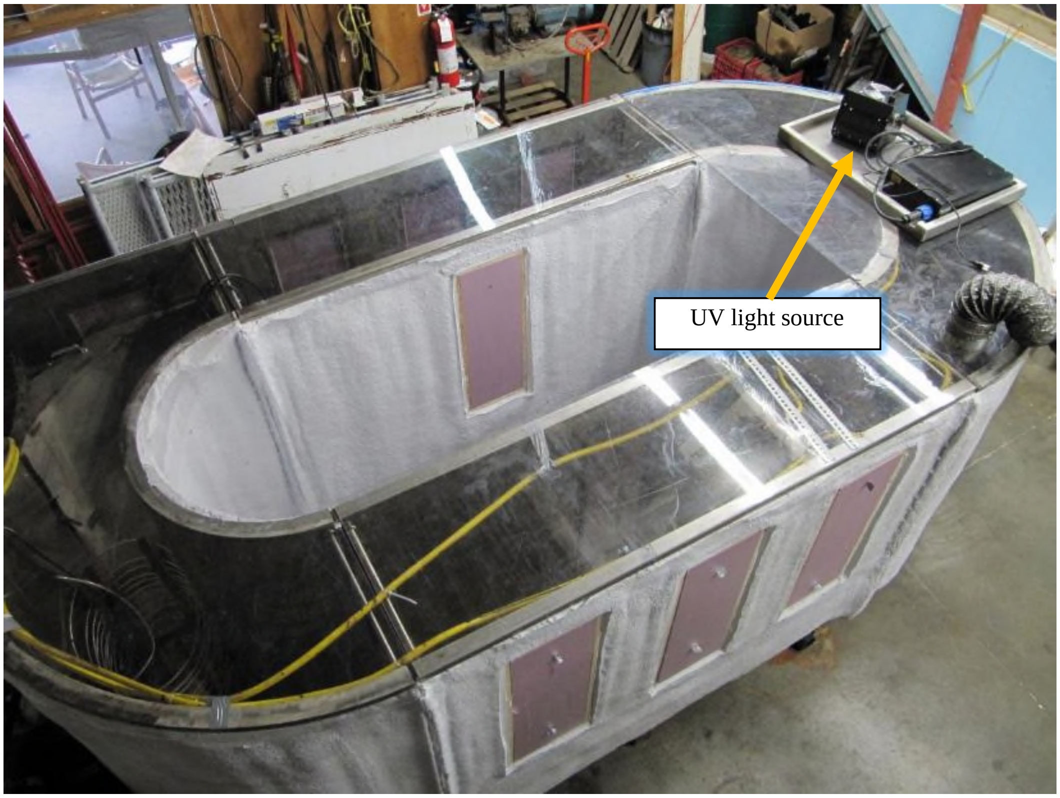


Figure 3-7: Recirculating Flume Tank Used for Meso-scale Weathering

The behaviour of each oil was observed and recorded according to: partitioning to the water column (droplets of oil observed in the water); adherence to the tank walls; over-washing; and temporary submergence or sinking of the oil to the bottom of the flume. A brief summary of observations at 1 hour and 48 hours into the baseline runs are listed below in Table 3-3. Details are contained in the main data report for each oil (SL Ross, 2020).

A test typically ran continuously until the rate of change of the measured surface oil properties became small. Past experience with the same tank showed that this point usually occurred within about 4 days. In order to address longer-term weathering behaviour recommendations identified in the RSC Expert Panel report, selected runs continued for extended periods of 7 days to two weeks.

Each test started with fresh, unweathered oil. Composite sampling of floating oil at 5-8 spots within the tank provided a representative sample for physical property determinations (viscosity, density, water content). Sampling times were established based upon results of historical testing. Typically, changes in properties happen at a fairly rapid pace initially, then gradually slow down as weathering progresses. Because of this, sampling started at 1 hour and was repeated at 3, 6 and 24 hours into each run. From that point on, sampling was usually performed once every 24 hours until the changes between measured properties slowed.

Table 3–3: Flume Tank Runs Selected Summary Observations

Oil		Observations
Condensate (CRW)	(0°C Run)	At 1 hour – oil flowed easily around flume, shearing in fine droplets At 48 hour – oil continued to flow, possible dispersion into column
	(20°C Run)	At 1 hour – fine droplets sheared by waterfall seen to rise quickly At 48 hour – edges of slick have slight foamy appearance, dispersion?
Light Sour Blend (LSB)	(0°C Run)	At 1 hour – oil circulating, with waterfall shearing 1-3 mm dia. oil balls At 48 hour – circ. is slowing, still shearing small droplets - resurface
	(20°C Run)	At 1 hour – oil circulating, waterfall shearing 1-3 mm dia. oil droplets At 48 hour – circulation continues, small bubbles in slick- waterfall
U.S. Bakken (NDB)	(0°C Run)	At 1 hour – slick sheared into tiny droplets in water column, flows well At 48 hour – some evidence of emulsification in slick
	(20°C Run)	At 1 hour – oil flows freely, waterfall shears small droplets (mist) At 48 hour – water column getting cloudy, dispersion into column
Mixed Sweet Blend (MSW)	(0°C Run)	At 1 hour – oil flows freely, many large 4-7 mm dia. balls in column At 48 hour – oil has emulsified appearance (although dark in color)
	(20°C Run)	At 1 hour – oil spreads easily, sheds into range of 1-2, 3-5mm dia balls At 48 hour – few droplets circ. in water column (<1mm, some 4-5mm)
Alaska North Slope (ANS)	(0°C Run)	At 1 hour – waterfall sheared 1-3 mm dia. oil balls resurfaced quick At 48 hour – water column remains clear, oil floating freely
	(20°C Run)	At 1 hour – waterfall sheared 1-5 mm dia. oil balls resurfaced quick At 48 hour – oil circulating, some 5-7 mm dia.oil balls in column
Medium Sour Blend (MSB)	(0°C Run)	At 1 hour – few waterfall sheared 1-3mm dia. oil balls resurface quick At 48 hour – water column clearing, oil circulating
	(20°C Run)	At 1 hour – oil sheared 1-3 mm dia. balls by waterfall, resurface quick At 48 hour – oil still being sheared, few small oil balls in water column
Conventional Heavy (CHV)	(0°C Run)	At 1 hour – oblong shaped blobs sheared by waterfall, resurfacing At 48 hour – waterfall had minimal impact on slick
	(20°C Run)	At 1 hour – non-spherical blobs sheared by waterfall resurface At 48 hour – some tiny oil droplets in water column – slowly resurfacing
Bunker C – Heavy Fuel Oil (HFO)	(0°C Run)	At 1 hour – viscous oil minimally impacted by waterfall At 48 hour – ring of oil submerged/overwashed along tank perimeter adhering to inner wall near surface

	(20°C Run)	At 1 hour – shredding from waterfall, spherical oil resurfacing. By 6 hours large (5-7mm) and small(1-3) oil balls apparent in water column At 48 hour – previous large (5-7mm) and small (1-3mm) balls circulating in water column diminished in concentration, resurfacing
Western Canadian Select (WCS)	(0°C Run)	At 1 hour – oil slick generates blobs/stringers from waterfall At 48 hour – increased viscosity apparent in slick. Sticking to side
	(20°C Run)	At 1 hour – slick is shedding blobby streamers at waterfall - resurface At 48 hour – impacts from waterfall diminish as viscosity increases
Access Western Blend (AWB)	(0°C Run)	At 1 hour – flowed well, shearing to 1-7mm blobs - resurface At 48 hour – impact of waterfall diminishing, shedded oil resurfacing
	(20°C Run)	At 1 hour – slick shearing into 1-7mm blobs at waterfall - resurface At 48 hour – oil slick shrinking, oil floating in water column
Cold Lake Blend (CLB)	(0°C Run)	At 1 hour – slick shedding into streamers in water column - resurface At 48 hour – slick still shedding, oil streamers slower to rise
	(20°C Run)	At 1 hour – viscosity increase apparent as blobs become stringers At 48 hour – oil impacted less by waterfall as viscosity increases
Albian Heavy Synthetic (AHS)	(0°C Run)	At 1 hour – Oil sheared into stringers/blobs from waterfall At 48 hour – Some droplets (1-2mm dia.) of oil in water column
	(20°C Run)	At 1 hour – Oil sheared into stringers from waterfall At 48 hour – Larger blobs submerged and stuck to walls/floor. End.
Synbit Blend (SYB)	(0°C Run)	At 1 hour – oil shredding under waterfall (streamers) At 48 hour – oil becoming more viscous, no droplets under waterfall
	(20°C Run)	At 1 hour – oil covering flume channel, circulating well (1-4mm dia) At 48 hour – viscosity climbs, non-spherical stringers from waterfall
Synthetic Sweet Blend (SYN)	(0°C Run)	At 1 hour – oil circulating under waterfall shearing <1 mm droplets At 48 hour – larger droplets in 1mm dia. range resurface quickly
	(20°C Run)	At 1 hour – oil sheds into tiny droplets under waterfall At 48 hour – oil behaves the same, water becoming cloudy

Tables 3-4 and 3-5 present a high-level overview of the flume tests focusing on density and viscosity data at 0°C and 20°C after 1 hour and 48 hours into each test that typically lasted 5 days.

CHV and HFO weathered towards similar densities at 48 hours for runs at both test temperatures. Oil sands-derived products showed higher densities after one hour of weathering at the warmer temperature. This behaviour is consistent with the rapid initial evaporation of the diluent at 20°C compared to 0°C. After 48 hours, the differences in densities between the two temperature runs were not significant for these products (confined to the third decimal place).

All of the oils were initially more viscous at 0°C than 20°C. Two of the dilbits (WCS and AWB) increased in viscosity more rapidly in the warm runs, effectively matching the viscosity reading in the cold run just beyond 48 hours. The third dilbit, CLB, stayed more viscous during the cold run (when compared with the warm 20°C run). The partially upgraded oil sands product (AHS) became more viscous in the warm run, while the two conventional heavy products (CHV and HFO) stayed more viscous in the cold run. Oil sands- derived products demonstrated accelerated weathering at the warmer test temperature but weathering rates tapered off after the first couple of days.

The HFO did show signs of submergence during the 0°C "baseline" run (no salt, no sediment), with some blobs of oil being observed stuck to the sidewalls of the flume tank at 6 hours into the run. By 24 hours a large portion of the slick was submerged below the waterline.

One oil, AHS, did show some submergence by 24 hours of the 20°C "baseline" run with some blobs of oil observed stuck to the walls and floor of the test flume. At 48 hours, most of the oil had submerged and the run was halted at that point.

Complete data sets for all the runs are contained in the main data report (SL Ross, 2020).

Table 3–4: Summary of Selected Result-Flume Tank Run at 0°C, fresh water, zero sediment,sample as retrieved from flume tank

Oil		Flume Test Summary					
		Sample Density at 0°C g/ml	Sample Water Content %	Sample Viscosity @ 0°C (100 s^{-1}) cP	Sample Density at 0°C g/ml	Sample Water Content %	Sample Viscosity @ 0°C (100 s^{-1}) cP
		1 hour	1 hour	1 hour	48 hours	48 hours	48 hours
1	Condensate (CRW)	0.820	0	14[1]	0.854	2	270
2	Light Sour Blend (LSB)	0.899	0	40	0.95	16	2,015
3	U.S. Bakken (NDB)	0.859	0	15[1]	0.887	24	87
4	Mixed Sweet Blend (MSW)	0.876	0	111	0.914[2]	21[2]	2,600[2]
5	Alaska North Slope (ANS)	0.914	4	145	0.935	0	910
6	Medium Sour Blend (MSB)	0.891	2	56	0.929	6	952
7	Conventional Heavy (CHV)	0.967	26	11,500	0.996	38	171,400[3]
8	Bunker C – Heavy Fuel Oil (HFO)	0.996	2	108,500[3]	1.002	22	201,700[3]
9	Western Canadian Select (WCS)	0.967	7	9,000	0.997	8	45,100
10	Access Western Blend (AWB)	0.973	15	29,400	1.004	15	151,000[3]
11	Cold Lake Blend (CLB)	0.973	18	22,600	0.998[2]	22[2]	273,750[2,3]
12	Albian Heavy Synthetic (AHS)	0.955	1	2,450[3]	0.997	10	51,400[3]
13	Synbit Blend (SYB)	0.961	8	2,927	0.975	20	12,020
14	Synthetic Sweet Blend (SYN)	0.889	0	26	0.936	39	70

Notes:

1. Shear rate @500 s^{-1}
2. CLB and MSW data is for samples taken at 96 hours.
3. Shear rate @25 s^{-1}

Table 3–5: Summary of Flume Tank Test Data at 20°C, fresh water, zero sediment

=	Oil	Flume Test Summary					
		Density at 20°C g/ml	Water Content %	Viscosity @ 20°C (100 s^{-1}) cP	Density at 20°C g/ml	Water Content %	Viscosity @ 20°C (100 s^{-1}) cP
		1 hour	1 hour	1 hour	48 hours	48 hours	48 hours
1	Condensate (CRW)	0.821	0	3[1]	0.863	69	42[1]
2	Light Sour Blend (LSB)	0.897	0	20[2]	0.927	14	540
3	U.S. Bakken (NDB)	0.856	0	7[1]	0.883	25	40[1]
4	Mixed Sweet Blend (MSW)	0.871	0	23[2]	0.942[3]	4[3]	723[3]
5	Alaska North Slope (ANS)	0.906	2	31	0.935	10	370
6	Medium Sour Blend (MSB)	0.896	1	31	0.922	7	200
7	Conventional Heavy (CHV)	0.969	23	4,080	0.991	27	26,900
8	Bunker C – Heavy Fuel Oil (HFO)	0.987	20	7,300	0.995	15	20,800
9	Western Canadian Select (WCS)	0.970	8	4,700	0.991	14	38,450
10	Access Western Blend (AWB)	0.985	13	27,300	0.998	9	275,000[4]
11	Cold Lake Blend (CLB)	0.985	26	20,100	0.997	21	50,200
12	Albian Heavy Synthetic (AHS)	0.986	23	23,200	1.017	12	Too Vis
13	Synbit Blend (SYB)	0.956	19	1,100	0.975	34	6,650
14	Synthetic Sweet Blend (SYN)	0.885	0	14[1]	0.900	4	31[1]

Notes:

1. Shear rate @500 s^{-1}
2. Shear rate @200 s^{-1}
3. MSW data is for samples taken at 75 hours.
4. Shear rate @20 s^{-1}

Figures 3-8 and 3-9 show a comparison of flume test results of heavy oils at 0°C with fresh water and no sediment. As discussed earlier, most of the oils reached their highest densities and viscosity over time at the colder temperature. The data clearly shows that weathered bitumen products do not exhibit unique properties in terms of density or viscosity compared with conventional heavy crude oil.

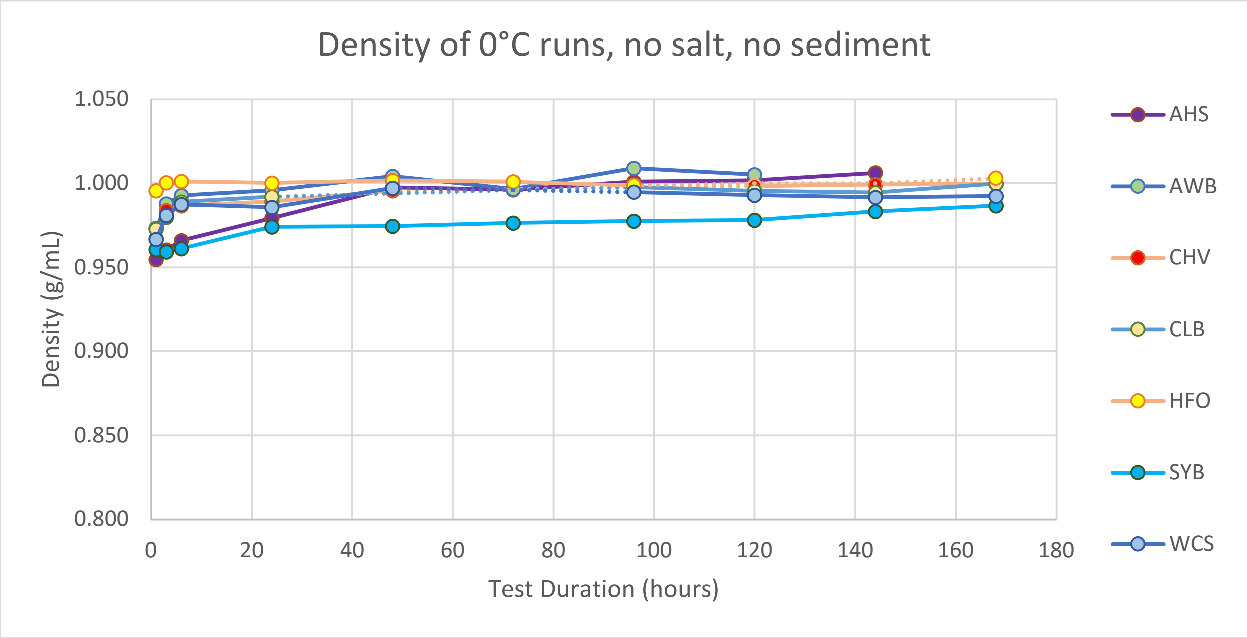


Figure 3-8: Comparison of Flume Weathering Density Measurements for Heavy Oils

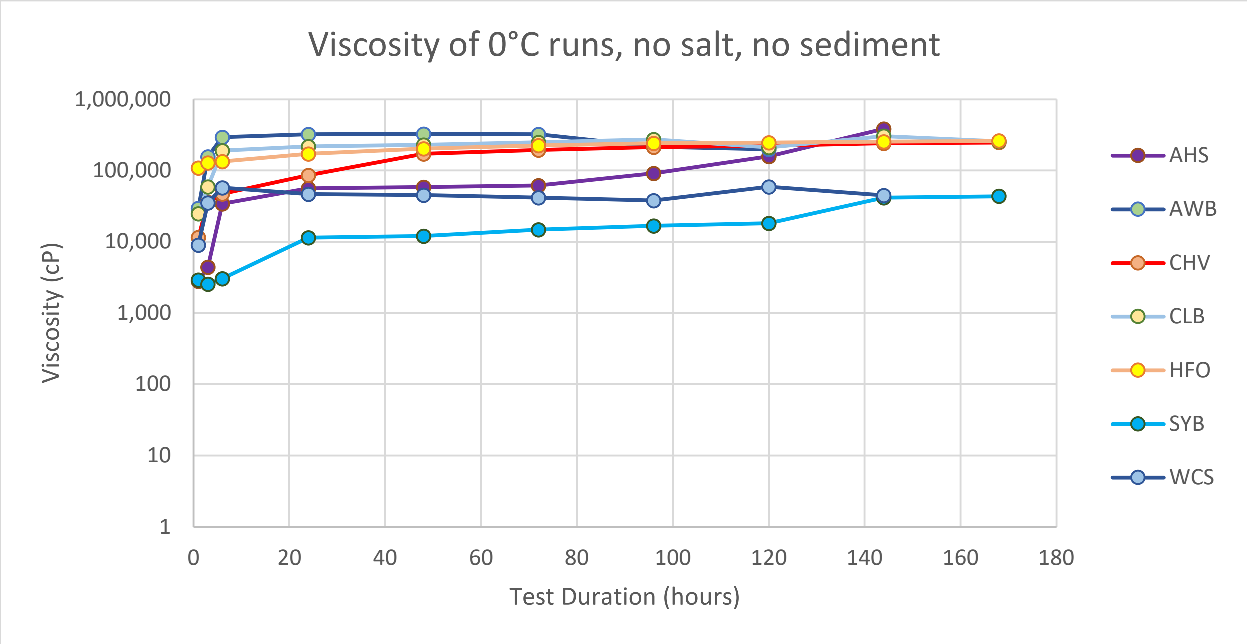


Figure 3-9: Comparison of Flume Weathering Viscosity Measurements for Heavy Oils

Results from the flume tests (run for a minimum of 5 days) led to the following conclusions:

- All light and medium oils floated in freshwater.
- All of the oils tested are expected to remain floating in marine (saltwater) environments.
- CHV together with oil sands-derived crudes reached densities very close to or slightly above unity (in the second or third decimal place) within 48 hours. This indicates a potential for temporary submergence or overwashing, but not necessarily sinking, in freshwater. Flume test observations showed that small bubbles or air entrainment likely imparted from the small waterfall act to keep mats afloat for extended periods even when the density slightly exceeds 1 g/mL.
- A portion of the partially upgraded oil sands-derived crude (AHS) did submerge with large blobs of oil settling to the bottom of the tank and sinking within the first 48 hours of the flume testing at 20°C. It remained floating in tests with fresh water at lower temperature and tests with seawater at both tested temperatures.
- Higher temperatures generally expedited the initial weathering process of oil sands-derived products, leading to higher densities for these oils in the first few hours. When comparing the results of the 0°C runs with the 20°C runs for each of these oils, there were no significant differences in density between them or the two heavy conventional oils by the 48 hours mark.
- All of the oils showed large increases in viscosity over the initial 48 hours, generally attributed to weathering and emulsification processes.
- The addition of sediment in the flume tests did not cause apparent gross submergence or sinking for any oil sands-derived products. There was one run, however, with HFO at 0°C with sediments which did demonstrate gross submergence.
- There was evidence of temporary submergence in some runs. The waterfall sheared off blobs of oil which then rose to the surface. As the oil weathered , the waterfall impact generally reduced as the slicks became more viscous, and the floating oil only submerged slightly before refloating, without breaking into droplets.
- Flume tank observations confirmed the rule of thumb that there is a viscosity window of opportunity for the uptake of sediments. Once an oil weathers past that time window, there is minimal driving force to uptake sediment into the body of a viscous oil slick.

3.5 Porous Media Tests

All 14 oils were subjected to soil penetration tests to establish any differences in behaviour between conventional and unconventional oils. The tests conducted at two different scales used three permeable substrates: silica sand, artificially created loamy soil and pea gravel (larger-scale tests only). Artificial soil was created using a standard method with water added to adjust moisture levels to a mixture of air-dried sand, kaolin clay and peat (sphagnum peat moss) in a 7:2:1 ratio.

Small-scale bench tests used either 650 g of sand or 475 g of artificial soil packed into straight walled mason jars. The small-scale tests were run to determine the operating parameters for the larger- scale tests, and to optimize the moisture contents of the different substrates.

The larger-scale bench tests used either 25 kg of sand, 26.5 kg of pea gravel or 16.4 kg artificial soil packed/settled to a volume of 15 L within test buckets. These tests provided a better resolution with respect to oil penetration and also allowed for the testing of the transport of soluble aromatics through the substrate by water. Refer to the main data report for the complete set of test data (SL Ross, 2020).

Figure 3-10 summarizes the oil penetration results from the larger-scale test with pebbles, sand and artificial soil for slightly weathered oils taken to Weathered State 1. Physical properties of the oils are shown in Table 3-6.

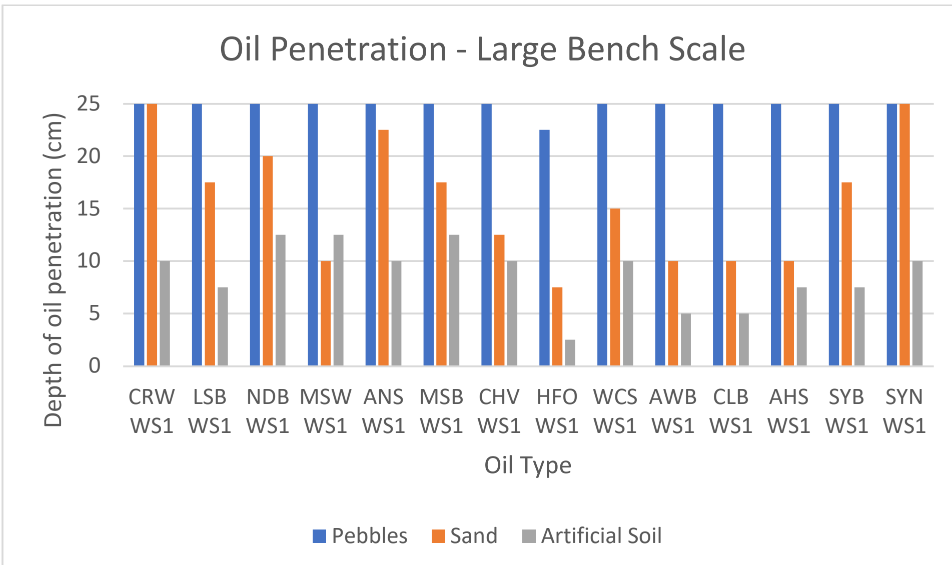


Figure 3-10: Oil Penetration Test Results

Note: *Oils are generally arranged light to heavy reading left to right. Conventional oils are grouped first, then oil sands-derived products with synthetics at the end. See Table 3-6 below for physical properties of the oils used in the penetration tests.*

Table 3–6: Oil Properties at Weathered State 1

Oil - Weathered State 1 (2 days in wind tunnel)	Density at 20°C (g/mL)	Viscosity at 20°C (cP)
Condensate (CRW)	0.838	12
Light Sour Blend (LSB)	0.906	59
U.S. Bakken (NDB)	0.871	19
Mixed Sweet Blend (MSW)	0.876	35
Alaska North Slope (ANS)	0.918	109
Medium Sour Blend (MSB)	0.909	65
Conventional Heavy (CHV)	0.957	1304
Bunker C – Heavy Fuel Oil (HFO)	0.986	6327
Western Canadian Select (WCS)	0.955	1320
Access Western Blend (AWB)	0.952	4551
Cold Lake Blend (CLB)	0.951	1651

Albian Heavy Synthetic (AHS)	0.977	4301
Synbit Blend (SYB)	0.951	678
Synthetic Sweet Blend (SYN)	0.891	17

Given the complexity of how oil can interact with different sediment types and the huge spatial variability of terrestrial environments, interpretations of the results from these relatively small-scale tests need to focus on relative differences in oil behaviour and not on specific values.

Results from the porous media tests showed that:

- The six lightest crudes ranging from CRW to MSB penetrated to an average depth of 17.6 cm in sand and 10.5 cm in the artificial soil. The six heaviest conventional crude and oil sands-derived crudes penetrated to equivalent average depths of 12.3 and 5.6 cm respectively. These results indicate that penetration depths are largely determined by oil viscosity.
- The two lightest, least viscous products, CRW and SYN had the greatest penetration depths while the heaviest and most viscous oil – HFO displayed much lower penetration depths.
- Pea gravel showed no oil retention capacity, with all the oils except HFO rapidly saturating the test column.
- The artificial soil, with its clay and organic material, retained selected chemical compounds and showed reduced concentrations in the run-off water when compared with the sand or gravel test results.

3.6 Shoreline Adhesion Tests

Currently accepted shoreline and inland oil recovery or treatment techniques for stranded heavy oils involve manual/mechanical removal or washing. Improving response in these situations will require a greater understanding of the fate and behaviour of the oil residues stranded on shorelines, riverbanks, and terrestrial substrates. Despite 30+ years of research, there is no field data and very little bench-scale data on rates of natural removal that can be used in the decision process on when to clean or treat, how to recover stranded oil, and how much to allow for natural cleaning.

The RSC 2015 report identified the behaviour of unconventional oils when interacting with shorelines as a knowledge gap. This was addressed by conducting a series of tests to provide insight into the effect of waves on the adhesion and mobility of selected oils on the surface of a beach subjected to wave action. Two types of substrates were evaluated, a small 10 mm pea gravel and a larger 3 to 7 cm river pebble. Waves were selected to provide different energy levels - high enough to have an effect on the oil, yet not so high that the substrate would be removed by the end of a test cycle.

Experiments were conducted in the SL Ross wind/wave tank, which measures 11 m long, 1.2 m wide by 1.2 m deep with a nominal operating depth of 85 cm (Figure 3-11). It is equipped with a computer-controlled, electrically driven wave paddle capable of producing sinusoidal, breaking, or random waves at one end of the tank. Wave-absorbing panels installed at both ends of the tank dissipate the wave energy.

A stabilized beach support structure was installed in the channel in the path of waves being generated. The wave paddle was programmed for two series of wave patterns, a series of sinusoidal waves and a series of breaking waves. Once in place, the pre-oiled shorelines were exposed to controlled environmental conditions with repeatable and precise wave energy. The aim was to consistently compare oil adhesion and remobilization using a range of oil types and two different beach types (substrates).

Figure 3-11: Views of Wind-Wave Tank and Test Tray mounted in the Tank

Table 3-7 shows a simplified test matrix used for the oil adhesion tests.

Table 3–7: Test Matrix for Oil Adhesion Tests

Parameter	Description
Oil	Each of the 14 selected oils – 250mL laid along a 10cm wide swath
Substrate	**Small:** 10 mm natural round fine pebbles – 15 kg **Large:** 3 cm to 7 cm rosa beach coarse pebbles – 23 kg
Waves	**Small substrate**: Low: 12 cm height every 3 seconds, non-breaking over 36 min. High*: 2 x 15 cm height every 30 seconds, breaking for a set lasting 120 min. **Large substrate**: 20 cm high every 30 seconds, breaking for a set lasting 150 minutes, 2 sets per run with an overnight pause between sets.
Water	Fresh or 35 parts per thousand NaCl – equivalent to natural seawater
Temperature	Ambient (20°C +/-3°C)

**The number of high waves includes intentionally propagated plus two secondary waves every 30 seconds, resulting in one breaking, one rolling, and one flooding wave.*

The following test protocol applies generally to both substrates – large and small. Oils were slightly weathered (WS-1: 2 days in the wind tunnel) equivalent to the same degree of weathering used in the porous media tests. A perforated "beach tray" anchored in the tank held a weighed amount of substrate. Approximately 250 mL of oil was spilled onto the pebbles (oil application was confirmed by mass) in a 10 cm wide swath starting at the midpoint in the tray prior to activation of the wave series. The analytical procedure used solvent extraction to determine the mass distribution of residual oil remaining within the substrate after the run. The main data report provides complete details of the test protocols and analysis methods (SL Ross, 2020).

Figures 3-12 and 3-13 show the starting and ending photographs for oil applied the substrates for two oils representative of the light and heavy end of the density/viscosity spectrum – a light to medium conventional crude (MSB) and a heavier oil sands-derived crude (CLB). The differences in oil retention over time and the effect of increasing the wave energy on the finer beach material are clearly apparent.

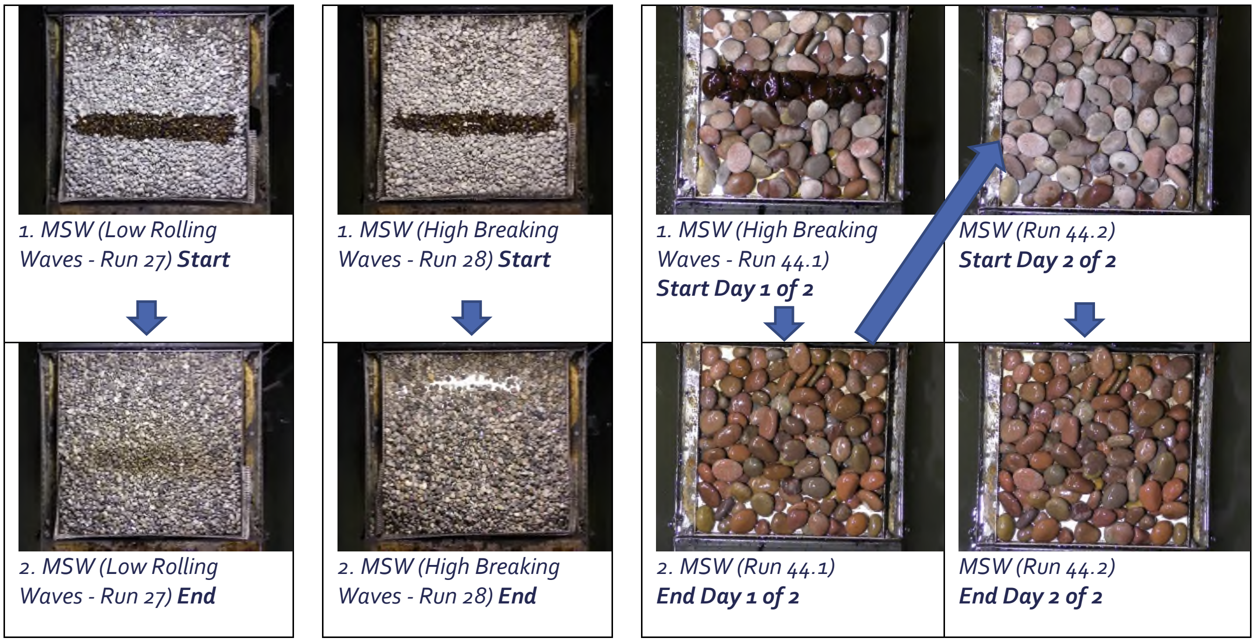


Figure 3-12: Appearance of Mixed Sweet Blend Crude Spilled on the Two "Beach" Types

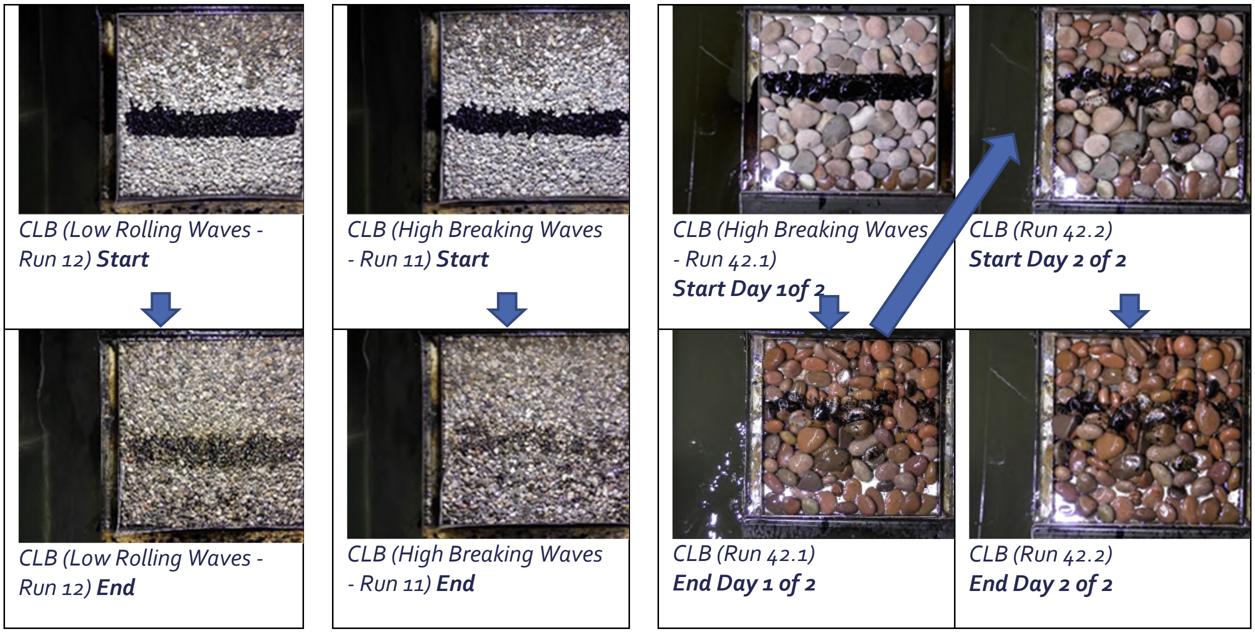


Figure 3-13: Appearance of Cold Lake Blend Spilled on the Two "Beach" Types

Notes to Figures 3-12 and 3-13: *"Start" and "End" means before and after being subjected to wave action. The high breaking wave runs with the large beach pebbles ran for two days with a pause overnight.*

Table 3-8 summarizes the percentage of oil retained in the small and large substrate with different wave energies. Results show that on average, the beach materials retained three times as much of the heavy conventional crude and oil sands-derived products compared to as the light to medium crudes. Not surprisingly, the very light condensate and North Dakota Bakken(NDB) showed the least retention. HFO, while showing the highest retention in the fine pebbles with low waves, behaved more like a light to medium crude at higher wave energies.

Table 3–8: Percent Oil Retention in the Shoreline Adhesion Tests

	Oil	Shoreline Retention Percentage - taken as weight of oil recovered from the beach/weight spilled		
		Small Substrate 10mm Fine Pebbles (Pea Gravel)		Large Substrate 3-5 cm – Coarse Pebbles
		Low Rolling Waves	Breaking 15 cm waves	Breaking 20 cm waves
1	Condensate (CRW)	2.2%	0.5%	0.3%
2	Light Sour Blend (LSB)	5.6%	0.8%	0.6%
3	U.S. Bakken (NDB)	1.8%	1.6%	0.6%
4	Mixed Sweet Blend (MSW)	5.8%	2.2%	1.7%
5	Alaska North Slope (ANS)	1.8%	1.6%	1.4%
6	Medium Sour Blend (MSB)	4.3%	1.4%	1%
	Average for light to medium oils	**3.6%**	**1.4%**	**0.9%**
7	Conventional Heavy (CHV)	12.2%	4.2%	3%
8	Bunker C – Heavy Fuel Oil (HFO)	14.9%	3.4%	1.5%
9	Western Canadian Select (WCS)	10.7%	8.2%	3.9%
10	Access Western Blend (AWB)	11.2%	21%	9.7%
11	Cold Lake Blend (CLB)	10%	7.3%	2.2%
	Average for conventional heavy crude and dilbits (excluding HFO)	**11.8%**	**8.8%**	**4.1%**
12	Albian Heavy Synthetic (AHS)	17.5%	3.6%	14%
13	Synbit Blend (SYB)	3.5%	1.1%	0.3%
14	Synthetic Sweet Blend (SYN)	2.2%	1.5%	0.5%

Key points from the shoreline adhesion tests are summarized as:

- Light and medium oils are more susceptible to relocation within the beach sediments and dispersion into the water column, potentially leading to shoreline oiling over a larger area.
- Heavy oils (higher viscosity) are less susceptible to relocation, indicating the possibility of a heavier more concentrated shoreline oiling over a smaller area.
- More viscous oils (e.g., HFO) tended to have a stabilizing effect on the small substrate (acting as a kind of glue). In other words, the oil tended to hold the substrate together which lessened the effect of the waves.
- The smaller fine pebble substrate was affected by wave action to a much greater degree than the larger coarse pebble substrate even at lower wave energies. There was some movement of the fine pebble substrate during the tests as shown by the formation of a trough in the stones in front of the wave break and the formation of a berm higher on the beach. This slight movement imparts an abrasion action between the particles.

- The simulated beach materials retained over three times as much of the heavy conventional crude and oil sands-derived products as the light to medium crudes. HFO showed the highest retention in the fine pebbles with low waves but behaved more like a light to medium crude at higher wave energies.
- The wave energy had a noticeable effect on the oil distribution. Low waves on the finer substrate did not observably redistribute the oil and most of the remaining oil stayed in the area of original application. Higher-energy waves acting on the finer substrate tended to move the oil up towards the upper beach area whereas the effects of higher-energy wave action on the large substrate were more variable.

From a spill remediation point of view, these tests indicate that heavier oils, conventional and non-conventional, would tend to stabilize a pebble beach, potentially resulting in a longer shoreline clean up window.

Caution is advised in interpreting laboratory tests for such a complex process as oil interaction with an actual shoreline. For example, the test results show the distribution of the oil remaining on the beach but not the oil removed and redistributed back into the water. In a natural environment oil is free to lift off and move laterally to potentially strand on a different section of shoreline or carry it back out to sea.

4 CONCLUSIONS AND RECOMMENDATIONS

The large amounts of test data from this study show the differences in a range of oil properties and behaviours for fourteen oils tested in a variety of simulated scenarios including oil spilled on water, land and shorelines. This synthesis covers the important findings from the most important and relevant tests considered representative of the most likely scenarios. The main data report contains full results and data tables/graphs from all of the test runs (SL Ross, 2020).

The series of small and meso-scale tests conducted in this project generated valuable input data needed to validate fate and behaviour computer models under controlled environmental conditions, with the overall goal being to improve the ability of models to predict oil property changes over time in a real-world situation.

Laboratory testing can never fully replicate a natural environment, but it can readily identify trends, and highlight relative differences in oil properties and behaviour. In interpreting the test results from this study, it is important to focus on the relative differences in behaviour (or similarities) between oils rather than concentrating solely on specific data values.

The likelihood or potential for oil to sink following a spill is an ongoing concern. Spills where oil is more likely to temporarily submerge, be over washed by wave action, become entrained in the water column or possibly sink may require emergency response strategies and equipment developed to deal with oil in the water column and/or on the bottom. In such cases, it is anticipated there would be the need for more extensive environmental remediation and restoration efforts. Results from the standardized physical properties and flume tests in this study can help determine which oils present a possible risk of sinking or submergence under different conditions.

The six specific research areas and their main conclusions are summarized briefly here:

1. Standardized analysis of physical properties
   - **Evaporative loss**
     - Some oil sands-derived products tend to evaporate somewhat more rapidly than Conventional Heavy Crude (CHV) in the initial few hours following a spill, especially at warmer temperatures. Over time (days to weeks), the oil sands-derived crude oils weather to reach densities and viscosities similar to conventional heavy crude oils. It is important to realize that as dilbits and related oil sands-derived crudes evaporate, there is no distinct separation into the parent oil stock (bitumen or heavy residue) and diluent components; both are infinitely soluble in each other.
     - With condensates, nearly all of the oil will naturally evaporate (and disperse/dissolve) from the water surface quickly after the spill. Light to medium crude oils can lose close to 50 percent of their volume within a week. Heavy conventional crudes and dilbits experience lower but still significant evaporative losses over the same time frame in the order of 25 percent. In contrast, heavy fuel oils (HFO) experience evaporative losses less than 5 percent.
   - **Density**
     - Oil sands-derived crudes have physical properties closely aligned with a range of intermediate fuel oils and other heavy conventional crude oils. Their behaviour is

consistent with what are known as Group 3 oils under an international oil classification scheme based on density. These oils tend to float on fresh water until densities increase enough through weathering and/or sediment uptake to increase the likelihood that a portion of the oil may undergo temporary submergence.
  - In the extended evaporation weathering WS-3 (6-week small-scale lab weathering results, representing time scales in the order of one week in flume tank testing), CHV and the oil sands-derived products reached specific gravities between 0.98 and 1.01 at 15°C. This indicates a risk of these oils in a weathered state becoming temporarily submerged or over-washed with wave action in fresh water, a conclusion subsequently confirmed in the recirculating flume tests (see following).
- **Viscosity**
  - The small-scale test results showed that any heavy oil, conventional or oil sands-derived, can become very viscous over a short period of time, emphasizing the importance of rapid response and selection of an appropriate recovery system (e.g. skimmers, pumps) designed to deal with viscous oils.
- **Pour Point**
  - In many cases the pour point was measured to drop below 10°C by WS-3. It may take 5-7 days of environmental exposure to reach this level in the event of a spill on water (or even longer time as weathering slows with lower temperatures). Once the pour point threshold is reached the behaviour of the oil will change and a modification of equipment (supplemental heat) or other techniques may be warranted for dealing with oil that is highly resistant to flow.
- **Emulsification**
  - Data showed that the two lightest products, condensate and SYN, were the only oils unlikely to emulsify in either a fresh or weathered state.
  - Light to medium crudes are unlikely to emulsify until they reach a highly weathered state after a few days.
  - Heavy oils and oil sands-derived crudes are very likely to form unstable to meso-stable emulsions with water contents over 50 percent in a fresh state, and to form emulsions with lower water contents as they rapidly weather. As weathering continues, these oils (including CHV and HFO) quickly become too viscous to emulsify any further.

2. <u>Comparison of different laboratory evaporation methods</u>
   - The different methods may arrive at a target endpoint at different times, but once a common target mass loss is reached, physical properties of the remaining oil sample were found to be remarkably consistent, irrespective of the technique used to generate the desired mass loss.

3. A study of <u>oil-particle interactions</u> used a small-scale shaking flask apparatus to determine the propensity of each oil to bind with sediment, forming what are known as oil-mineral aggregates (OMAs). These are oil droplets stabilized by fine mineral particles in the water column, thereby potentially removing oil from the surface.
   - At moderate turbulence levels (160 rpm) and particle concentrations (500 mg/L), on average, less than 6 percent of the oil on the surface was agglomerated and transferred into the water column as part of OMA (so called "removal rate"). This rule of thumb applied across all of the oil types from light or heavy conventional crudes to a wide range of oil sands-derived crudes.
   - At high turbulence levels (200 rpm) and particle concentrations (1,500 mg/L) a small number of the tests resulted in oil removal rates between 20 percent and 60 percent, while one run with

ANS crude saw 90 percent and one run with SYN resulted in 92 percent removal. However, these elevated results occurred with particle concentrations at the extreme end of conditions expected in a natural environment with high turbulence and sediment loads such as might be found for short periods of time in a fast-flowing river during spring freshet.

4. Long-term Flume Weathering Tests used on-water weathering in a recirculating flume, representing a more "realistic" weathering environment than the wind tunnel employed in the small-scale tests. Results support conclusions drawn from the small-scale physical properties data, specifically:
   - All of the test oils are expected to remain floating in marine (saltwater) environments in any of the weathering states tested in the flume tank. However, scenarios involving highly turbulent water with suspended sediments or stranded oil being refloated after picking up beach material could increase the risk of submergence for any oil.
   - Light and medium oils continued to float in fresh water as their specific gravity remained less than 1.0 g/mL even after the long duration test runs (minimum 5 days).
   - Heavy oils (conventional and non-conventional) weathered to have specific gravities very close to or equal to neutral buoyancy in freshwater (e.g. 0.98 to 1.02) within a few hours to days. This characteristic makes them more susceptible to temporary submergence/over washing and entrainment in the natural environment. It is important to note that a density slightly greater than 1.0 does not mean that large portions of a weathered oil slick will necessarily sink. Blobs of oil may separate and submerge from under the main slick but slightly negatively buoyant oil mats with entrained air bubbles were observed to remain floating in the recirculating flume for extended periods of time.
   - The potential for entrainment in the water column through an uptake of suspended sediments is not unique to oil sands-derived crudes and can occur for medium to heavy crudes and fuel oils. The only oils substantially affected by the addition of sediments to the flume tank in these tests was the Heavy Fuel Oil (HFO) during a cold temperature run. In that case, noticeable submergence occurred at the 1-hour mark in the cold water run.

5. Porous Media Tests determined the depths of penetration of each of the oils when spilled onto three soil types: small pebbles, sand, and loamy soil. Results showed that:
   - The most viscous oils (e.g. HFO) displayed the lowest penetration and the least viscous oils (notably CDW, NDB and SYN) penetrated the furthest. The six heaviest oils including conventional crude and oil sands-derived crudes showed no significant pattern in terms of penetration depths vs. oil type.
   - The pea gravel had no significant retention capacity for any of the oils in the test column, indicating that a spill on fine-grained gravel would penetrate quickly as confirmed in the shoreline adhesion tests.

6. Shoreline Adhesion Tests used a wave tank and artificial "beach" to determine the propensity of the oil to adhere to two different beach substrates after being subjected to low rolling waves and higher breaking waves.
   - Light and medium oils were more susceptible to lifting off and relocating laterally. In a natural environment, this behaviour could theoretically result in the oil dispersing into the water column as well as causing lighter shoreline oiling over a larger area.
   - Heavy oils (higher viscosity) were less susceptible to relocation resulting in a more concentrated shoreline oiling over a smaller area.

- The more viscous oils (e.g. HFO) tended to have a stabilizing effect on the small substrate (acting as a kind of glue). In other words, the oil tended to hold the substrate together which lessened the effect of the waves.

5 SUMMARY

Fresh oil sands-derived crudes are similar to heavy conventional crude and fuel oils in their physical characteristics. Proven response equipment developed over several decades is readily available to deal with the high viscosities of weathered heavy oils such as HFO, CHV, and oil sands- derived crudes, even as viscosity exceeds 100,000 cP (centipoise).

Heavy conventional and unconventional oils may reach a density close to or equal to neutral buoyancy in fresh water which makes them more susceptible to temporary submergence/over washing and entrainement but not inevitably to sinking. In specific scenarios, the partially upgraded oil sands product sank in fresh water at 20°C, as did the heavy fuel oil at 0°C. None of the oils tested were likely, or observed, to submerge or sink in the saltwater runs under the conditions tested.

Data generated in this project covers the full spectrum of expected behaviours for a wide range of oils. In particular, results show that oil sands-derived crudes (including dilbits) do not exhibit unusual characteristics that would substantially affect decisions to use oil spill response strategies already developed to deal with a wide range of spill-related scenarios and oil types.

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