Floating Heavy Oil Recovery:
Current State Analysis

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US Coast Guard
Research and Development Center
1082 Shennecossett Road
Groton, CT 06340

Prepared by:

David Cooper
SAIC Canada
Environmental Technologies Program
335 River Road
Ottawa, Ontario
K1A 0H3

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To provide comments on this report or obtain additional copies please contact:

Kurt A. Hansen, P.E.
Spill Response Program Area Manager
US Coast Guard Research and Development Center
1082 Shennecossett Road
Groton, CT 06340
(860) 441-2865

EXECUTIVE SUMMARY

Spills of heavy oils behave differently than lighter oils which affects recovery operations and costs. The oils are typically viscous and sticky in nature, and may require specialized equipment to effectively and efficiently contain and recover. Heavy oil spills have traditionally been infrequent in nature, but the trend of frequency is slowly increasing. This trend, coupled with their greater impact due to response difficulties has led to this review of the technologies and techniques used to contain and recover floating heavy oils.

Technologies reviewed include pumps, containment strategies and equipment, skimmers, and storage with an emphasis on Coast Guard Vessel of Opportunity Spill Systems (VOSS) and Spilled Oil Response System (SORS). Research over the past five years has led to dramatic advances primarily in the pumping of heavy oils through the adaptation of steam/water injection systems on the inlet of pumps and annular water injection systems on the discharge end of pumps though some areas of investigation still exist. Additional advances have been made through the use of belt and brush adapters on weir skimmers commonly used by both the US and Canadian Coast Guards. Recent testing has demonstrated improvements in collection efficiencies which more than doubled the quantity of fluid being recovered while simultaneously reducing water up-take. These advances are helping to build heavy oil recovery capacity but target equipment areas still require additional development. Data gaps are identified and suggested areas of future research are summarized.

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1 INTRODUCTION

Heavy oil is usually viscous and can either sink, float, or remain neutrally buoyant and stay suspended in the water column when spilled. A number of factors can affect this behaviour and impact recovery efforts including water temperature, weathering, and emulsification over time. Recovery efforts when dealing with heavy oil are complicated by the behaviour of the oil when compared with lighter oils, and their impact is usually greater due to Coast Guard and industry inability to effectively and efficiently respond. Recent spills in U.S. waterways including the T/V ATHOS I spill in the Delaware River (November 2004) and the T/B DBL-152 in the Gulf of Mexico (November 2005), demonstrated that response capabilities for this class of oil is limited.

Continued efforts to detect and track heavy oil spills are hampered to some extent by inefficient and ineffective methods currently used to recover surface and subsurface oil. Current recovery methods include skimmers for surface spills and diver operated vacuum pumps and adsorbent snares attached to anchoring devices. The Coast Guard's Ocean Engineering Division (CG-432) has conducted a project on the Viscous Oil Pumping System (VOPS) but this only deals with the transfer of product that has already been collected and contained (Moffatt et *al.*, 2004). The Coast Guard Research and Development Center (RDC) has contacted CG-432 to share information and begin coordinating and aligning efforts.

2 PROJECT OBJECTIVE AND SCOPE

The overall project objective is to analyze and document the current state of technology for floating heavy oil recovery operations. This includes documenting lessons learned during recent heavy, viscous oil tests and a chemical characterization for floating heavy oil.

3 METHODOLOGY

A number of heavy oil tests have taken place over the past few years involving organizations such as:

- U.S. Coast Guard
- SAIC Canada/Environment Canada
- Canadian Coast Guard
- Ohmsett
- Navy/SupSalv
- Commercial manufacturers

Techniques and equipment used in these tests are reviewed from reports and discussions with personnel involved in the testing, with a specific focus on qualitative and quantitative improvements resulting from the tests.

Floating oil characteristics are also identified that correspond to the recent spill experiences and tests. In addition, weathered oil data and descriptive characteristics for floating oils are provided.

4 HEAVY OILS PROPERTIES

Heavy oils are defined as asphaltic, dense (low API gravity), and viscous oils that are typically composed of relatively low proportions of volatile compounds with low molecular weight such as benzene, toluene, ethylbenzene, and xylene (BTEX). They also typically contain some two ring napthalenes and high proportions of high molecular weight compounds. The high molecular weight compounds can be paraffins (straight chain alkanes), asphaltenes (aromatic-type hydrocarbon), resins and other compounds with high melting points and high pour points (Chevron, 2006 and Hollebone, 2006). Paraffins tend to act as solvent molecules for a mix of high molecular weight compounds and actually help improve the overall flow characteristics of the oil (viscosity). Some, but not all, heavy oils contain moderate to high levels of asphaltenes (Chevron 2006). These asphaltenes can become problematic if they precipitate out and build up on equipment.

The density of the oil is the result of a large proportion of a mixture of complex, high molecular weight, non-paraffinic compounds and a low proportion of low molecular weight, volatile compounds. Heavy oils typically contain very little paraffin and the quantity of asphaltenes can vary greatly (Chevron, 2006 and Hollebone, 2006).

A number of heavy oils have been characterized in past laboratory studies (Jokuty *et al.*, 1999; Wang *et al.*, 2002; and Wang *et al.*, 2004). The properties of studied oils are given in Table 1. A summary of recently-measured properties is shown in Table 2. Both Table 1 and Table 2 show that the properties of residual fuel oils and bitumens (including Orimulsion, a fuel comprised of approximately 70% bitumen, 30% water and a small quantity of surfactant) are relatively similar. Table 2 shows that the five oils compared in this table have very similar properties and composition in terms of hydrocarbon groups. In fact, in most cases, the properties are within 10% of each other despite the widely-separated origin and processes of preparation.

Heavy oils have been found to lose as much as 20% by mass through evaporation (Wang *et al.*, 2002), though heavy fuel oils such as Bunker 6 (Bunker C) types may only weather by a few percent (Jokuty *et al.*, 1999). Bitumens have been found to lose very little if any mass through evaporation. At the end-state of weathering, light ends ($<C_{20}$) are completely removed, and high-ring number PAH, asphaltenes, paraffins and resin components are enriched in the residual oil. Densities may approach or slightly surpass the density of fresh water 1.00 grams/millilitre (g/mL) or 62.4 lb/cubic foot, and viscosities may rise by two orders of magnitude or more.

Table 1 - Heavy Oil Properties

Heavy Oil Properties	Emulsion Formation				Chemical Dispersibility		Hydrocarbon Groups		
	Visual Stability	Viscosity (mPa·s)	Complex modulus (Pa)	Water content (wt%)	Corexit 9500	Corexit 9527	Saturates	Aromatics	Resins
Boscan							25	35	22
Bunker C Fuel Oil	entrained	110,000	720	26	7	0			
Bunker C Fuel Oil (Alaska) (fresh)	entrained	28,000	130	35	14		25	47	17
Bunker C Fuel Oil (Alaska) (%Ev=8)	unstable			6	6		23	42	20
Bunker C Fuel Oil (Irving Whale)							32	32	17
California (API 11)	entrained			35	0	0			
California (API 15)	entrained			39	0	0	19	35	23
Coal Oil Point Seep Oil	entrained	280,000	1,200	32			21	35	24
Cold Lake Bitumen	entrained		2,800	17			46	24	13
FCC Light Cycle Oil							17	58	4
FCC Medium Cycle Oil						60	30	62	7
Fuel Oil No. 5 (2000) (fresh)	stable		1,540	78	15		44	40	8
Fuel Oil No. 5 (2000) (%Ev=7)	stable		2,490	73	7		40	39	8
Heavy Fuel Oil 6303 (fresh)	entrained		752	58	9		43	29	16
Heavy Fuel Oil 6303 (%Ev=2)	entrained		984	24	6		39	27	17
High Viscosity Fuel Oil	entrained	74,000	310	48	0		18	43	13
Intermediate Fuel Oil 300 (fresh)	entrained	97,000	390	52	0		26	52	12
Intermediate Fuel Oil 300 (%Ev=5)	unstable				0		24	28	30
Marine Intermediate Fuel Oil									
Orimulsion 400 (2001) (wet)	unstable				100		32	20	10
Orimulsion 400 (2001) (dry)							45	27	13
Orimulsion-100 (fresh)									
Orimulsion-100 (%Ev=26)							17	47	16
Orinoco Bitumen	entrained		36,000	8			41	21	17
Platform Irene	entrained	390,000	1,400	62			26	29	22

(Jokuty *et al*., 1999; Wang *et al*., 2002; and Wang *et al*., 2004)

Table 2 - Selected Properties of Heavy Oils

		Cold Lake Bitumen	Orinoco Bitumen	Orimulsion-400	Fuel Oil #5		HFO 6303	
					0.00%	7.20%	0.00%	2.50%
Density (g/mL) @	0°C	1.0096	1.018	1.0155	1.0034	1.016	1.0015	1.0101
	15°C	1.0016	1.0166	1.0093	0.9883	1.0032	0.9888	0.9988
	20°C	0.9987	1.0141	1.0073	0.9884	0.9993	0.9853	0.9955
	30°C	0.9927	1.0083	1.0021	0.9818	0.9919	0.9783	0.9887
	40°C	0.9868	1.0024	0.9969	0.9752	0.9853	0.9722	0.9822
API Gravity		9.68	7.65	8.63	11.55		11.47	
Dynamic Viscosity (mPa•s)	0°C	1.08E+07	2.66E+08	3.30E+02	1.86E+04	7.20E+04	2.41E+05	3.60E+06
	15°C	8.25E+05	1.02E+07	2.56E+02	1.41E+03	4.53E+03	2.28E+04	1.49E+05
Flash Point (°C)		N.M.	146	N.M.	94	136	111	133
Pour Point (°C)		18	30	1	-19	-3	-1	11
Adhesion (g/m2)		570	1800	90	34	47	100	240
Hydrocarbon Groups (w/w)	Saturates	45.7	40.7	32.1	44.2	39.9	42.5	38.8
	Aromatics	24.1	21.5	19.7	39.5	39.1	29	26.9
	Resins	13.2	17	9.6	8	8.3	15.5	16.6
	Asphaltenes	16.9	20.8	10.6	8.4	12.8	13	17.7
Wax Content (w/w)		0.00%	0.00%	N.M.	2.30%	2.50%	2.50%	2.70%
Sulphur Content (w/w)		4.44%	3.86%	2.00%	1.00%	1.08%	1.48%	1.50%
Water Content (w/w)		11.80%	<0.1%	28.00%	3.10%	<0.1%	0.10%	<0.1%
Emulsion Formation	Visual Stability	Entrained	Entrained	Unstable	Stable	Stable	Entrained	Entrained
	Complex Modulus (Pa)	2800	36000		1590	2490	752	984
	Water Content (w/w)	17	8		78.3	72.8	57.7	24.1

(Hollebone, 2006)

4.1 Heavy Oils Behaviour

Heavy or high density oils (API gravity less than 22) are produced from residues of various refinery processes and primarily used to run boilers for power generation and to propel tankers and other large vessels (EIA, 2006). Similar to crude oils they continue to be shipped worldwide for consumption. The characteristics of high density oil when spilled, however, differentiate them from crude oils in the affect that their behaviour will have on required response techniques and clean-up operations.

High density oils typically have higher pour points, which is a measurement indicated by the temperature below which the oil becomes a semi-solid and will not flow. Because of this, high density oils are typically shipped in a heated state to allow loading and off-loading of product. This phenomenon can help recovery efforts because the oil will have a tendency to form large mats of varying thicknesses as it cools provided the sea is calm and personnel have access to the oil before wind and waves break-up the mats into tar balls of varying sizes.

Heavy oils also tend to have high viscosities when compared with lighter oils. The actual viscosity range is quite wide as indicated in the previous tables, with dynamic viscosity (cP) typically starting in the thousands ranging up to over one million, depending upon the actual starting oil, temperature, weathering, and emulsification. This will be more pronounced in colder waters and during winter months. Higher viscosities will have an impact on pumping as higher viscosity fluids will resist flow.

Heavy oils with high pour points and high viscosities will have less of a tendency to spread which will aid recovery efforts when containing and controlling a spill. It may be possible to recover semi-solid product in calm seas – although spill incidents rarely happen during ideal weather conditions. Heavy oils also tend to be sticky in nature, which can prolong the clean-up operation by adding to the decontamination process. Clean-up may be difficult once the oil impacts shorelines, although emulsified oil may tend to adhere less than non-emulsified oils.

Identifying and assessing where the oil is situated can be difficult from the air or even from craft on the water if over-washing or partial sinking occurs. Movement may be difficult to predict as wave action may carry the oil below the surface. After oil is submerged little weathering will take place. The most important process that affects the density of the spilled product is the uptake of particulate matter (Fingas *et al*., 2006) which will impact the ability of the oil to resurface. Due to the density of heavy oil and the low level at which it will float at the surface, an assessment of the thickness of oil patches to provide an estimate of the quantity will be very difficult to provide.

Skimmers that perform successfully on lighter to medium oils may be rendered ineffective when attempting to collect heavy oils that tend to float low in the water. Even skimmers that rely on oleophilic properties such as drum, disk, and belt skimmers may have difficulty with heavy oils depending upon their design and the viscosity of the product being recovered. High density oils may tend to collect under a stationary skimmer and may result in a large quantity of oil that will resurface once skimming operations are halted.

Heavy fuel oils tend to be less toxic to animals than their crude oil counterparts due to the chemical make-up of the oil. One problem with this product, however, is its adhesive properties and persistence. Heavy oils do not disperse naturally in any significant manner and oil spill dispersants have not proven effective against heavy oils. The result may be a larger impact on mammals and seabirds than previously assumed.

5 RECENT HEAVY OIL SPILL INCIDENTS

Recent spill incidents have highlighted problems with current equipment and techniques for responding to heavy oil spills.

5.1 T/V ATHOS I Spill

The T/V ATHOS I spill in the Delaware River occurred on November 26, 2004. The 750 foot tanker carrying 10 million gallons of heavy crude oil cargo hit an object in the Delaware River near Philadelphia spilling approximately 265,000 gallons of crude oil. Part of the spilled oil submerged causing the closure of the Salem Nuclear Power Plant, the second largest in the U.S. Just over 200 miles of shoreline were oiled to varying degrees.

Figure 1 - T/V ATHOS I (source: U.S. Coast Guard)

5.2 T/B DBL-152 Spill

On November 10, 2005, Barge DBL-152 struck a submerged object in the Gulf of Mexico and ultimately capsized four days later. A total of over 2.7 million gallons of slurry oil with a density of 1.04 g/cm^3 was spilled and sank in the water (Usher, 2006). Traditional oil spill response equipment was mobilized but was of little practical use because the oil did not float and form traditional slicks.

An adsorbent trawling device, called the Vessel-Submerged Oil Recovery System (V-SORS) and side-scan sonar were used in an attempt to identify the location of submerged oil, while remotely operated vessels and divers were used to confirm the presence of oil and determine how much, if any, could be recovered.

Figure 2 - Barge DBL-152 (source: U.S. Coast Guard - Petty Officer 1st Class Gary Sanchez)

5.3 Lake Wabamun Spill

Early in the morning of August 3, 2005, 43 of 140 CN railcars went off the tracks spilling Bunker C oil (Bunker 6) and pole treating oil into Lake Wabamun, situated about 65 kilometres west of Edmonton, Alberta. The Bunker C oil had recently been loaded and was still at an elevated temperature (consequently a lower viscosity than at ambient temperatures) when the accident occurred, permitting a substantial amount of the spilled oil to flow into the fresh water lake. By mid-morning the oil slick had spread, driven by wind, contaminating 12 km of shoreline (Goodman, 2006).

Response efforts were hampered by the density of the oil which was close to that of water, with portions ultimately sinking in the water column. Containment of the spilled oil was attempted using sorbent booms and containment booms with limited success due to the oil properties and changing wind directions.

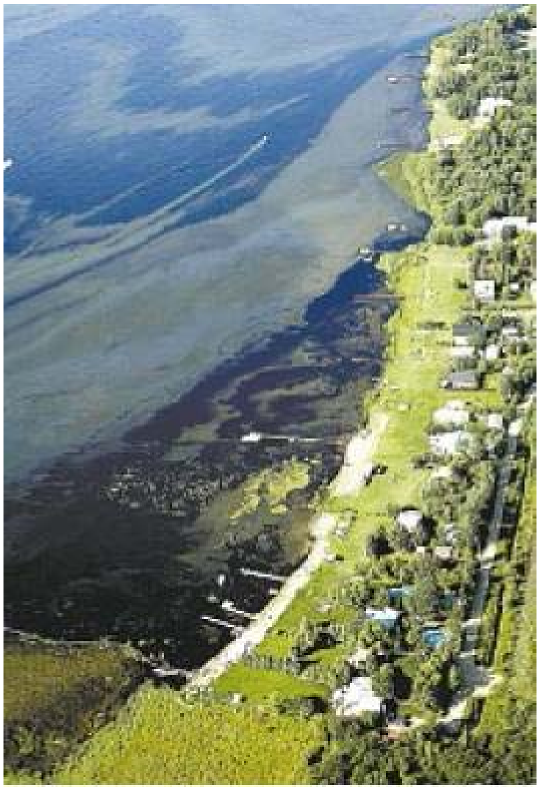

Figure 3 - Wabamun Spill (source: University of Alberta, Chemical and Materials Engineering Department)

Figure 4 - Wabamun Spill (source: Lake Wabamun Residents Committee)

6 CURRENT STATE ANALYSIS

A number of testing projects related to the collection and recovery of heavy, viscous oils have taken place since the late 1990s. Research in Canada related to heavy oil recovery has centered on the importation of Orimulsion and the identification of response issues associated with spills of this product. It was discovered that spills of Orimulsion that would initially flood the water column with finely dispersed droplets would eventually coalesce leading to the refloatation of its bitumen constituent depending upon the salinity of the water.

This heavy floating product had some unique characteristics including very high viscosity that rendered typical equipment used by response organizations in Canada ineffective. Initial testing with a Pharos Marine GT185 skimmer, a main component of the Canadian Coast Guard's recovery inventory, demonstrated that the equipment was unable to effectively collect the refloated bitumen. When manually fed a quantity of bitumen, the GT185 was unable to pump product at a throughput that would be considered to be "operational". This initial test started a program to investigate and improve heavy viscous oil recovery operations in Canada.

Research in the United States was catalyzed by a number of spills including the New Carissa spill in 1999. Again, heavy oil response was hindered by problems with stock equipment that had difficulties processing viscous oil and was limited by high operating pressures and short transfer distance capabilities. Technologies such as annular water injection, which actually forces water into the flow of a pumping system to form a lubricating “sleeve” that greatly decreases resistance to flow, have been investigated to increase performance capabilities of the Desmi DOP250 pump that are in the US Coast Guard inventory.

6.1 Pumps

A number of developments have taken place over the past seven years on a series of pumps known as positive displacement Archimedes’ screw pumps commonly used in the oil spill response market. Research has progressed in improving their abilities to handle heavy and consequently viscous oils. Three manufacturer’s designs were initially available: Desmi DOP series, Foilex TDS series, and the Pharos Marine GT series. A fourth was recently added that incorporates some of the advances made over the past seven years, known as the Lamor GT-A series.

Testing on behalf of the Canadian Coast Guard (CCG) and Environment Canada has primarily focussed on the GT series of pumps which are commonly used by the CCG and Spill Response Organizations (RSOs) in Canada. Testing of the pumping capabilities of skimmers performed at Environment Canada’s Environmental Technology Centre initially focussed on adapting annular water injection techniques. This initial testing program involved the adaptation of an annular water injection flange to the GT185 skimmer operating as a transfer pump.

Performance testing of a stock GT185 using a standard hydraulic motor and plate wheels provided disappointing results. The skimmers hopper was manually filled with refloated bitumen from a different phase of testing. The GT185 had a 5 metre discharge hose with a 4” diameter attached to the pump outlet. The flow rate through the pump was estimated to be less than 1 m^3/hr (Cooper and Hvidbak, 2000). This data was used as the starting point for subsequent research to increase capacity for the GT line of skimmers.

The annular water injection system was first tested in Canada in 2000. A number of test runs were planned using a range of flow rates and two test oils: bitumen and bunker C (bunker 6). One of the initial baseline runs with bunker C provided results of 6.2 m^3/hr while operating at a pump discharge pressure of 58 psi. When the annular water injection ring was engaged, the pressure dropped below 5 psi at the pump discharge and total flow was measured at 20.2 m^3/hr. The water content was high (about 30% of the flow) but the test run demonstrated the potential of the technology to improve pumping capabilities (SAIC Canada, 2001).

Testing to date showed that annular water injection techniques were promising, and some successes had been demonstrated by injecting water in the inlet hopper of the skimmer to assist in the internal lubrication of the pump. A series of tests were conducted on a GT185 modified with a new inlet hopper assembly with integrated manifold to accept steam/hot water injection around the perimeter of the hopper along with an annular water injection ring mounted at the discharge flange of the pump. A final modification was the replacement of the standard hydraulic motor with a Ross Series ME15 unit, capable of higher torque.

Baseline testing (no annular water injection) through a short 3.7 m length of 4" diameter hose yielded a bitumen flow rate of 1.1 m^3/hr. Additional runs were performed while activating the water injection at the pump hopper and annular water discharge flange. This provided a bitumen pumping rate of up to 12.1 m^3/hr through 12 m of 4" diameter discharge hose representing a substantial improvement in capacity. Problems were encountered when hot water injection at the pump inlet was activated for an extended period of time before starting a subsequent test run in an attempt to pre-lubricate the pump and part of the longer test loop. When the pump was engaged, no appreciable flow of bitumen was witnessed. It was ultimately discovered that a failure had occurred in the rotating sealing disk which forms the seal against the Archimedean screw. Seven of the eight teeth which make up the rotating disk were missing. Recommendations were made to retest for extended periods of time to determine wear characteristics when actually pumping heavy products and stressing the equipment. Additional recommendations were made to ensure material compatibility of all wetted parts with elevated operating temperatures (SAIC Canada, 2002).

A review of the pumping cycle was performed to determine if other components might suffer wear or degradation when pumping heavy, viscous product for an extended period of time. Testing was performed on stock plate wheels using a heavy oil for up to nine hours with wear inspections being performed every three hours involving the plate wheel. Baseline testing was also performed using water to determine sealing characteristics within the pump. Testing of a prototype high temperature plate wheel and backing plate was then performed to determine their sealing characteristics. The new prototype plate wheel and backing plate combination were able to provide impressive results, surpassing stock equipment for maximum pressures attained during baseline water testing. The prototypes did not show any appreciable drop in performance following wear testing in hot water (SAIC Canada, 2003).

Similar improvements to the inlet and discharge water injection systems were concurrently being made to the Desmi DOP-250 pump. Previous workshops demonstrated that oil in the 16,000 cP range (density ~1.0) could be pumped a distance of 1500 feet at over 400 gpm using the Desmi DOP-250 pump which is approximately 90% of the maximum capacity of the pump. Additional testing at Desmi in Denmark performed by Mr. Flemming Hvidbak showed the DOP-250 was capable of pumping cool bitumen with a viscosity over the measured limit of 3 million cP through a 66 foot long 6 inch diameter hose at a rate of 198 gallons per minute (Drieu *et al*., 2003).

Prototype plate wheels for both the GT-260 and DOP-250 were further evaluated in a subsequent series of tests to determine wear and sealing capabilities. The GT-260 was subjected to test runs in hot bitumen with a partially closed valve assembly mounted at the pump discharge to permit back pressure to be controlled. After heated bitumen runs of 90 minutes or 180 minutes baseline tests using water were performed to determine sealing characteristics of the pump. Testing results showed that the plate wheel wear was minimal and sealing characteristics surpassed those of the stock equipment. The DOP-250 with a newly designed prototype plate wheel was only available for a limited number of runs but performed very well with no appreciable degradation of performance following a limited hot bitumen "wear" test run. In fact, flows actually improved for a given pressure drop indicating that the pump was actually sealing better after an initial "break-in" period, as shown below in Table 3 (SAIC Canada, 2004).

Table 3 - DOP-250 Prototype Plate Wheel Testing Results

Plate wheel ID	**Hydraulic Flow Rate (lpm)**	**Flow at 0 psi (m3/hr)**	**Flow at 40 psi (m3/hr)**	**Flow at 60 psi (m3/hr)**
Prototype	120	59.3	35.0	29.7
Prototype	120	n/a (wear test in bitumen)		
Prototype	120	61.1	38.9	44.5

Several of the improvements up until this point in time had been evaluated using relatively short test loop lengths or by using low to moderate viscosity oils. The Joint Viscous Oil and Pump Test and Workshop #6 held at the Cenac Towing Company facility in Houma, Louisiana provided a platform to test offloading capabilities of pumps over distances of 500 feet through six inch diameter hoses using a heavy oil with a viscosity in the 500,000 cSt range (~500,000 cP) for the GT-185 pump and a distance of 1500 feet through six inch hoses using a heavy oil with a viscosity in the 200,000 cP range for the DOP-250 pump.

The GT-185 with a high torque motor, inlet and discharge water flanges, and high temperature plate wheel transferred 480,000 cSt oil through 515 feet (152.4 m) of hose at a rate of 26.6 m^3/hr (very close to the maximum capability of this pump/hydraulic motor combination) and a discharge pressure of approximately 12 psi using 4% hot water at the inlet and 4% cold water at the outlet of the pump. The DOP-250 pump with a high torque motor and inlet and discharge water flanges transferred 190,000 cSt oil through 1506 feet (459 m) of hose at a rate of 60 m^3/hr (very close to the maximum capability of this pump/hydraulic motor combination) and a discharge pressure of 45 psi using 3.5 % hot water at the inlet and 4% cold water at the outlet. A third pump, the GT-A was evaluated using a 304 foot (92.6 m) section of test hose. This unit was able to transfer 210,000 cSt oil at a flow rate of 46.7 m^3/hr with a pump discharge pressure of 11 psi (GPC, 2004).

Table 4 summarizes the test results in comparison to runs without water injection systems activated.

Table 4 - Water injection improvements

Pump	Oil Viscosity (cSt)	Distance (m)	Discharge Pressure (psi)	Measured Flow Rate (m^3/hr)	Performance Improvement Factor (PIF)**
GT 185	530,000	1*		0.5	
GT 185	480,000	152.4	12	26.6	>8000
DOP 250	210,000	92.3	181	5.9	
DOP 250	210,000	92.3	7	58.2	~250
DOP 250	190,000	459	45	60.7	~215
GT-A	210,000	92.6	181	4.5	
GT-A	210,000	92.6	9	46.7	~210

*estimated value used for calculations based upon evidence that the limiting factor during this run was the apparent inability of the pump to pull in the oil without hot water injection at the inlet or localized heating of the test oil. Actual hose was 30 metres in length.

6.2 Containment Strategies and Equipment

Many commonly available containment booms are constrained by operational conditions that limit their ability to contain oil. A number of parameters have been identified which have an impact on performance but have not been well documented in tests. Physical parameters such as buoyancy to weight ratio, boom draft, oil viscosity and oil density seem to have the most impact and have come under some scrutiny in recent years, but questions remain as to their direct influence on containment.

Booms can be towed in the catenary mode at speeds of up to 0.9 knots in calm water without losing oil, but this limit is restricted to approximately 0.7 knots when short regular waves or harbour chop is present. When operated in a diversionary mode or Vee-Sweep, this limit raises to 1.2 knots and possibly more (Schulze and Lane, 2001).

The Vee-Sweep configuration (used by the US Coast Guard for the Spilled Oil Recovery Systems (SORS) and Vessel of Opportunity Skimming systems (VOSS)) limits the sweeping width but this is offset by the ability to operate at higher speeds in the water while retaining reasonable maneuverability. A bottom net built into the apex of the Vee helps to retain its shape and allows the oil to be concentrated into thicker layers for skimmer recovery operations (Schulze and Lane, 2001). This configuration may be beneficial for vessels operating with a boom mounted on one side of a vessel and to an outrigger which holds the boom open. The Vee pocket would allow a deeper layer of oil to build which would support higher skimmer efficiencies.

Additional containment techniques have been attempted including the use of rope snares which act as barriers to the migration of heavy oil by allowing the oil to penetrate into the body of the snare and be held by oleophilic properties of the rope snare combined with the heavy oil's typical resistance to flow. This technique might be useful in its ease and short time of deployment, but concerns remain as to their absolute effectiveness and operating limits when acting as a barrier.

The use of bubble barriers which use air bubbles rising to the surface to cause a counter-current have been used to restrict the flow of oil under limited current conditions. This technique is effective in protected areas and may offer the advantage of aerating the oil to some extent which would alter the bulk density and reduce the oil's tendency to sink over time. This technique would typically be used where traffic obstruction would be a concern.

Very limited information on current research into containment strategies and equipment for heavy viscous oil was uncovered during this study. General principles used to minimize entrainment under a boom via a sweep system or through the use of localized diversionary techniques seem the most likely targets for further study although additional work in this area is needed for heavy oils. Additionally, work has been conducted developing deep skirted booms for containment of Orimulsion that may have applicability for heavy viscous oils.

6.3 Skimmers

Initial tests of skimmers conducted by SAIC Canada to collect refloated bitumen demonstrated the differences between available technologies for dealing with heavy oil recovery. Four units were compared for their ability to collect and process a heavy and extremely viscous product. The results are summarized below.

The ERE Skimmer (Dynamic Inclined Plane) incorporates a mesh steel belt with a honey-comb structure which measures approximately 1.53 m x 0.46 m x 0.15 m (Length by Width by Height - LWH). As the belt rotates, oil is forced down at the water/air interface and is trapped between the belt and lower plate which squeezes oil into the mesh. This device was able to recover the heavy oil and demonstrated a wide range of influence by pulling the oil in from a wide area due, in part, to the properties of the bitumen.

The KLK 602 skimmer uses two counter-rotating non-symmetrical drums which "scoop" the heavy oil. The unit is approximately 2.6 m x 2.6 m x 1.3 m (LWH). Spring mounted scrapers ride the surface of the drums and guide the oil into a recovery canal. This drum skimmer had initial difficulty processing the thin layer of refloated bitumen. As the non-symmetrical drum (one drum only was operated during testing) rotated in the water, it created small waves that caused the trail of bitumen to "break" and be pushed away from the skimmer. Operating the drum at slower speeds solved most of this problem.

The Hobs belt skimmer extends to overall dimensions of approximately 5.2 m x 1.7 m x 2.0 m (LWH). The skimmer uses a reinforced rotating belt to collect oil and lifts oil up off the surface carrying product to the top of the unit where a mounted scraper causes excess oil to drop off into a trough. The skimmer was able to pick up and process the refloated bitumen, although some build-up was noticed on the belt support rollers which may indicate problems with long-term recovery. The diverter at the end of the unit which directed the recovered oil to a chute cause some build-up of oil, but the retained amount was not considered substantial enough to warrant any design changes.

The GT 185 skimmer was not able to process the refloated bitumen by itself since the bitumen would take too long to “flow” into the weir mechanism. Manually pulling the refloated bitumen into the weir was attempted in order to determine the pumping capabilities of the unit. This manual process was extremely labour intensive and only resulted in the processing of small quantities of oil thus would not be practical as a technique for use during an actual spill response (Cooper and Hvidbak, 2000).

Recent testing in February of 2006 involving brush adapters for weir-type skimmers to enhance their abilities to recover heavy, viscous product was performed at Environment Canada’s Environmental Technology Centre. A total of three adapters were tested in two oils with densities very close to 1.0 g/cm^3 and viscosities of 50,000 cP and 100,000 cP (SAIC Canada, 2006).

The first unit was a Desmi Helix brush adapter (shown in Figure 5) using black rotating brushes configured in a pattern of four double brushes in six general clusters mounted on a circular ring around the weir of a GT-185 skimmer. The brushes aid in the selective collection of oil by pulling oil into the unit, moving the brushes through scrapers which remove the oil and direct it to flow into the hopper.

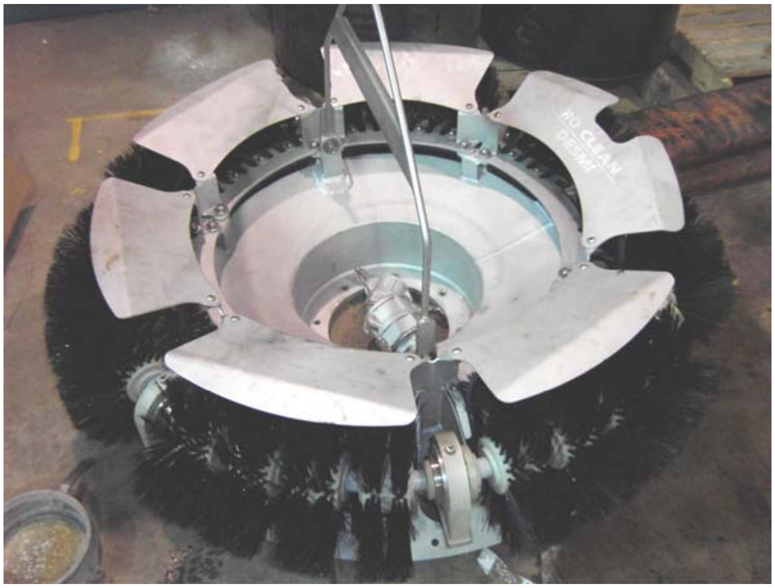

Figure 5 - Desmi Helix

The second unit, the Lamor Quattro brush adapter (shown in Figure 6), uses yellow rotating brushes configured in a square pattern mounted around the perimeter of the weir skimmer. Three clusters of brushes are incorporated into each side of the square shaped mechanism. The brushes rotate and pull oil into the unit, moving the brushes through scrapers that remove the oil and direct the resulting flow into the hopper for processing.

Figure 6 - Lamor Quattro

The third unit was the Lamor Brush Conveyor (shown in Figure 7) which uses a yellow V-brush design to recover oils and uses a propeller to draw water through the brushes to increase performance. The brush conveyor pulls oil up off of the surface where residual water has an opportunity to cascade down away from the collection point. The brush conveyor is passed through a scraping mechanism to remove the oil which is then directed into the GT-185 hopper.

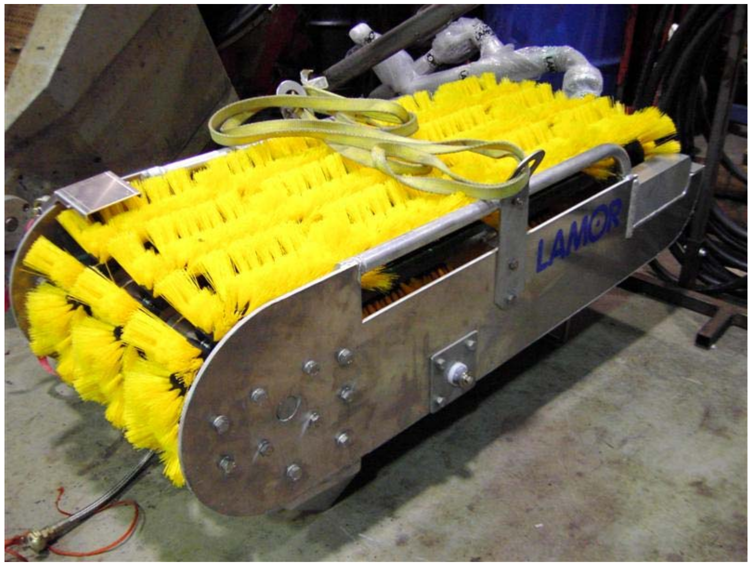

Figure 7 - Lamor V-Brush

During the first set of tests in the lighter oil (50,000 cP) all of the brush and belt adapters were successful in improving the efficiency (selectivity) of the GT-185 skimming system. The stock weir appeared to be processing almost pure oil during the baseline test run, but this was ultimately determined not to be the case as the water content was shown to be approximately 50% of the total flow based upon observations during the manual drum fill. The brush and belt adapters were able to help increase throughput by allowing the hopper to be selectively filled with oil at a rate faster than the oil would overflow the weir on its own. This allowed the GT-185 pump to be operated at a faster rate and not be starved for product. Improvements ranged from 130% increase in actual oil flow for the Desmi Helix, to 85% improvement in oil flow for the Lamor V-Brush and finally a 45% oil flow increase for the Lamor Quattro as shown below in

Table 5.

Table 5 - Collection Results for 50,000 cP Oil

Product	Pump Hydraulic Flow (L/min)	Pump Hydraulic Pressure (psi)	Brush/Belt Hydraulic Flow (L/min)	Fluid Collection Flow (m3/hr)	Estimated Water Collected* (% total flow)	Calculated Oil Flow (m3/hr)	Improvement (% oil flow)
Baseline	45	600	n/a	12.2	50	6.1	
Desmi Helix	58	1150	5	15.8	10	14.2	130%
Lamor V-Brush	38	700	6**	12.4	10	11.2	85%
Lamor Quattro	40	600	3	11.8	25	8.9	45%

* estimated based on observations during drum fill and discharge.
** flow is split between the V-Brush Conveyor and the propeller

During testing with the 105,000 cP oil, the brush and belt adapters were again successful in improving the efficiency of the GT-185 skimming system. The stock weir was able to recover a reasonable 9.7 m^3/hr fluid, but despite the best efforts of the operator, the water content was observed to be between 50% and 70% during the test run. The Desmi Helix, Lamor V-Brush Conveyor and the Lamor Quattro were all able to recover fluid containing less than 10% water while allowing higher oil throughput than the baseline test. Again, improvements were impressive: the Desmi Helix imparting a 70% improvement in oil flow over the baseline run, the Lamor V-Brush was able to attain a 140% improvement in oil flow, and the Lamor Quattro was able to provide a 45% improvement in oil flow. These improvements in efficiency and throughput demonstrate the strong benefit of using these products.

Table 6 - Collection Results for 105,000 cP Oil

Product	Pump Hydraulic Flow (L/min)	Pump Hydraulic Pressure (psi)	Brush/Belt Hydraulic Flow (L/min)	Fluid Collection Flow (m3/hr)	Estimated Water Collected* (% total flow)	Calculated Oil Flow (m3/hr)	Improvement (% oil flow)
Baseline	31	680	n/a	9.7	60	3.9	
Desmi Helix	30	1400	4	7.4	10	6.7	70%
Lamor V-Brush	42	1600	7	10.5	10	9.5	140%
Lamor Quattro	25	1200	3	6.3	10	5.7	45%

* estimated based on observations during drum fill and discharge.

6.4 Storage

Temporary storage during recovery of spilled oil may present a logistical problem that is compounded by the recovery of heavy oils. Due to the physical characteristics of heavy oil and their tendency to resist flow offloading operations of temporary storage tanks and floating storage bladders can be a slow process. Limitations may be encountered by the size of the fill and drain valves unless the storage units can be lifted to allow the contents to run towards the valves during pumping operations because the heavy oil may not flow easily. Adapting pumping equipment with either heat generating abilities or smaller versions of annular water injection pumping systems may be necessary for offloading of stored product to maintain adequate storage space to keep pace with other recovery operations.

Bulk and localized heating through the use of steam coils and steam lances have provided some qualified success in recent testing at the Cenac Towing Company facility and recovery operations concerning the S.S. Jacob Luckenbach. The heat lowers the viscosity of the oil near the pump allowing it to flow into the pump inlet as pumping progresses. In general, pumping into and out of on-board or temporary storage is much more difficult for heavy oil transfers than when dealing with lighter oils.

Very limited additional information pertaining to research into the storage of heavy oils was uncovered during this study.

6.5 Current State Analysis Summary

A number of technologies have been identified for dealing with heavy oils. A summary of advantages and disadvantages are listed in Table 7 below.

Table 7 - Advantages and Disadvantages of Identified Technologies

Pumps – Positive Displacement Pumps with Annular Water Injection Flow	
Advantages	*Disadvantages*
- dramatic increase in flow rate - dramatic decrease in operating pressures - expanded operational envelope for heavy/viscous oil - eliminate/reduce bulk heating requirements to mobilize heavy oil	- additional complexity / more ancillary equipment needed to support pumping operations - system may not function adequately in freezing conditions - restart may be difficult to accomplish
Containment Strategies and Equipment	
Advantages	*Disadvantages*
- principles that minimize oil entrainment under booms have been successful in actual spills (LORI System, NOFI current buster) - bubble barriers may help drive oil to surface for conventional recovery - V-configurations improve on typical U-configurations by concentrating oil enabling better skimmer performance. Containment is effective at slightly higher operating speeds.	- specialized equipment - may preclude adaptations to current booms stocked by response organizations - little recent data is available as to the effectiveness of bubble barriers when dealing with heavy, viscous oil - V-configurations reduce the oil collection swath when compared with a U or J configuration.
Skimmers – Brush Modifications for Weir Skimmers	
Advantages	*Disadvantages*
- increase in oil recovery rate for weir-type skimmers in heavy oil - increase in oil recovery efficiency - should be effective over a wide range of environmental conditions / rougher sea states	- adds complexity to the skimming system - diverts hydraulic fluid from the pumping system - increases skimmer weight which may adversely affect sea keeping abilities - may require additional / higher buoyancy floats - may require different brushes for different oils or viscosity ranges
Storage	
Advantages	*Disadvantages*
- storage on barges or conventional storage bladders are readily available - allows storage of recovered oil which prevents sinking and loss of oil	- larger bladder units may be restricted by valve size unless unit can be lifted to allow recovered oil to flow towards valve during temporary storage off-loading - transfer rates may be slow if no localized heating is available - pumping into and out of storage is much more difficult than with lighter oils - barges may require extended time to offload, or require a return to port to effectively remove heavy oil from storage

7 RECOMMENDATIONS FOR FURTHER STUDY

The heavy oils identified in this report have some unique characteristics when compared with lighter oils. Their high persistence suggests that additional efforts should be made to isolate and remove them from the water surface before they impact shoreline. They typically will spread more slowly than lighter oils, which increase the window of opportunity for recovery operations. Their higher viscosity and adhesion properties dictate that the recovery operation will be slower than for lighter oils – and may be more complicated. They do tend to float low in the water which makes detection through observation difficult.

A number of issues have been brought fourth during this review of techniques and technologies for dealing with heavy oils. Recommendations for further study have been separated into the four primary technological areas.

7.1 Pumps - Recommendations

The development of annular water injection systems has had a large impact on increasing the capacity of commonly used positive displacement pumps. Recommendations for further research center on minimizing water injection requirements and troubleshooting “worst case” scenarios of pump stoppages during pumping operations and attempting to reinitiate flow.

- Employ different lubrication settings to start the long distance pumping and initiate annular flow process.
- Test reinitializing flow in long distance after a temporary shut-down (content will settle and possibly cool).
- Test clearing clogged hose with hot water injection and high pressure output from pump.
- Test water systems and reinitializing flow in freezing conditions.
- Determine if water can be removed prior to discharge tank to reduce storage requirements.

7.2 Containment Strategies and Equipment – Recommendations

Although some work had been performed on the development of new containment devices, the oil type used in modelling the process was light oil. Recommendations for further review include simple containment testing using heavy oils and lighter oils to gauge the differences in performance based on this property. Booms with netting as part of the skirt may perform well as the netting would allow some water to pass but retard the flow of oil. The cohesive forces within the heavy oil should minimize shedding. The following tests are recommended:

- Perform testing on containment boom using dense and medium oils with similar viscosity ranges to determine the influence on containment and identify failure modes.

- Perform testing on rope snares to determine containment abilities in conjunction with "typical" sorbent booms (which performed poorly at a recent spill of heavy oil in Lake Wabamun, Alberta.)

7.3 Skimmers – Recommendations

Weir skimmers (the largest number in the US Coast Guard inventory) commonly used for spill response in a range of oil types would perform poorly in heavy oil unless the layer was sufficiently thick to overcome the oil's resistance to flow. Belt and brush skimmers have proven effective at recovering heavy, viscous oils and now modifications are being adapted by multiple manufacturers for use on the most popular weir skimmers used in North America. Initial testing of three adapters showed core performance benefits but highlighted some areas of concern. The following recommendations are made to improve performance:

- Increase the buoyancy of the skimmer and determine the performance impact under a range of operating conditions.

- Reduce the volume of the hopper and determine the performance impact under a range of operating conditions.

- Test the brush adapters and stock weir skimmers in waves to determine the performance impact.

7.4 Storage – Recommendations

Storage of heavy oil during skimming operations could easily become a limiting factor when recovering oil. Problems in handling and pumping heavy, viscous oil may limit the speed at which temporary storage can be offloaded, or even if the stored oil can be accessed because it may cool below its pour point. The following are recommendations that may overcome some storage limitations:

- Identify and test methods of localized heating to enable oil temporarily stored on barges to flow.

- Identify and test methods of lifting floating storage bladders to force the oil to flow towards valves during pumping operations (techniques such as bridles have been used in conjunction with a crane, but simpler methods such as the use of inflation bags secured under one end of the storage bladder may provide sufficient lift to force the oil towards valves used to discharge the bladder).

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