STATUS REPORT ON THE KNOWLEDGE OF THE FATE AND BEHAVIOUR OF DILUTED BITUMEN IN THE AQUATIC ECOSYSTEMS

Context

Effective spill response depends on a good scientific understanding of the fate and behaviour of a specific product when it is released into the environment (e.g., changes in physical properties and chemical composition that influences its environmental persistence and potential biological effects). As part of the Government of Canada's (GOC) strategy to implement a world class prevention, preparedness and response regime, investments into Fisheries and Oceans Canada (DFO), Environment and Climate Change Canada (ECCC), and Natural Resources Canada (NRCan) have been made to conduct research on diluted bitumen fate, behaviour and biological effects when spilled into aquatic environments under climatic conditions relevant to a Canadian context.

These research investments are ongoing over a period of years; however, in advance of the publication of final findings, it is important that the aforementioned government agencies share and exchange new information; validate their work against industry-led initiatives; and work to make interim knowledge available in support of a robust and leading-edge emergency response regime.

The overarching objective of this Science Response Process (SRP) was to summarize information that has been obtained to date about the fate, behaviour, biological effects, and mitigation techniques for diluted bitumen in order to inform future research work; support current and future emergency response planning/preparedness and operations; as well as to inform the public about recent findings. Collectively, the group of meeting participants sought to respond to the following questions:

1. What is diluted bitumen and how does its composition vary between gathering lines within Alberta, and transmission pipelines that carry diluted bitumen out of Alberta?
2. What do we know about diluted bitumen behaviour when spilled under which defined conditions? What environmental conditions or other factors influence their behaviour when spilled?
   a. Real-world spill experience (e.g. Kalamazoo, MI spill, Gogama, ON spills, North Saskatchewan River, SK spill, etc.)
   b. Results of laboratory and meso-scale studies
3. What do we know about the effectiveness of response options to treat diluted bitumen spills? What environmental conditions or other factors influence their effectiveness?
   a. Are conventional crude oil spill response countermeasures effective for diluted bitumen spills?
   b. Is the countermeasure "time window-of-opportunity" for diluted bitumen different than for conventional crudes?

4. Are the products currently being tested a fair representation of what is being transported throughout Canada?
5. What are the priority gaps in knowledge related to diluted bitumen, and what are their implications for spill response and recovery?
6. Compare the relative risks of diluted bitumen to conventional crudes if spilled into ecologically sensitive areas under which defined conditions?
7. What analytical methods need to be updated to improve their accuracy and precision for predicting crude behavior including heavy oils?
8. How do responders access GOC knowledge to obtain the information needed during a spill event?
9. How can GOC scientists obtain samples and technical information from spill events to benchmark tank- and lab-scale results?

This Science Response results from the Science Response Process held on April 19th and 20th, 2017 in Ottawa, Ontario providing a status report on the knowledge of the fate and behavior of diluted bitumen in the aquatic ecosystems. As part of the process, information was presented by DFO, ECCC, NRCan, government agencies from outside Canada, industry and response organizations. A SRP meeting format was used because this is an interim update in advance of publication of final research results.

Analysis and Response

In order to support answering each of the nine (9) questions posed to meeting participants, presentations were made focusing on the most recent industry updates, real-world spill incidents, and recent research findings, including those from unpublished science. Summaries from these presentations can be found in the proceedings for the SRP.

Following the presentations, two breakout groups were formed to consolidate the information presented, discussed and recently observed. The first group populated a table summarizing information from recent spill incidents into the aquatic environment. The table (Table 1 below) provides a consolidation of information about: incidents, products, volumes, fate and behaviour, key conditions that may have influenced the fate and behaviour, as well as clean-up methods used. An analysis of this information was not feasible within the time allotted for this process; however, such an exercise would be beneficial in the future. The second group populated a table summarizing preliminary results from recent meso-scale lab experiments. The table (Table 2 below) provides a consolidation of information about the study: methodology, parameters, products tested and overall results or outcomes. This table also includes an initial characterization of the potential implications the research findings could have on operational response options. A more in-depth analysis of the information was not feasible within the time allotted for this process; however, such an exercise would be beneficial in the future.

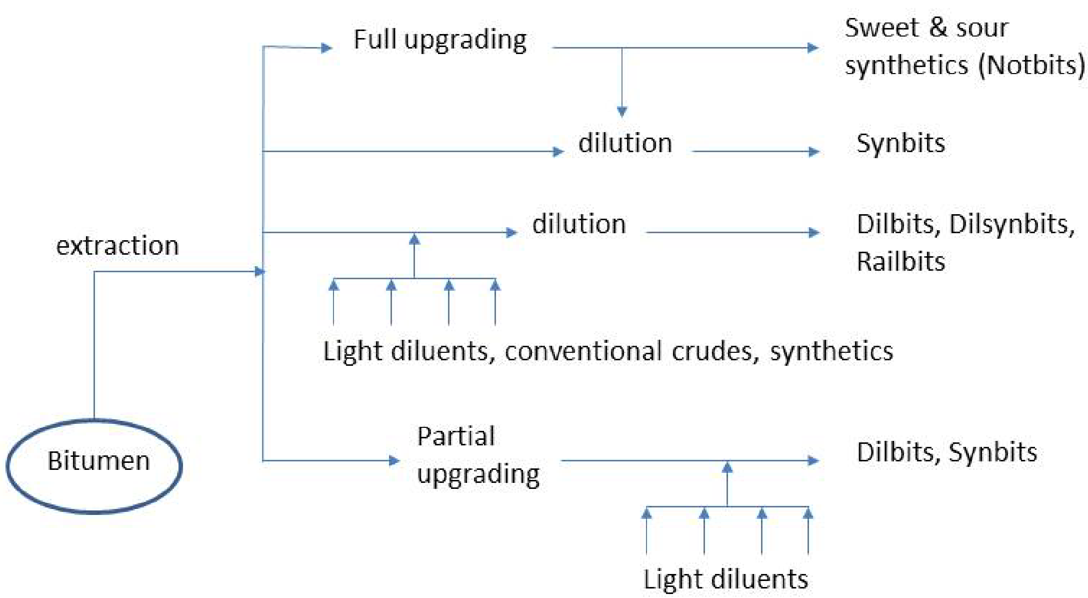
The responses/conclusions of the SRP are as follows:

1. What is diluted bitumen and how does its composition vary between gathering lines within Alberta, and transmission pipelines that carry diluted bitumen out of Alberta?

Bitumen is oil that does not flow at reservoir conditions. In Canada, bitumen is oil that is extracted from the northern region of Alberta and Saskatchewan, and then blended with diluent to make diluted bitumen that meets pipeline density and viscosity specifications for transportation.

Inland, bitumen and its diluted derivatives are transported by pipelines, trains and trucks. In most cases, as it relates to pipelines, it flows from gathering lines near the extraction sources (northern region of Alberta and Saskatchewan) towards regulated transmission lines. Research completed by DFO, ECCC and NRCan has only focused on the standardized product that would be found in the regulated transmission lines. Subsequently, only those were discussed in the context of this SRP; however, it is acknowledged that the gathering lines may transport products that do not meet the market specifications. Standard response methods may need to be further refined for any products spilled from gathering lines; however, those are not covered as part of this Science Response.

For the purposes of this Science Response, diluted bitumen refers to a variety of products with varying names, as described within Figure 1. The focus of the SRP was on diluted bitumen products (as presented in Figure 1), and the examination of synbits and synthetics was considered external to this discussion but convention crude behaviour was included for reference.



Extraction includes, but is not limited to, mining and mineral separation, Steam Assisted Gravity Drainage (SAGD) and its variants, pure solvent processes, non traditional thermal processes (e.g. microwaves), polymer floods
Full upgrading includes hydrogen addition and/or carbon rejection followed by distillation to produce intermediates that are blended to form a bottomless synthetic crude oil
Light diluents include streams having a density below 760 kg/m³ (commonly referred to as condensate or condensate blends)
Partial upgrading can include deasphalting and/or thermal processes. These processes materially change the physical properties of the native bitumen, making the final product lighter (lower density)

Figure 1: General Creation Pathways for Diluted Bitumen from the Northern Region of Alberta and Saskatchewan (Source: B. Lywood 2017)

2. What do we know about diluted bitumen behaviour when spilled under which defined conditions?

A summary of the information presented and discussed as part of the SRP was compiled into Tables 1 and 2 (below). A further comparative analysis of both real-world and laboratory experiments is required in order to: leverage existing knowledge; highlight information gaps and priority research areas; and support informed decision making processes.

a. Real-world spill experience

A comparative summary of the information relevant to product fate, behaviour and response options resulting from real-world spill experience is presented in Table 1. This table was compiled as part of the SRP, based on the knowledge and experience of the meeting participants. Further analysis of this information, relative to the meso-scale experiments (Table 2) is warranted in order to better understand the variability in environmental factors that may have influenced the observed behaviours; validate the lab results; and highlight priority research areas.

b. Results of laboratory and meso-scale studies

Both government agencies and industry are currently conducting meso-scale laboratory studies in an effort to better understand and predict the fates and behaviours of diluted bitumen products in the field. Recent research has examined freshwater and saltwater conditions, over variable time scales and using a variety of lab-based methods. A summary of these preliminary findings, as well as the potential implications for response options is presented in Table 2 below. This table was compiled as part of the SRP, based on the knowledge of, and presentations made, by meeting participants. A comprehensive analysis of this information, in comparison to the fates and behaviours observed during real world events (summarized in Table 1) is warranted to validate lab results and identify priority research areas for future work.

Table 1: Comparative Overview of Some Recent Oil Spill Incidents into the Aquatic Environment

Incident (Year) and Type	**Product (Volume in cubic metres [m^3])**	**Initial Fate**	**Subsequent Fates/ Behaviours**	**Clean-up Methods**	**Key Conditions**
St. Clair River Sarnia, Ontario (2003) Barge transfer operation	Asphalt-flux (2.4 m^3)	Light sheening, tendrils through water column, clumps on the bottom	Sank	• Surface recovery – sorbent • Mechanical containment - booms • Water bed recovery – manual and mechanical	• Fresh water river system • Warm weather conditions • Product state changed with temperature
Lake Wabamum, Alberta (2005) Train derailment	Bunker C (730 m^3)	Floated	Tar logs on shore that remobilized	• Surface recovery – skimmers & sorbent • Mechanical containment – booms • Shoreline – vegetation cutting including near shore sunken oil	• Fresh water lake • Wave influence • Integration of fine sediment • Water temperature near pour point • Buoyancy of oil influenced by temperature (thermal cycling)
Westridge, British Columbia (2007) Pipeline rupture (Construction unrelated to pipeline caused rupture)	Albian Heavy Synthetic Crude (232 m^3) [a partially upgraded dilbit]	Floated	Formed tar balls	• Surface recovery – skimmers, vacuum truck & sorbent • Mechanical containment – booms • Shoreline – flushing and surface washing agent (Corexit 9580)	• Saltwater estuary • Rapid containment • Land-based incident that influence the level of preparedness and the marine impacts

Incident (Year) and Type	Product (Volume in cubic metres [m^3])	Initial Fate	Subsequent Fates/ Behaviours	Clean-up Methods	Key Conditions
Kalamazoo, Michigan (2010) Pipeline rupture	Diluted Bitumen (Cold Lake, Western Canada Select) (3,200 m^3)	Floated and became entrained	Formation of oil-mineral aggregates. Submerged and suspended but easily remobilized with persistent sheening	• Surface recovery – skimmers, vacuum truck and sorbent • Subsurface recovery – modified boom with snare and netting • Waterbed recovery – dredging, agitation toolbox (sediment mixing ineffective) and draining /excavation of sediments • Shoreline – vegetation cutting, manual and mechanical removal	• Fresh water river system • Wide, shallow, low energy system with dams impoundments • Variable turbulence • Warm water temperature • Flooded over banks • Low suspended sediments concentration
North Saskatchewan River, Saskatchewan (2016) Pipeline rupture	Saskatchewan Crude (225 m^3)	Floated and significant shoreline contamination	Floated (predominantly), subsequently submerge and sank	• Surface recovery – mechanical • Shoreline – flushing and manual removal	• Freshwater river system • Warm weather conditions • Heavy sediment • High energy system

Incident (Year) and Type	**Product (Volume in cubic metres [m^3])**	**Initial Fate**	**Subsequent Fates/ Behaviours**	**Clean-up Methods**	**Key Conditions**
Lac Megantic, Quebec (2013) Train derailment and subsequent fire	Bakken Crude (5,600 m^3) [conventional light sweet crude oil - not dilbit]	Floated	Became entrained in bottom sediment	• Surface recovery – sorbent and skimmers • Shoreline – flushing and manual removal • Waterbed recovery – agitation , manually and by pressurised water	• Freshwater lake and river system • Fluctuating water levels with control dams
Gogama, Ontario (2015) Train derailment and subsequent fire	Sweet Synthetic Crude (1,300 m^3) [not dilbit]	Floated and became trapped under ice	No change from initial fate	• Surface recovery – skimmers, vacuum truck & sorbent in ice conditions • Mechanical containment – booms and ice slotting • Ice conditions/ subsurface identification of oil using modified gabion baskets filled with oil snares	• Freshwater river system • Winter conditions

Note: Other spills of diluted bitumen and/or closely related hydrocarbon products that were noted but not discussed in detail and could be considered for future reviews include the following:

1. March 2013 rupture of the Pegasus Pipeline in Mayflower, AR releasing Wabasca Heavy dilbit into Dawson Cove of Lake Conway;
2. July 2011 rupture of the Silvertip Pipeline in Laurel, MT releasing Cold Lake dilbit into Yellowstone River; and
3. November 2004 rupture of the Athos I in Paulsboro, NJ releasing Venezuelan diluted extra heavy crude into Delaware River.

Table 2: Comparative Summary of Meso-Scale Lab Experiments Completed by Fisheries and Oceans, Natural Resources Canada, Environment and Climate Change Canada and the US Geological Survey

Water Type	Study Method	Oil Type	Time Scale	Temperature		Energy	Sediments	General Results / Outcomes / Key Considerations	Implications for Response Options	Dispersants Used	Treatments
				Air	Water						
Saltwater	Wave Tank	DB (AWB & CLB)	1 hour	Seasonal (outdoor facility)	Temperature ~8 ˚C and ~17 ˚C	Breaking and non-breaking waves	Kaolin 50 g/L	Mineral fines had a minor impact on droplet size; no OMA formed over short periods of mixing; no oil dispersion with non-breaking waves	Need high mixing energy to disperse oil	Yes	Kaolin 50 g/L +/- Corexit 9500A
Saltwater	Wave Tank	DB (AWB & CLB)	1 hour	Seasonal (outdoor facility)	Temperature > 15˚C and < 8˚C	Breaking waves	N/A	Dispersant more effective in warmer water; oil viscosity affects dispersion	Dispersants may be an effective response option in marine environments; however, window of opportunity may be limited	Yes	Dispersant DOR 1:10, 1:20 (Corexit 9500A, SPC 1000)
Saltwater	Wave Tank	DB (AWB & CLB)	4 hour	Seasonal (outdoor facility)	Temperature < 10 ˚C and > 10 ˚C	Breaking waves	Sediment 15 ppm	No OMA formed over short time scale, flocculation of sediment particles impacted by presence of dispersant	May need longer interaction time for OMA formation, dispersants may reduce sedimentation	Yes	Dispersant DOR 1:10
Saltwater	Flume Tank	DB (AWB & CLB)	2 weeks	Seasonal (outdoor facility)	Temperature > 15˚C and < 8˚C	Surface currents, wind, sunlight	N/A	Significant increase in density and viscosity in first 24 hours; some products reached a density where they would sink in freshwater after 14 days; slick thickness impacts the rate of weathering and dissolution	Rapid loss of light ends limits window of opportunity for certain countermeasures, increased potential to sink and interact with sediments	No	Natural weathering
Seawater	Baffle Flask	DB (AWB & CLB)	20 hours	Room Temperature (~20˚C)	Room Temperature (~20˚C)	High	15 to 50 ppm sediment	OMA formation - larger particles, faster settling at higher concentrations	Potential for OMA formation in field with high energy and longer interaction at environmentally relevant sediment loading	Yes	Dispersant DOR 1:20
Fresh Water	Test Tank (1200 L)	DB	8 days	18.4˚C	15.0˚C	Cycling 2 days breaking waves and 2 days no waves	2000 ppm North Saskatchewan River sediment	Oil floated and little dispersed into water or sediment. KF results showed 32% water in oil collected	High oil recovery from water surface; low loss to water and sediment	No	N/A
Fresh Water	Test Tank (1200 L)	CC	8 days	18.8˚C	14.3˚C	Cycling 2 days breaking waves and 2 days no waves	2000 ppm North Saskatchewan River sediment	Oil dispersed into water and sediment and trapped in the sediment	Low oil recovery from water surface; high loss to water and sediment	No	N/A
Fresh Water	Test Tank (1200 L)	DB	8 days	20.1˚C	24.6˚C	Cycling 2 days breaking waves and 2 days no waves	2000 ppm North Saskatchewan River sediment	Most of the oil remained floating on the water. Oil contained ~50% water. Water was turbid	High oil recovery from water surface; low loss to water and sediment	No	N/A

Water Type	Study Method	Oil Type	Time Scale	Temperature		Energy	Sediments	General Results / Outcomes / Key Considerations	Implications for Response Options	Dispersants Used	Treatments
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Fresh Water	Test Tank (1200 L)	DB	8 days	20.1˚C	25.1˚C	Cycling 2 days breaking waves and 2 days no waves	2000 ppm North Saskatchewan River sediment	Most of the oil remained floating on the water. Oil contained ~30% water. Water was turbid	High oil recovery from water surface; low loss to water and sediment	No	N/A
Fresh Water	Test Tank (1200 L)	DB	30 days	14.3˚C	15.4˚C	Cycling 2 days breaking waves and 2 days no waves	2000 ppm North Saskatchewan River sediment	Oil separated into blobs, drops and strings. Oil was either dispersed in water or remained floating on water. Water was quite turbid	High to medium oil recovery from surface over time period; low to medium loss to water and sediment over time period	No	N/A
Fresh Water	Test Tank (1200 L)	DB	30 days	14.7˚C	15.3˚C	Cycling 2 days breaking waves and 2 days no waves	2000 ppm North Saskatchewan River sediment	Oil formed large, stable blobs on surface of sediment. Not much oil remained on water surface	High to medium oil recovery from surface and low to medium loss of oil to water and sediment up to 21 days; low oil recovery from surface and high loss to water and sediment after 21 days	No	N/A
Fresh Water	Test Tank (1200 L)	CC	8 days	9.3˚C	14.6˚C	Cycling 2 days breaking waves and 2 days no waves	2000 ppm North Saskatchewan River sediment	Oil formed a mousse on surface of water. Water very dark brown; oil dispersed in water column. Lots of oil trapped in sediment	Low oil recovery from surface throughout time period; high loss to water and sediment throughout time period	No	N/A
Fresh Water	Rotary Agitation (600 mL)	DB, CC	7 days	20 to 24˚C	20 to 24˚C	47 RPM for 12 hours, then left motionless for 1 week	None	Both DB and CC floated throughout test period in a closed system. Floating DB formed a water-in-oil emulsion containing ~ 75% water; floating CC did not. DB resulted in water with high turbidity; CC resulted in water with low turbidity. Deasphalted DB behaved similarly to CC	Recovered DB will have a higher water content and will be more viscous than recovered CC or deasphalted DB	No	N/A
Fresh Water	Rotary Agitation (600 mL)	DB, CC	7 days	20 to 24˚C	20 to 24˚C	47 RPM for 12 hours, then left motionless for 1 week	2000 ppm North Saskatchewan River sediment	Both DB and CC floated throughout test period in a closed system. Floating DB formed a stable water-in-oil emulsion containing ~50% water; floating CC did not. DB resulted in water with moderate turbidity; CC resulted in water with low turbidity	Recovered DB will have a higher water content and will be more viscous than recovered CC	No	N/A

Water Type	Study Method	Oil Type	Time Scale	Temperature		Energy	Sediments	General Results / Outcomes / Key Considerations	Implications for Response Options	Dispersants Used	Treatments
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Saltwater	Rotary Agitation (600 mL)	DB, CC	7 days	20 to 24˚C	20 to 24˚C	47 RPM for 12 hours, then left motionless for 1 week	None	Both DB and CC floated throughout test period in a closed system. Floating DB formed a stable water-in-oil emulsion containing ~ 65% water; CC did not. Both DB and CC resulted in water with low turbidity	Recovered DB will have a higher water content and will be more viscous than recovered CC	No	N/A
Saltwater	Rotary Agitation (600 mL)	DB, CC	7 days	20 to 24˚C	20 to 24˚C	47 RPM for 12 hours, then left motionless for 1 week	2000 ppm North Saskatchewan River sediment	Both DB and CC floated throughout test period in a closed system. Floating DB formed a stable water-in-oil emulsion containing ~ 65% water; CC did not. Both DB and CC resulted in water with low turbidity. DB resulted in more sunken "tar balls" than CC	Recovered DB will have a higher water content and will be more viscous than recovered CC	No	N/A
Fresh Water	Rotary Agitation (600 mL)	DB, CC	7 days	20˚C and 30˚C	20˚C and 30˚C	Breaking waves: 38.7 RPM & 55.4 RPM for 12 hours, then left motionless for 1 week	2000 ppm Diatomaceous Earth and Sand	CC dispersed more into water than DB and was seen trapped in the sediment at the bottom of the jar. DB had a higher water content. DB contained ~65% water and CC contained ~14% water. Water was very turbid	Recovered DB will have a higher water content and will be more viscous than recovered CC	No	N/A
Saltwater	Rotary Agitation (600 mL)	DB, CC	7 days	20˚C and 30˚C	20˚C and 30˚C	Breaking waves: 38.7 RPM & 55.4 RPM for 12 hours, then left motionless for 1 week	2000 ppm Diatomaceous Earth and Sand	DB and CC floated above water. DB formed round OMAs while CC mixed into the sediment. DB had a higher water content. DB contained ~62% water and CC contained ~9% water. Water was relatively clear	Recovered DB will have a higher water content and will be more viscous than recovered CC	No	N/A
Saltwater	Rotary Agitation (600 mL)	DB	7 days	20˚C and 30˚C	20˚C and 30˚C	Rolling waves: 2.3 RPM & 8.2 RPM for 12 hours, then left motionless for 1 week	2000 ppm Diatomaceous Earth and Sand	DB floated above water. OMA formation was very prominent (flakes and drops). Water content in floating oil was ~30%. Water was clear	Recovered DB will have a higher water content and will be more viscous than recovered CC	No	N/A

Water Type	Study Method	Oil Type	Time Scale	Temperature		Energy	Sediments	General Results / Outcomes / Key Considerations	Implications for Response Options	Dispersants Used	Treatments
				Air	Water						
Fresh Water	Rotary Agitation (600 mL)	DB, CC	10 days	22 ± 2˚C	22 ± 2˚C	16.4 RPM for 12 hours, then left motionless for 10 days	Sand / 2000 ppm	Both DB and CC floated throughout test period in a closed system. Higher turbidity was obtained for CC compared to DB. CC and DB formed similar types and amounts of sand-oil aggregates	Recovered DB will have a higher water content and will be more viscous than recovered CC	No	N/A
Fresh Water	Rotary Agitation (600 mL)	DB, CC	10 days	22 ± 2˚C	22 ± 2˚C	16.4 RPM for 12 hours, then left motionless for 10 days	Sand / 5000 ppm	Both DB and CC floated throughout test period in a closed system. For both oils, turbidity was lowered than that obtained at sand content of 2000 ppm due to greater amount of spherical aggregate formation	Recovered DB will have a higher water content and will be more viscous than recovered CC	No	N/A
Fresh Water	Rotary Agitation (600 mL)	DB, CC	10 days	22 ± 2˚C	22 ± 2˚C	33.1 RPM for 12 hours, then left motionless for 10 days	Sand / 2000 ppm	Both DB and CC floated throughout test period in a closed system. CC had higher turbidity than DB and was similar to that found at 16.4 RPM. Only CC formed significant amount of aggregates that were highly variable in size	Recovered DB will have a higher water content and will be more viscous than recovered CC	No	N/A
Fresh Water	Rotary Agitation (600 mL)	DB, CC	10 days	22 ± 2˚C	22 ± 2˚C	33.1 RPM for 12 hours, then left motionless for 10 days	Sand / 5000 ppm	Both DB and CC floated throughout test period in a closed system. For both oils, turbidity was lower than that found with 2000 ppm sand. Amount of sand-CC aggregates increased but were more uniform and spherical shape than found when sand content was 2000 ppm	Recovered DB will have a higher water content and will be more viscous than recovered CC	No	N/A

Water Type	Study Method	Oil Type	Time Scale	Temperature		Energy	Sediments	General Results / Outcomes / Key Considerations	Implications for Response Options	Dispersants Used	Treatments
				Air	Water						
Fresh Water	Rotary Agitation (600 mL)	DB, CC	10 days	22 ± 2˚C	22 ± 2˚C	55.6 RPM for 12 hours, then left motionless for 10 days	Sand / 2000 ppm	Both DB and CC floated throughout test period in a closed system. The turbidity of both oils was higher than that found at lower speeds but now the DB was more turbid than the CC. CC water phase was a transparent white color that was relatively stable over time. There was a significant reduction in aggregation for the CC	Recovered DB will have a higher water content and will be more viscous than recovered CC	No	N/A
Fresh Water	Rotary Agitation (600 mL)	DB, CC	10 days	22 ± 2˚C	22 ± 2˚C	55.6 RMP for 12 hours, then left motionless for 10 days	Sand / 5000 ppm	Both DB and CC floated throughout test period in a closed system. The turbidity of both oils was similar to that found at 2000 ppm sand where the DB was more turbid than the CC. Increasing sand content from 2000 ppm to 5000 ppm led to significant reduction in the amount of CC-sand aggregates	Recovered DB will have a higher water content and will be more viscous than recovered CC	No	N/A
Saltwater	Rotary Agitator Jars	DB, CC	12 hours	20˚C	20˚C	55 RPM	2000 ppm North Saskatchewan flood plain sediment	Water and sediment, an order of magnitude greater tar balls precipitate from the flocculation compared to conventional crude	DB emulsification could increase volumes of material to be recovered. Despite oil floating, tar balls would be dropped to the seabed	No	N/A
Fresh Water	Rotary Agitator Jars	DB	12 hour mixing followed by 1 hour rest	20˚C	20˚C	Rotary agitation at 47 RPM	None	The tendency of DB to disperse in water (conductivity = 100 µS/cm) was greater at pH = 10 ($[DB \geq 200°C]_{water}$ = 1.70 g/L) than at pH = 8 (0.15 g/L) or pH = 5 (0.13 g/L). The water content of the floating water-in-oil emulsion at pH = 5-10 was high (75-90 wt %), with higher water contents at lower pH and lower salinity	Containment and recovery may be most effective in water with high salinity, e.g., marine water, and low pH. Dispersion may be most effective in fresh water at high pH	No	N/A

Water Type	Study Method	Oil Type	Time Scale	Temperature		Energy	Sediments	General Results / Outcomes / Key Considerations	Implications for Response Options	Dispersants Used	Treatments
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Brackish Water	Rotary Agitator Jars	DB	12 hour mixing followed by 1 hour rest	20˚C	20˚C	Rotary agitation at 47 RPM	None	The tendency of DB to disperse in water (conductivity = 5,200 µS/cm) was greater at pH = 10 ($[DB \geq 200°C]_{water}$ = 0.95 g/L) than at pH = 8 (0.26 g/L) or pH = 5 (0.09 g/L). The water content of the floating water-in-oil emulsion at pH = 5-10 was high (75-90 wt %), with higher water contents at lower pH and lower salinity	Containment and recovery may be most effective in water with high salinity, e.g., marine water, and low pH. Dispersion may be most effective in fresh water at high pH	No	N/A
Marine Water	Rotary Agitator Jars	DB	12 hour mixing followed by 1 hour rest	20˚C	20˚C	Rotary agitation at 47 RPM	None	The tendency of DB to disperse in water (conductivity = 40,000 µS/cm) was greater at pH = 10 ($[DB \geq 200°C]_{water}$ = 0.22 g/L) than at pH = 8 (0.13 g/L) or pH = 5 (0.10 g/L). The water content of the floating water-in-oil emulsion at pH = 5-10 was high (75-90 wt %), with higher water contents at lower pH and lower salinity	Containment and recovery may be most effective in water with high salinity, e.g., marine water, and low pH. Dispersion may be most effective in fresh water at high pH	No	N/A
Saltwater	Small Mesocosm 15 cm columns	DB (AWB & CLB)	1 to 24 hours	15 to 20°C	10°C	Low energy tidal flushing	Coarse sand to cobbles with and without fucus and barnicles	Penetration of highly weathered DB is low across all substrate types (< 1 cm depth) but is high for the fresh oil. Following a simulated tidal cycle, retention is high for fresh and weathered DB on small pebbles, but low for fresh DB in a very coarse sand	Sediment characteristics including pore water content and oil weathering affects duration and impacts on shore	No	N/A
Fresh Water, specific conductance 450 µS/cm, pH 8.6	Rotary Mixer	DB, Heavy oil	12 hours	25°C	25°C	30 RPM followed by 24 hours settling after transfer of aqueous phase	North Saskatchewan River sediment, 10,000 mg/L; size distribution centred on 100 µm	Fresh and lightly weathered oil formed sediment-laden particulate that resurfaced in quiescent conditions. The particulate agglomerated, with denser components at the interface concentrating to form sinking globules. Small percentage fate	Sediment accumulation on particulate may result in formation of sinking globular forms when floating particulate collect and interact at the surface, resulting in riverbed impacts	No	N/A

Water Type	Study Method	Oil Type	Time Scale	Temperature		Energy	Sediments	General Results / Outcomes / Key Considerations	Implications for Response Options	Dispersants Used	Treatments
				Air	Water						
Saltwater	Rotary Mixer	DB (CLB Summer & Winter)	16 hours	0 and 15°C	0 and 15°C	55 RPM followed by 24 hours settling	10,000 mg/L Kaolin, sand, and natural Douglas Channel bottom sediment	Mixed with fine- and medium-sized sediments, the fresh to moderately weathered oils formed OPAs which sank in saltwater. Heavily weathered oil did not interact as much, instead forming discrete tarballs. Microscopic examination show that the OPAs consisted of oil droplets surrounded by sediment particles and were present in single or multiple droplets clusters. Density and particle size analysis reveal that the OPAs of oils with high viscosity tended to have higher densities and larger particle sizes. Aggregates of the natural sediment were consistently larger than those of the oil-Kaolin aggregates for the same oil	Oil weathering states as well as sediment particle size are important factors influencing formation of OPAs and the properties of OPAs with regards to density, and buoyancy in saltwater	No	N/A
Saltwater	Baffle Flask on Oscillating Table	DB (AWB & CLB)	10 min	0 and 15°C	0 and 15°C	200 RPM followed by 10 min settling	N/A	Dispersant effectiveness under high energy conditions is limited by a rheologic threshold. The influence of temperature and oil weathering are generally related to this property, although composition does factor into the degree of effectiveness	The window of opportunity for using dispersants may be very short due to the rapid change in DB properties with evaporation	Yes	1:25 dispersants

Water Type	Study Method	Oil Type	Time Scale	Temperature		Energy	Sediments	General Results / Outcomes / Key Considerations	Implications for Response Options	Dispersants Used	Treatments
				Air	Water						
Fresh Water, Specific conductance 640 µS/cm	Shaker / Epifluorescense	CLB	Constant:1 hour; Pulsed 5 minutes mixing, 2 minute rest, 3 minutes mixing and repeated	21/22˚C	21/22˚C	Conventional mixing and pulse mixing: 160, 180, 200 RPM	Kalamazoo River sediment, D16 7.6 µm, D50 29 µm, D85 84 µm (silty, mix of mineral and organic), 50 mg/L	Conventional mixing: weathered CLB formed relatively stable OPA droplet surrounded by particles attached to the surface. Some in aggregates of 2-3 droplets. Size of OPA = 5-100 µm. Pulsed mixing resulted in solid type OPA with sediment inside varying sizes and shapes of oil mass, typically > 1 mm common	OPA forms with low sediment concentration and silt-sized particles. Turbulent mixing In low energy rivers is adequate for oil droplet and OPA formation	No	N/A
Fresh Water, Specific conductance 305 µS/cm	Annular Flume	CLB	Variable, minutes	Room Temperature (~22/23˚C)	22/23˚C	River flows	Kalamazoo River sediment, D16 7.6 µm, D50 29 µm, D85 84 µm (silty, mix of mineral and organic)	Weathered CLB formed OPA formed entrainment similar to silt/sand sized particles. Range of critical shear stresses from 0.0057 (2 RPM, 13.6 cm/s) to 0.14 Pa (10 RPM, 68 cm/s) with OPA in full suspension and bedload	Resuspension of OPA in rivers may happen often with varying flows, carried along when silt is re-suspended	No	N/A
Fresh Water, Specific conductance 640 µS/cm	Settling Tank	CLB	Variable, minutes	Room Temperature (~21/22˚C)	21/22˚C	Quiescent	Kalamazoo River sediment, D16 7.6 µm, D50 29 µm, D85 84 µm (silty, mix of mineral and organic)	Tested both oil droplet and solid type OPA. Large range of settling rates depending on size and shape/arrangement of oil droplets and aggregates, settling rates of 1-11 mm/s with 1-3 mm/s most common	Once in river suspension, OPA can settle at different rates in the downstream direction depending on the wide range of types, sizes, and shapes	No	N/A

Acronyms :

%	percent
AWB	Access Western Blend
^{o}C	degrees Celsius
CC	conventional crude
CLB	Cold Lake Blend
cm	centimetre
cm/s	centimetre per second
D	diameter
DB	dilbit
DOR	dispersant to oil ratio (volume)

g/L	grams per litre
KF	Karl Fischer titration method
L	litre
mL	millilitre
mg/L	milligrams per liter
mm/s	millimetre per second
N/A	not applicable or not available
OMA	oil-mineral aggregates
OPA	oil-particle aggregates
Pa	Pascal
pH	potential hydrogen
ppm	parts per million
RPM	rotations per minute
µm	micrometre
µS/cm	microSiemen per centimetre
wt	weight

3. What do we know about the effectiveness of response options to treat diluted bitumen spills? What environmental conditions or other factors influence their effectiveness?

Prompt response actions are of upmost importance for any spill. It was agreed that conventional spill response countermeasures are as effective for diluted bitumen as they are for conventional oil products. The fate and behaviour of diluted bitumen is within the spectrum observed for conventional petroleum products but the routine adaptation of response tactics (e.g., the specific type of skimmer) may need to occur more rapidly. A greater understanding of fate and behaviour for diluted bitumen will help to better inform the tactical strategies for the deployment of specific countermeasures.

a. Are conventional crude oil spill response countermeasures effective for diluted bitumen spills?

Diluted bitumen exists within the broader continuum of petroleum products. Like conventional oil products, it has a range of potential fates within different environmental components (i.e., surface, bottom, water column, shoreline, atmosphere, etc.).

Conventional spill response countermeasures are similarly effective for diluted bitumen because its fate and behaviours remain within the existing range for conventional petroleum products. There is an acknowledgement that the viscosity and density changes more rapidly for diluted bitumen compared to conventional oil products due to evaporation losses and high, heavy-end content of the weathered oil. These changes in property mean that diluted bitumen may require a faster adaptation of routine response options for equipment (e.g., skimmers) designed for high viscosity heavy oils.

Response options will always be site-specific, as they are for any conventional oil spill and the sequencing of countermeasures will be based, in part, on a net environmental benefit analysis. Performance, as with conventional oil spills, will vary based on the current state of the product, which will change over the course of a spill.

Although new emerging technologies may improve efficiencies, no new response countermeasures are specifically required to address diluted bitumen because its fate and behaviour is within the range observed for other conventional oils, for which there exist response countermeasures.

b. Is the countermeasure “time window-of-opportunity” for diluted bitumen different than for conventional crudes?

It is acknowledged that quick, efficient and effective application of countermeasures is critical to the recovery of any spilled product. Although conventional crude oils may enter the water column and settle temporarily under specific conditions, the window-of-opportunity for using certain response options may be shortened.

Based on the behaviour observed during recent incidents (refer to Table 1) and laboratory experiments (Table 2), the window-of-opportunity for surface-focused countermeasures can range from less than 24 hours to weeks, depending on specific products and site-specific environmental conditions.

4. Are the products currently being tested a fair representation of what is being transported throughout Canada?

As noted above, the focus of the SRP was on diluted bitumen and the examination of synbits, and synthetics was considered external to this discussion.

Generally, the products being researched (refer to Table 2) cover the range of most commonly transported products in Canada; however, the scope of products could be further narrowed in order to support improved comparative analysis between studies.

Access Western Blend (AWB) and Cold Lake Blend (CL) have been used in a number of studies conducted to date. In general, these two diluted bitumen blends reasonably represent the “normal” chemical and physical characteristics of diluted bitumen used and transported in Canada. It is recommended that AWB and CL continue to be the primarily tested diluted bitumen blends. Should an expansion of the researched diluted bitumen blends be considered, based on the volume of product shipped and the compositional differences that result in a range of physical and chemical properties for diluted bitumen, it is suggested that the following additional blends be examined (by order of priority): Borealis Heavy Blend (BHB), Seal Heavy (SH) and Wabasca Heavy (WH).

5. What are the priority gaps in knowledge related to diluted bitumen, and what are their implications for spill response and recovery?

The following is a summary of the knowledge gaps and operational support tools that were noted by meeting participants during the SRP. The majority of the identified knowledge gaps relate to environmental settings and characteristics that affect the fate and behaviour of the diluted bitumen blend. The lists are not ranked by priority and should not be considered exhaustive; instead, they highlight opportunities for future work.

Additional research is required to better understand:

- The fate and behaviour of diluted bitumen under low temperature and ice conditions;
- Physical, chemical and environmental processes that most influence diluted bitumen fate and behaviour;
- Natural weathering processes;
- Impacts of degradation and weathering on toxicity;
- The vulnerability of species to diluted bitumen blends;
- Methods to detect, track and monitor product movement when spilled;
- Processes for the formation and breakup of oil-mineral aggregates in the environment; and
- Further analysis of hydrocarbon composition present in fresh and weathered diluted bitumen blends.

Operational tools required to enable the integration of scientific research into emergency response planning, preparation and operations:

- Countermeasure decision tree that considers the most influential factors for diluted bitumen fate and behaviour;
- Support tools for the net environmental benefit analysis (including the evaluation of natural attenuation as a shoreline clean-up strategy);
- More robust and comprehensive predictive models (including improvements to mass balance models);
- Summaries of the characteristics of the AWB and CL diluted bitumen blends; and
- Simplified, comparative categorizations of known diluted bitumen blends.

6. Compare the relative risks of diluted bitumen to conventional crudes if spilled into ecologically sensitive areas under which defined conditions?

As noted above, diluted bitumen generally has similar chemical and physical properties as other conventional petroleum products; however, its viscosity and density can change more rapidly which can necessitate a faster adaptation of response actions towards equipment (e.g., skimmers) designed for high viscosity heavy oils and being aware of the window-of-opportunity for the potential use of dispersants. For this reason, the potential risk of toxic compounds within diluted bitumen, as compared to other conventional crude products, is comparable to other oil products. However, the rate at which the toxic compounds reach a specific environmental component (e.g., shoreline) may be different. As with any spill incident, the relative risks to ecologically sensitive areas will be site and condition-specific.

7. What analytical methods need to be updated to improve their accuracy and precision for predicting crude behavior including heavy oils?

It was acknowledged by meeting participants that a number of analytical methods currently exist and the ongoing innovation and development of new technologies will continue to benefit the response regime. It was also noted that improvements to the following could help advance the accuracy and precision of predictive tools:

- Analytical tools that can measure a full range of product compounds;
- In-situ detection and monitoring techniques;
- Improvements to mass balance estimates and calculations;
- Standardized protocols for the analysis of physical properties of fresh and weathered crudes for use in spill behaviour modelling;
- Standardized analytical methods for the quantitative preparation of oil sub-fractions;
- Standardized analytical methods to quantify large, polar molecules; and
- Standardized analytical methods to address spatial and temporal variability.

8. How do responders access GOC knowledge to obtain the information needed during a spill event?

The GOC proactively plans and prepares for spills by:

- Establishing a response planning/preparedness network and working collaboratively across jurisdictions and boundaries;
- Activating a streamlined, regimented and standardized response framework; and by
- Supporting the development of expert capacities available during an incident.

The mechanism by which the GOC knowledge is accessed in response to a spill incident can vary slightly depending on the location and nature of the spill; however, in general, strategic technical advice is coordinated through ECCC's National Environmental Emergency Centre (NEEC). The NEEC provides support for environmental emergencies on a 24/7 basis and is the federal government agency that typically coordinates GOC stakeholder collaborations.

In response to an incident, to the extent possible, it is ideal to have access to the best, most accurate and most up to date information. For this reason, where appropriate, external stakeholders, including Indigenous groups can also be called upon to provide input. Similarly, as appropriate, relevant internal and external information resources will also be utilized (for example: databases such as Crude Monitor, open data posted on the Federal Geospatial Platform, Marine Traffic Shipping applications, crowd-sourced species tracking, etc.).

9. How can GOC scientists obtain samples and technical information from spill events to benchmark tank- and lab-scale results?

In response to an incident, there are a variety of activities happening concurrently. Most notably: the operational response to the spill and the regulatory enforcement process. In light of pending enforcement actions, it can be difficult to obtain consent from a polluter or the proprietor of a spilled product to release samples for scientific research.

While an ongoing discussion with industry and partners about the benefits of opportunistic research following a spill event are highly encouraged, there are also a number of challenges that need to be addressed (e.g., limitations of liabilities, limitations on the publication of results, potential conflicts with the enforcement actions, etc). For these reasons, meeting participants suggested the following as the most tangible mechanisms to validate tank and lab-scale results based on spill events:

- Participating in response actions and seeking opportunistic sampling opportunities;
- Accessing and learning from post-incident reports/summaries; and
- Participating in the review of lessons learned from incidents and integrating that knowledge into subsequent planning initiatives.

Conclusions

Diluted bitumen exists within the broader continuum of petroleum mixtures. Like conventional oil products, it has a range of potential fates within different environmental components (i.e., surface, bottom, water column, shoreline, atmosphere, etc.).

Existing response measures are effective on diluted bitumen, in general, to the same extent as they would be for other petroleum products of similar properties. The success of existing response measures may be enhanced through greater awareness of the fate and behavior of diluted bitumen to inform decision-making on how to best deploy countermeasures for the specific spill scenario, as well as the development of additional response tools to expand the available options.

Knowledge gaps exist that relate primarily to the environmental setting (e.g., rivers, lakes, marine, estuarine, etc.) and variables within these settings (e.g., temperature, water quality parameters, wind, wave, and currents) that affect the fate and behavior of the product. Improvements to the available response options are common to all spills of petroleum products. It is also acknowledged that there are related but distinct knowledge gaps related to environmental effects.

The following recommendations were made by meeting participants:

- Initiate additional research specific to freshwater and cold-water conditions is warranted. This will become even more relevant with the increased distribution of diluted bitumen across greater and more varied geographic areas;
- Undertake a consolidation and analysis of the information and lessons learned from past incidents against current research needs in order to identify knowledge gaps, prioritize research needs and continue to build research collaborations;
- Integrate available information into existing operational decision-making tools;

- Encourage the development of innovative response options to continue to improve response techniques on an ongoing basis and expand the available options where applicable; and
- Collaborate with industry to maximize the benefit and sharing of this information in order to enhance the ability to respond quickly because the window-of-opportunity for oil spills is so critical.

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