Husky Energy

White Rose Extension Project

SBM Accidental Release and Dispersion Modelling

June 2012

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Environmental Impact Assessment

White Rose Extension Project

SBM Accidental Release and Dispersion Modelling

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Executive Summary

The development of the White Rose Extension Project (WREP) will involve the use of synthetic-based muds (SBMs), due to their unique performance characteristics, as well as their low toxicity and relatively low environmental effects compared to oil-based muds (OBMs).

As part of the environmental assessment process, a review was conducted of the latest scientific literature and industry spill databases from Atlantic Canada and the United States Outer Continental Shelf (US OCS) to determine the most probable modes of accidental SBM release. Four potential release spill scenarios were selected as being most representative for the WREP:

- Surface tank discharge
- Riser flex joint failure (two scenarios, for two fall velocities)
- BOP disconnect

Subsequently, a numerical dispersion modelling study was conducted to predict the potential seasonal footprints of SBM spills on the seafloor for each of the four scenarios. The numerical model used a full-year time series derived from ADCP current measurements at White Rose from 2008 to the end of 2010, with approximately 13,000 model realizations being simulated in each seasonal scenario per release mode. The total spill footprint area, length and distance from release site, as well as projected initial SBM layer thickness on the seafloor, were estimated for each simulated event, and seasonal median, maximum and average values were derived.

The maximum predicted distances from the release site are those for the winter surface dispersion scenario, where the maximum concentrations of the footprint are found at up to 1,061 m from the release site. For the other dispersion scenarios, the spill footprints remain within a maximum distance of 201 m or less. These maximum distances are expected to occur if a spill occurs during periods when the current magnitudes are at the seasonal maximum.

The footprint areas, and the associated footprint lengths, are expected to be influenced by the period over which the SBM is released and the fall velocities, as well as the variability of the currents over the release and settling periods. The largest footprint areas were found for the first riser flex joint scenario, which had the lowest fall velocity and the longest release period of 3 h. The single largest spill area in this scenario was observed in the winter season, and represented an area spanning approximately 579 m long by 40 m wide. The majority of the spill footprints were 1,800 m^2 or smaller, corresponding to spill areas measuring 30 m by 60 m. The smallest footprints (30 m by 30 m) were predicted for the BOP disconnect scenarios, which exhibited a combination of low height above sea bottom, relatively quick release time (1 h) and high fall velocities.

The interpretation of the predicted footprint areas and thicknesses should take into account that these are only preliminary dimensions of the projected landing area for the SBM droplets, and the estimated SBM layer thickness if the full spill volume landing in each model cell were to be equally distributed within that cell. The subsequent fate and

the footprint are likely to evolve in a less predictable fashion, as the negatively buoyant SBM droplets are expected to coalesce into streams or pools, and flow under the influence of gravity and the local bathymetric features. As there is a tradeoff between the area covered by the spill and the thickness of the spill, it can be expected that an area of the seafloor that is relatively flat and with few roughness features is likely to result in a thinner and widely distributed SBM layer, while a localized depression in the seafloor could retain the received SBM as a thicker layer within a smaller area.

While the weathering properties for the SBM considered in the present study are not precisely known, it is expected that the biodegradation of the SBM on the seafloor would take place over periods on the order of several weeks. This timescale far exceeds the duration of the spill and settling of SBM to the floor; therefore, the SBM is considered to be stable during the entire duration of the physical dispersion of the droplets in all modelled scenarios.

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1.0 INTRODUCTION

1.1 Project Background

An option for the development of the White Rose Extension Project (WREP) includes the operation of a semi-submersible drilling rig to perform the drilling, completions and well interventions for up to 64 wells within up to four glory holes. It is anticipated that the drilling operations for the intermediate and main well hole sections will necessitate the use of synthetic-based mud (SBM). The use of SBMs in offshore drilling operations is regulated in accordance with the Offshore Waste Treatment Guidelines (OWTG) (NEB et al. 2010), which dictate the following:

> Where there is technical justification (e.g., requirements for enhanced lubricity or for gas hydrate mitigation), operators may use synthetic based mud (SBM) or enhanced mineral oil based mud (EMOBM) in the drilling of wells and well sections. Other than the residual base fluid retained on cuttings as described in the operator's EPP, no whole SBM or EMOBM base fluid, or any whole mud containing these constituents as a base fluid, should be discharged to the sea (NEB et al. 2010).

For this (subsea drill centre) development option the drill cuttings recovered from operations involving the use of SBM will be treated and, for each well, approximately 500 t of cuttings with approximately 26 m^3 of SBM on cuttings will be released[1] from the drilling rig in accordance with the OWTG. The OWTG specify the performance target for the retained SBM on cuttings that may be discharged to the environment as follows:

> The 48-hour mass weighted average of retained "synthetic-on-cuttings" or "enhanced mineral oil-on-cuttings" discharged to sea should not exceed 6.9 g/100 g oil on wet solids (NEB et al. 2010).

SBMs are defined as drilling muds in which the continuous phase consists of a synthetic base fluid, while the dispersed phase consists of brine and other additives. SBMs have been developed as a more environmentally friendly alternative to oil-based muds (OBMs), as the synthetic fluids that comprise the continuous phase exhibit low toxicity to aquatic life and are more biodegradable in marine sediments than OBMs. SBMs exhibit several performance advantages over the more commonly used WBMs; therefore, they are commonly used for challenging wells in deep water, or wells with highly deviated wellbores. They serve several essential functions during the drilling process: transport of cuttings to the surface; cooling, cleaning and lubrication of the drill bit; maintaining a pressure balance between the geological formation and the borehole; reduction of friction in the borehole; sealing of permeable formations; and maintaining stability of the borehole walls (Burke and Veil 1995).

[1] Under the wellhead platform (WHP) development option (the alternative to the subsea drill centre option), for both intermediate and main well sections, all SBM will be treated and reinjected or stored/ transferred to the next well.

1.2 Objectives

As part of the environmental assessment process, the requirement for an assessment of the zone of influence of potential accidental SBM spills has been identified. The following sections present the results of a modelling study undertaken by AMEC, aimed at characterizing the dispersion and zone of influence of potential accidental releases of SBM for the WREP. The objectives were to:

- assess the potential modes of accidental releases of SBM to the marine environment
- model the most likely scenarios of SBM dispersion and deposition in the marine environment, based on possible combinations of potential accidental release modes and seasonal environmental conditions.

It is noted that these studies are preliminary and the information will be updated as design progresses through FEED and detailed engineering.

2.0 MODES OF ACCIDENTAL SYNTHETIC-BASED MUD RELEASES

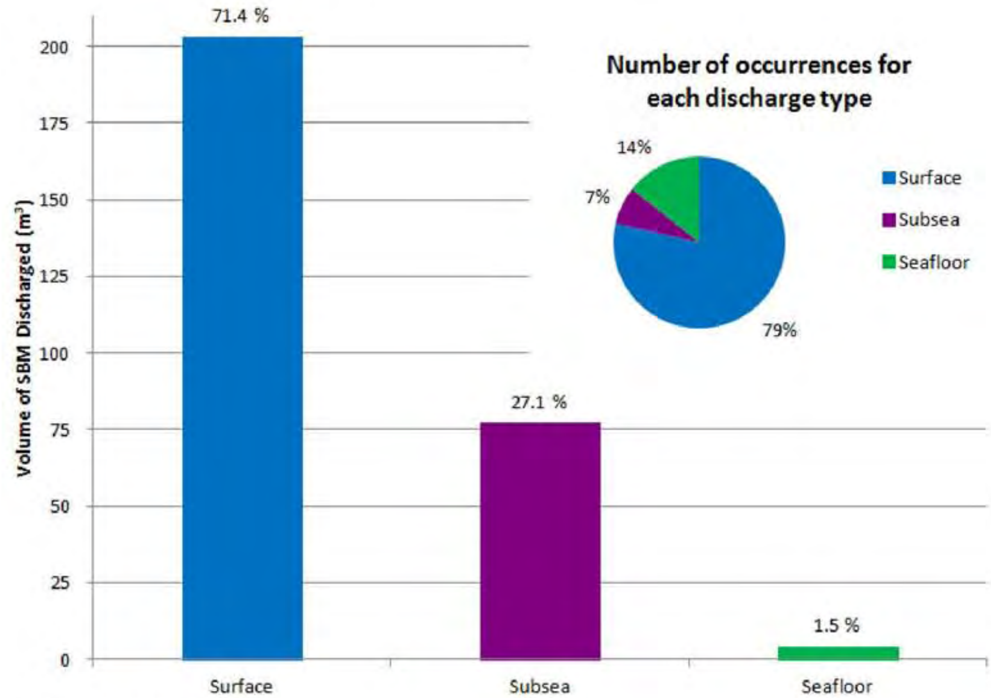
2.1 Historical Events in Industry Databases

SBMs have been adopted for use in offshore drilling operations for nearly two decades. In order to characterize the most likely modes of accidental SBM releases, industry reports and spill statistics databases were investigated, and the frequency of occurrence, specific amounts and locations of the spills were analyzed. The main sources of relevant information comprised of the publicly-available databases of oil spill events resulting from oil and gas operations in Atlantic Canada, maintained by the Canada-Newfoundland and Labrador Offshore Petroleum Board (C-NLOPB 2012) and the Canada-Nova Scotia Offshore Petroleum Board (CNSOPB 2012). Additionally, the study considered the comprehensive database of substantial spills (greater than 50 bbl, or 7.95 m^3) resulting from oil and gas activities in the United States Outer Continental Shelf (US OCS), compiled by the United States Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE), formerly the Minerals Management Service (BOEMRE 2012).

The oil spill incident database for the Newfoundland and Labrador offshore area covers the period from 1997 to 2011, and contains a listing of the reported spill amounts, the operators and rigs involved, as well as the locations on the rig system where the reported spill likely originated. For the period of record to the end of 2011, accidental spills of SBMs and synthetic-based fluids constituted approximately 18 percent of all recorded spill events greater than 1 L by frequency of occurrence; however, they accounted for approximately 61 percent of the spilled volume. There were 43 spill events greater than 1 L, amounting to a total of approximately 286 m^3 of spilled volume over the entire period of data coverage. The spill events were categorized into surface spills, subsea spills and seafloor spills, based on the likely location where the spill originated. The frequency of occurrence and volumes of the three main categories of spills for the Newfoundland and Labrador offshore area are presented in Figure 2-1.

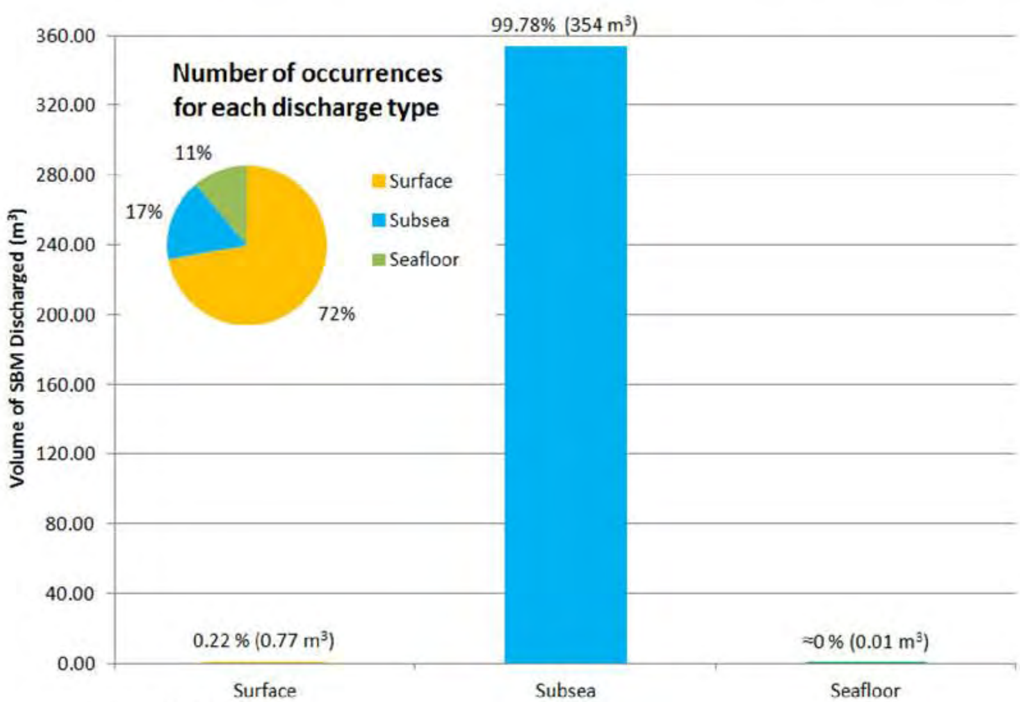
The data show that synthetic based fluid spills occurred most often at the sea surface (79 percent of the time), contributing over 71 percent of the total spilled volume. These spills are associated with leaks from mud pits, tanks, shale shakers, slip joints, hoses and other components of the mud circulation system found near the sea surface. Subsea spills, occurring under the surface and anywhere along the marine riser, kill lines, choke lines, boost lines and blowout preventer (BOP) control lines, occurred approximately 10 times less frequently, but still contributed over 27 percent of the volume. Spills near the seafloor contributed the least in terms of spilled volume, as they seem to have mostly consisted in minor events.

Similar statistics were derived from data from the Nova Scotia offshore area, as well as the US OCS, as shown in Figure 2-2 and Figure 2-3, respectively. There were a total of 18 spill events in the Nova Scotia offshore area, all except one being below 1 m^3 in volume. The most substantial event recorded was the 2004 spill of 354 m^3 of SBM, caused by a failure in the riser flex joint during abandonment of the Crimson F-81 exploration well by Marathon Canada Petroleum ULC.



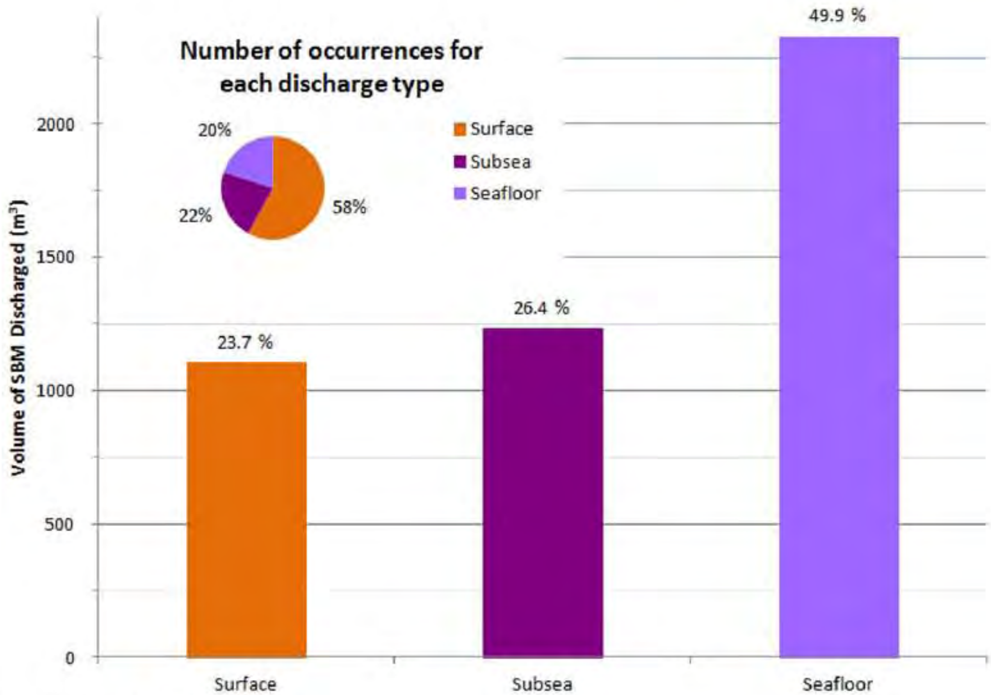
Source: data from C-NLOPB 2012

Figure 2-1 Synthetic-based Fluids Spill Statistics for the Newfoundland and Labrador Offshore Area, 1997 to 2011



Source: data from CNSOPB 2012

Figure 2-2 Synthetic-based Fluids Spill Statistics for the Nova Scotia Offshore Area, 1997 to 2011



Source: data from BOEMRE 2012

Figure 2-3 Synthetic-based Fluids Spill Statistics (greater than 7.95 m^3) for the United States Outer Continental Shelf, 1999 to 2010

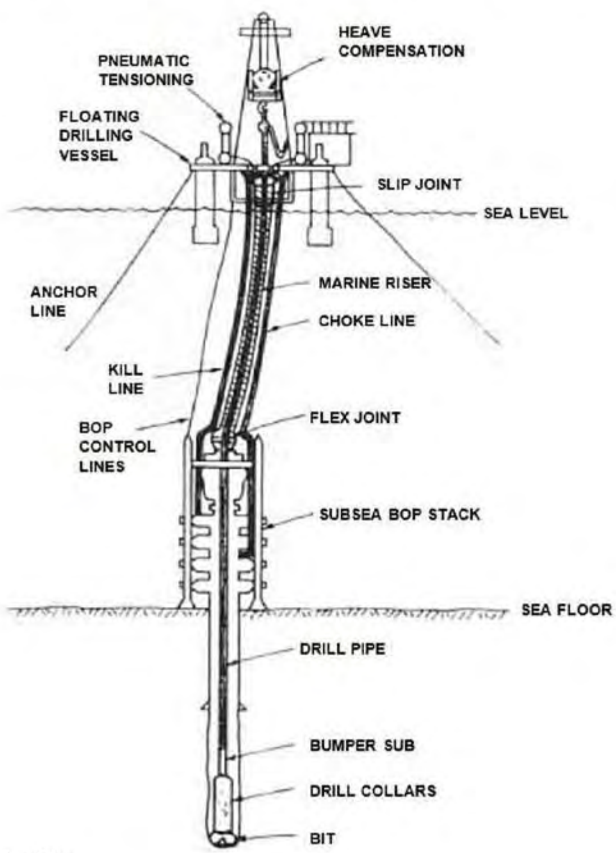
The data from the BOEMRE show that for the US OCS surface spills are also the most frequent mode of SBM release; however, the seafloor spills contribute a disproportionately higher percentage of the volume compared to the Atlantic Canadian datasets. The discrepancy between the datasets can be attributed to the fact that the BOEMRE data include a larger number of drilling operations, with multiple incidents of BOP disconnection events due to severe weather and other emergencies in the US Gulf of Mexico. An additional factor in the spilled volumes at the seafloor is the fact that the drilling operations in the US Gulf of Mexico are in deeper water (e.g., 2000 m), necessitating the use of up to 20 times larger amounts of SBMs compared to operations on the Grand Banks of Newfoundland and Labrador. This fact is reflected in the total spill volume for the 50 events included in Figure 2-3, which is an order of magnitude larger than the total spill volumes in Atlantic Canada. The shallower water depths on the Grand Banks (on the order of 100 m) dictate that the capacity of the marine riser, as well as the associated mud transport system components of a typical drilling rig, are proportionately lower, and therefore, the overall potential effect of accidental spills is expected to be lower compared to that in deeper waters.

2.2 Potential Synthetic-based Mud Accidental Release Scenarios for the White Rose Extension Project

In order to capture the full range of possible accidental spill scenarios within a reasonable scope, it was necessary to consider the possible release modes based on past events, while taking into account the characteristics and capacities of the drilling rig likely to be used for WREP development. A conservative approach, assuming worst case scenarios for each potential mode of release, dictated that the full amount of SBM potentially affected by the mode of release should be considered.

A surface accidental release scenario is potentially the most likely based on historical data. The most severe hypothetical scenario that can be anticipated for the WREP involves the inadvertent discharge of the entire volume of a mud tank, resulting in 60 m^3 of SBM being discharged through a 25 cm (10 inch) (internal diameter) pipe a few metres below the sea surface. The discharge would be expected to happen over a short period of time, over the course of several minutes to several tens of minutes.

Another potential location of an accidental release would be a subsea release in the lower half of the water column or near the seafloor. This type of release is associated with leaks at the riser joints, leaks and ruptures of the choke, kill and boost lines, or emergency disconnection of the riser and mud transportation lines. The components of a typical offshore drilling rig are illustrated in Figure 2-4. The most severe accidental release considered might occur at or near the riser flex joint, where the marine riser and other mud transport system components connect to the subsea BOP stack. The flex joint is a crucial component that provides flexibility for the riser to operate in a wide range of current conditions, while maintaining the pressure integrity of the mud circulation system.



Source: Bourgoyne et al. 1986

Figure 2-4 Main Components on a Typical Offshore Drilling Rig

The most substantial example of such a release in Atlantic Canada is the previously mentioned event at the Crimson F-81 well in 2004. A latent manufacturing defect in the seal ring of the flex joint was identified as the root cause of the substantial SBM spill. Since the Crimson F-81 well was in approximately 2,000 m depth, a total of 466 m^3 of SBMs were used in the marine riser, choke, kill and booster lines. The emergency response actions of the crew in that case allowed for 25 percent of the volume to be recovered. This included amounts from the choke and kill lines, the wellbore and the drill pipe, as well as the marine riser. In this case, SBM was released in the form of relatively fast and narrow jets pouring out through two ports in the riser wall over the course of three hours, ultimately forming streams and pools on the seafloor around the wellhead (CNSOPB 2005). This event illustrates one possible sequence of events following a subsea spill scenario.

Another potential severe scenario that could result in a different kind of subsurface release of most or all of the SBM contents, from the marine riser and associated transport lines, would be an emergency disconnection of the riser, which might prevent the crew from taking the necessary actions to displace the transport lines to seawater and therefore minimize spill amounts. In such an event, it would be expected that the SBM would be released within a shorter period of time (on the order of an hour or less), and through large orifices, resulting in a wider but slower jet of SBM being released. The rate of release and the size of the orifices are expected to contribute substantially to the subsequent behaviour and dispersal of the SBM in the environment. While it is difficult to predict the exact mode of failure of mechanical components and their behaviour during rare extreme weather events, the two subsea scenarios described here are expected to capture the range of possible conditions under which SBMs might be released under extreme conditions.

The drilling system planned for WREP development is expected to have a riser capacity of 29 m^3, and the associated mud transport lines would have a combined capacity of 20 m^3, for a total of 49 m^3. In a worst case scenario, either of the two modes of potential subsea release of SBM could result in the loss of all 49 m^3 of SBM at a height of approximately 20 m above the seafloor, or at approximately 100 m water depth. Therefore, even though these events are classified as subsea releases, they capture scenarios categorized under both the “subsea”, as well as the “seafloor” spill category in the historical industry databases. The modes of release and the associated details selected for the modelling study are summarized in Table 2-1.

Table 2-1 Modes of Release Selected for Synthetic-based Mud Dispersion Modelling

Mode of Release	Location of Release	Rig Components Contributing to SBM volume	Total Volume (m^3)	Period of Release (hours)	SBM Flow Type
Surface	120 m above seafloor	Mud tank	60	0.5	Wide, low-speed jet
Subsea (flex joint failure)	20 m above seafloor	Marine riser; choke, kill, booster, surface lines; mud gas separator	49	3	Narrow, high-speed jet
Subsea (BOP disconnect)	20 m above seafloor	Marine riser; choke, kill, booster, surface lines; mud gas separator	49	1	Wide, low-speed jet

3.0 SYNTHETIC-BASED MUD SPILL DISPERSION MODELLING

The faithful representation of the dispersion of SBM spills in the marine environment requires knowledge of the properties and behaviour of the SBM fluid in the immediate vicinity of the release site under different release scenarios, as well as the subsequent behaviour under the influence of the ambient ocean currents. A literature review of the current state of scientific knowledge of the behaviour of SBM in the marine environment, as well as reports of observations of actual SBM spill events, revealed that SBMs exhibit a unique behaviour in the marine environment due to the fact that they are immiscible in water (i.e., cannot be mixed with), and are negatively buoyant. Unlike water-based fluids, they tend to form distinct jets and droplets that fall relatively rapidly through the water column, and they are prone to form visible and clearly-defined streams and pools at the seafloor, where their dispersion is in large part driven by gravity in conjunction with the local seafloor features. The approaches for modelling the dispersion of WBMs and other water-based fluids are therefore not applicable to SBMs.

The scientific literature treating SBM spills is, in most cases, focused on the effects of SBMs at the seafloor, their persistence and biodegradability, as well as the biological effects on a number of marine species. To date, there have been no systematic field observations of SBM dispersion in the marine environment that could be used to quantify their dispersion properties in a real world scenario. The modelling study conducted by AMEC relies on data from an experimental study of SBM fall velocities under several release scenarios, which was commissioned by the BOEMRE and conducted by the Southwest Research Institute (SwRI) (2007). The following subsections briefly describe the findings of the experimental study, and the methods AMEC used to implement them in an SBM dispersion model. Furthermore, the ocean current inputs, limitations and assumptions behind the modelling study are described, and results are presented for all release modes.

3.1 Synthetic-based Mud Properties and Behaviour

The drilling operations during WREP development will use SBM that represents an emulsion in which the continuous phase is comprised of Puredrill IA-35LV, a non-toxic and readily biodegradable synthetic fluid produced by Petro-Canada. The synthetic fluid will comprise 65 percent of the SBM volume, with other additives (barite, viscosifiers, emulsifiers, lime, fluid loss control agents and water) accounting for the rest. The overall density of the SBM will be 1,350 kg/m^3.

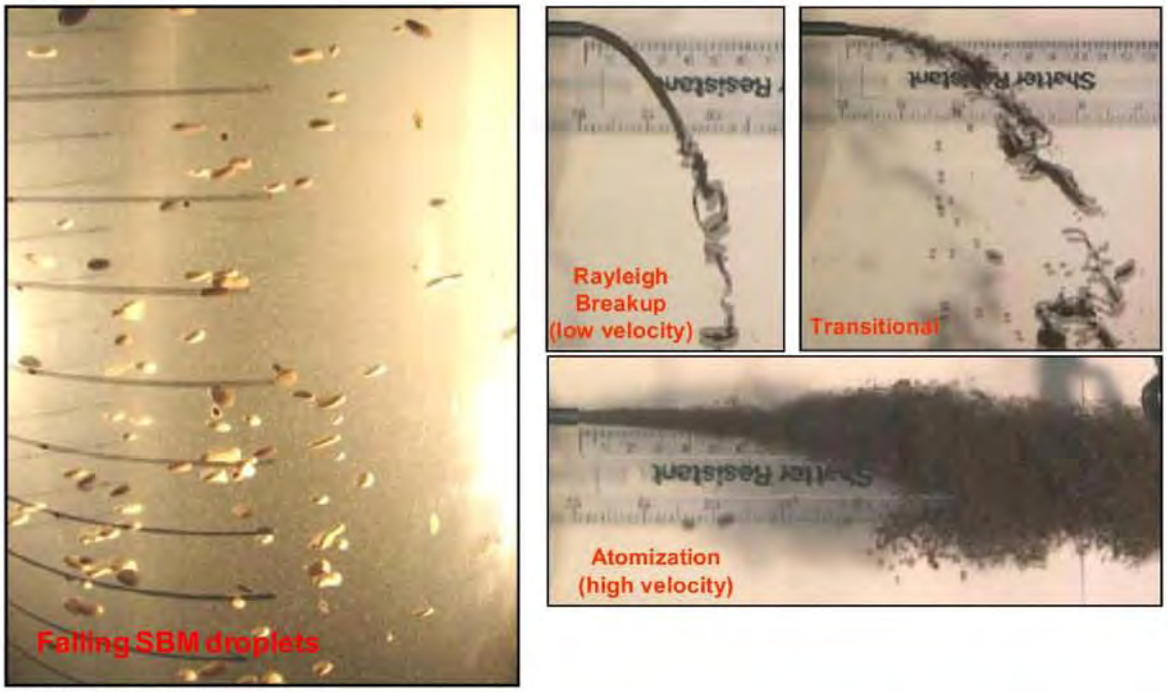
Since SBMs are immiscible in water, once released, they would form droplets of various sizes that are then subject to dispersal by the ocean currents. Some key aspects of the SBM behaviour that determine how it would spread in the marine environment are the breakup of the fluid into droplets of varying sizes and the stability of the SBM emulsion under different release and environmental conditions, as well as the terminal fall velocity of the droplets. For immiscible fluids, there exists a maximum stable droplet size at terminal fall velocity, which is governed by the balance between the interfacial tension holding the drop together, and the deforming force imparted by the buoyant flow (Grace et al. 1978). If the droplets formed in a spill event are larger than the maximum stable size, they will break up as they fall through the water column until they reach a stable size at the final fall velocity. The deforming shear forces are expected to be much larger for higher jet speeds, when it is likely that the SBM would be broken into droplets that are smaller than the stable droplet size.

Clift et al. (1978) have shown that droplets fall faster as they grow bigger in diameter, up to a certain threshold size beyond which increasing the droplet size does not increase the fall velocity. This was explained by the fact that drops retain their spherical shape only until a certain threshold in size, beyond which the deforming forces act on the drops to make them flatter and resistant to further increases in fall velocity.

The behaviour of immiscible fluids becomes more complex when they are discharged as jet of varying speed. Kitamura and Takahashi (1986) showed that there are three main flow regimes that a jet undergoes, depending on the fluid properties and the relative speed of the jet and the receiving fluid. At low jet velocities, large drops form from a laminar jet of fluid in which Rayleigh instabilities grow until they pinch off the jet into individual drops – a flow regime named Rayleigh breakup, or laminar breakup. This flow regime results in a relatively uniform distribution of droplet sizes. In contrast, higher speed jets break up into a spray of fine drops that have a wide size distribution – a flow regime called the spray or atomization breakup. Instead of Rayleigh instabilities, the dominant breakup forces in the atomization regime are exerted by the fluid momentum in conjunction with the viscous forces. At intermediate jet speeds, there exists a transitional flow regime in which both the Rayleigh instabilities and the fluid momentum impart a substantial influence on the breakup process.

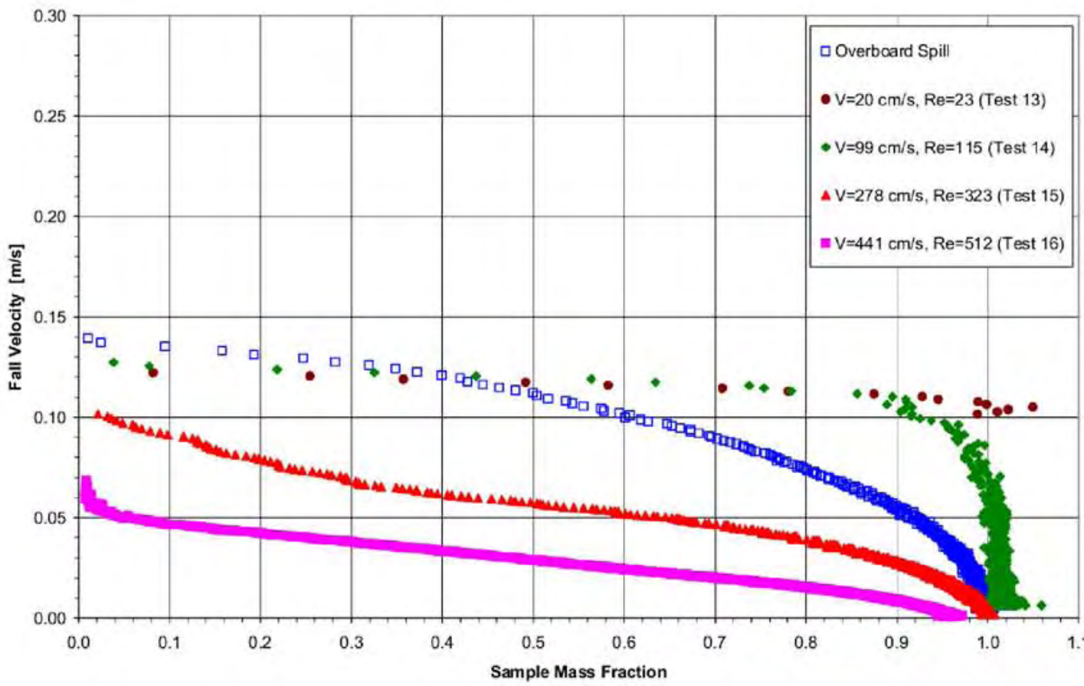
The SwRI (2007) conducted an experimental study of fall velocities for five different batches of SBM, labelled from A through E, exhibiting a range of densities used by industry in offshore drilling in the Gulf of Mexico. Out of these, the mud sample D exhibited the most similar density (1,402 kg/m^3) to the SBM planned for use in the WREP. They designed their experiment in such a way as to capture the most frequent spill modes, which they determined partly by conducting an industry survey, and partly by analysis of spill modes in the Gulf of Mexico from BOEMRE database statistics similar to those presented in Section 2.0. Furthermore, their experimental setup allowed them to simulate overboard spills of SBM (dropped above the sea surface), as well as to capture the different flow regimes (Rayleigh to atomization) for low- and high-speed jets (Figure 3-1) for each of the SBM samples, and to measure the fall velocity distributions for each of the spill scenarios.

The SwRI (2007) experimental study focused on producing fall velocity distributions instead of the more difficult to measure droplet size distributions, due to the fact that the fall velocity of the resulting SBM droplets is the controlling factor that determines the time period in which they would settle and reach the seafloor. The settling period also represents the time during which they would be subject to horizontal dispersal by the ambient ocean currents. Therefore, the expected terminal fall velocities under each release scenario will be a primary factor in their fate and footprint on the sea bottom. The fall velocity distributions for mud D, presented in Figure 3-2, were used as the basis for the SBM dispersion model.



Source: SwRI 2007

Figure 3-1 Falling Synthetic-based Mud Droplets (left panel) and Jet Breakup Regimes (three right panels)



Source: SwRI 2007

Figure 3-2 Fall Velocity Distributions for Synthetic-based Mud Droplets under Different Flow Regimes

The experimental scenario with the lowest jet speed (V=20 cm/s) for mud D corresponded to a laminar (not turbulent) breakup regime and as such, is considered representative of the SBM release scenarios involving large orifices or pipes, and the lowest expected jet speeds (e.g., surface release of mud tank contents through pipe; subsea release via BOP disconnect). The highest tested SBM jet speed (V=441 cm/s) was found to produce an atomization regime and as such, is representative of subsea releases through small cracks or orifices in the riser or mud transport system. It is notable that the two extreme jet regimes produced very different distributions of fall velocities – while the droplets produced by the low-speed jet exhibited very uniform fall velocities (centred around 11 cm/s), the highest-speed jet produced droplets with a variety of fall velocities, ranging from nearly 0 to 7 cm/s. In order to incorporate this aspect of the fall velocity distribution for the high speed jet, the two border values of 1 and 5 cm/s were selected as representative model inputs for this mode of release, accounting for approximately 95 percent of the points in the distribution.

3.2 Ambient Ocean Current Conditions

The ocean currents at White Rose are characterized by high variability, most of which is associated with the ocean's response to various atmospheric disturbances, ranging from atmospheric pressure systems, wind forcing during storms, to the influence of tropical cyclones tracking in the area. In contrast, the highly-predictable tidal current components play a relatively minor role, and explain approximately 20 percent of the annual current variability in the area (Oceans Ltd. 2011). In order to capture the full range of ocean current variability, including components driven by factors that are difficult to predict, it was deemed appropriate to adapt a subset of the currents measured throughout the full water column at White Rose over the past several years.

The Acoustic Doppler Current Profiler (ADCP) datasets for the three-year period from 2008 through 2010 (S. Russell, pers. comm.) were analyzed by AMEC for completeness of coverage in each season. The 2010 dataset was found to be the most complete, with only three gaps: 8 h, 3 days, and one spanning from mid-November to the end of year. To fill the gaps, and yield a representative one year time series, current data from the 2008 dataset from the representative periods were substituted satisfactorily.

It was found that the raw data contained a high-frequency (at periods less than 1 h) variability, particularly pronounced in the upper half of the water column. This current variability could not be linked to any plausible physical process, therefore it is likely attributable to measurement errors related to unfavourable sampling conditions. The factors affecting the quality of near surface data included surface reflection of the acoustic beam, high mixing rates, turbulence and water mass quality (S. Russell, pers. comm.).

In order to eliminate this unexplained variability, as well as to produce a uniform sampling interval for use in the SBM dispersion model, the raw time series were resampled at a uniform sampling rate of 10 minutes; they were then low-pass filtered by using a 30-point Finite Impulse Response filter to eliminate signals with a period smaller than two hours; finally, the filtered signal was resampled at the original 10 minute interval. Three ADCP depth bins, at depths of 28 m, 60 m and 112 m, were selected to represent the conditions at the surface, mid-depth and near the bottom. The seasonal statistics for the processed current for the three depth layers are presented in Table 3-1.

Table 3-1 Seasonal Current Statistics for the Processed Currents Used as Model Inputs

Season	Depth	Max Speed (cm/s)	Mean Speed (cm/s)	Mean Velocity (cm/s)	Direction To (° True N)
Winter (Jan-Mar)	Near surface	62	15	4	180
	Mid-depth	62	14	3	178
	Near bottom	40	13	4	165
Spring (Apr-Jun)	Near surface	43	12	2	173
	Mid-depth	26	10	0	175
	Near bottom	31	10	2	170
Summer (Jul-Sep)	Near surface	65	12	1	187
	Mid-depth	51	10	1	183
	Near bottom	31	8	1	174
Fall (Oct-Dec)	Near surface	61	20	4	175
	Mid-depth	47	15	2	179
	Near bottom	40	12	5	163
Source: ADCP data from Oceans Ltd. 2011.					

3.3 Synthetic-based Mud Model Setup

A modelling effort aimed at capturing the fate of accidental SBM spills would need to incorporate in a meaningful way the timing, location and amounts of each potential spill event, as well as the ocean current variability over the duration of the spill event. Moreover, since the timing of the spill cannot be predicted, it should be assumed that the spill can take place at any time during the year. Therefore, the SBM dispersion model runs should take into account the full ocean current time series available. In this context, the modelling approach was based on the consideration of the specific parameters and assumptions for each of the scenarios, which were derived from the details of each of the three selected release modes described in Section 2.2.

The scenario details are listed in Table 3-2 as they apply to the SBM dispersion model. Two main SBM flow regimes are considered in the modeled scenarios, the wide, low-speed jet that produces relatively uniform fall velocity distributions (approximately 11 cm/s), and a narrow, high-speed jet that produces droplets with a wider range of fall velocities (mostly within 1 to 5 cm/s). In order to capture the wide range of fall velocities expected for the subsea release mode resulting in a high-speed jet flow (e.g., a flex joint failure), this scenario was modelled separately at the two ends of the fall velocity range (plotted with pink markers in Figure 3-2). The four release scenarios were modelled for each of the four seasons, resulting in a total of 16 scenarios.

The settling times shown in Table 3-2 are a function of the fall velocity, as well as the location of the release above the seafloor. It is expected that the SBM droplets would reach the seafloor within a period from 3 to 30 minutes. Therefore, each collection of droplets released simultaneously would be subjected to a relatively narrow range of ocean currents, as the currents are not expected to change substantially within 30 minutes. The implication of this is that the droplets from spills with shorter durations of release are expected to fall within a relatively narrower area at the seafloor compared to longer-duration spills, all other factors being equal. In contrast, if the SBM is released over a longer period of time (e.g., 3 h in the flex joint failure scenarios), the droplets released toward the end of the spill event are likely to experience different current conditions compared to those at the beginning of the spill.

Table 3-2 Synthetic-based Mud Model Input Parameters for Each Release Scenario

Release Scenario	Total Volume (m^3)	Duration of Release (hours)	SBM Flow Type	Fall Velocity (cm/s)	Location of Release	Settling Time (seconds)
Surface Tank Discharge	60	0.5	Wide, low-speed jet	11	120 m above seafloor	1,091
Flex Joint Failure I	49	3	Narrow, high-speed jet	1	20 m above seafloor	2,000
Flex Joint Failure II	49	3	Narrow, high-speed jet	5	20 m above seafloor	400
BOP Disconnect	49	1	Wide, low-speed jet	11	20 m above seafloor	182

The modelling procedure included splitting the full spill volume into discrete collections of droplets over the duration of the release. Since the input current series had a time resolution of 10 minutes, the currents were linearly interpolated so that each collection of packages experienced the most up-to-date set of current conditions. To calculate the horizontal trajectory of the droplets, it was necessary to compute the time they would spend in each of the three depth layers. Based on an analysis of the ADCP data, the surface layer was defined as extending from 0 to 30 m depth (25 percent of the water column), while the bottom layer was taken from the seafloor to 12 m above the seafloor (10 percent of the water column). The mid-depth currents were applied to the middle 65 percent of the water column. The destination at the seafloor for each collection of droplets experiencing a set of current conditions [(u_s, v_s),(u_m, v_m),(u_b, v_b)] is computed according to the following equations:

$$x = x_0 + u_s \times t_s + u_m \times t_m + u_b \times t_b$$

$$y = y_0 + v_s \times t_s + v_m \times t_m + v_b \times t_b$$

where the subscripts *s, m, b* stand for *surface, mid-depth* and *bottom*, respectively. The time spent in each of the three layers is defined in terms of the initial height above the seafloor, $H_{release}$, and the settling velocity, $w_{settling}$, as follows:

$$t_s = \frac{H_{release}}{w_{settling}} \times 0.25$$

$$t_{sm} = \frac{H_{release}}{W_{settling}} \times 0.65;$$

$$t_{b} = \frac{H_{release}}{W_{settling}} \times 0.10.$$

for the surface release, and in the following manner for the subsea release scenarios:

$$t_{p} = \frac{H_{release}}{W_{settling}} \times 0;$$

$$t_{sm} = \frac{H_{release}}{W_{settling}} \times 0.40;$$

$$t_{b} = \frac{H_{release}}{W_{settling}} \times 0.60.$$

Each set of east and north destination components (*x, y*) were fit within a horizontal grid with a 30 m resolution, and the amount of SBM within each grid cell was counted for the full duration of the spill event. Any model grid cell that received any amount of SBM was included within the spill area. The thickness of the initial SBM layer on the seafloor was computed on the assumption that the SBM was equally distributed across the area of each cell. In order to capture the full range of seasonal conditions, approximately 13,000 independent spill events were simulated for each of the four seasons. The distance from the release site, as well as the size of the footprint of each spill event, was recorded separately, and the most probable and extreme seasonal statistics were derived for each modelled scenario. The presentation and discussion of these results are the subject of the next section.

3.4 Synthetic-based Mud Dispersion Model Results

The outcomes of the modelled scenarios reveal several ways in which the mode of release and the ocean current conditions influence the spill footprint. The results for the modelled scenarios are presented in Table 3-3. These include the maximum and median seasonal values for the area of the predicted spill footprints, as well as the maximum and average values of the thickness of SBM within the projected spill area. In addition to the size of the spill area, it was important to characterize the location of the spill relative to the position of the release. This distance was calculated in each model realization as the location of the model cell that received the highest fraction of the spilled SBM volume. In the majority of the realizations, the spill footprints exhibited an elongated shape, which was measured and recorded as the length of the footprint, and it represents the longest horizontal dimension of the area in which the SBM droplets land.

The distance from the release site at which most of the SBM droplets will land appears to be largely dependent not only on the height of release above the sea bottom and the droplet fall velocity, but also on the seasonal currents. Overall, there was no strong tendency for the spills to land in a particular direction from the spill site in any given season. The maximum predicted distances from the release site are those for the winter surface dispersion scenario and the first riser flex joint scenario (high-speed jet, low fall velocity), where the maximum concentrations of the footprint were found at 1,061 and

1,008 m from the release site, respectively. For the other dispersion scenarios, the spill footprints remain within a maximum distance of 201 m (second riser flex joint scenario, high fall velocity), and 108 m (BOP disconnect scenario). These maximum distances are expected to occur during periods when the current magnitudes are at the seasonal maximum. However, this does not necessarily imply that the spill footprint is larger than normal, only that the footprints are shifted horizontally with respect to the release location.

Table 3-3 Synthetic-based Mud Dispersion Modelling Results for All Scenarios

SBM Dispersion Scenario		Distance from Release Site (m)		Footprint Length (m)		Footprint Area (m^2)		SBM Layer Thickness (cm)	
		max	med	max	med	max	med	max	mean
Surface Tank Rel.	Winter	1,061	201	101	47	4,500	1,800	6.7	4.4
	Spring	458	162	81	47	3,600	1,800	6.7	4.5
	Summer	677	134	106	47	4,500	1,800	6.7	4.4
	Fall	834	212	133	51	5,400	1,800	6.7	4.1
Riser Flex Joint I	Winter	1,008	192	579	161	23,400	6,300	5.4	0.9
	Spring	443	175	465	164	18,900	6,300	5.4	0.9
	Summer	836	150	839	166	34,200	6,300	5.4	0.9
	Fall	757	234	826	206	32,400	8,100	5.4	0.7
Riser Flex Joint II	Winter	201	42	140	56	5,400	1,800	5.4	2.9
	Spring	108	30	117	57	5,400	1,800	5.4	2.8
	Summer	190	30	192	57	9,000	1,800	5.4	2.8
	Fall	175	60	189	65	8,100	2,700	5.4	2.4
BOP Disc.	Winter	108	30	46	34	2,700	900	5.4	4.9
	Spring	67	30	44	34	3,600	900	5.4	4.9
	Summer	108	30	53	34	3,600	900	5.4	4.8
	Fall	85	30	55	35	3,600	900	5.4	4.8

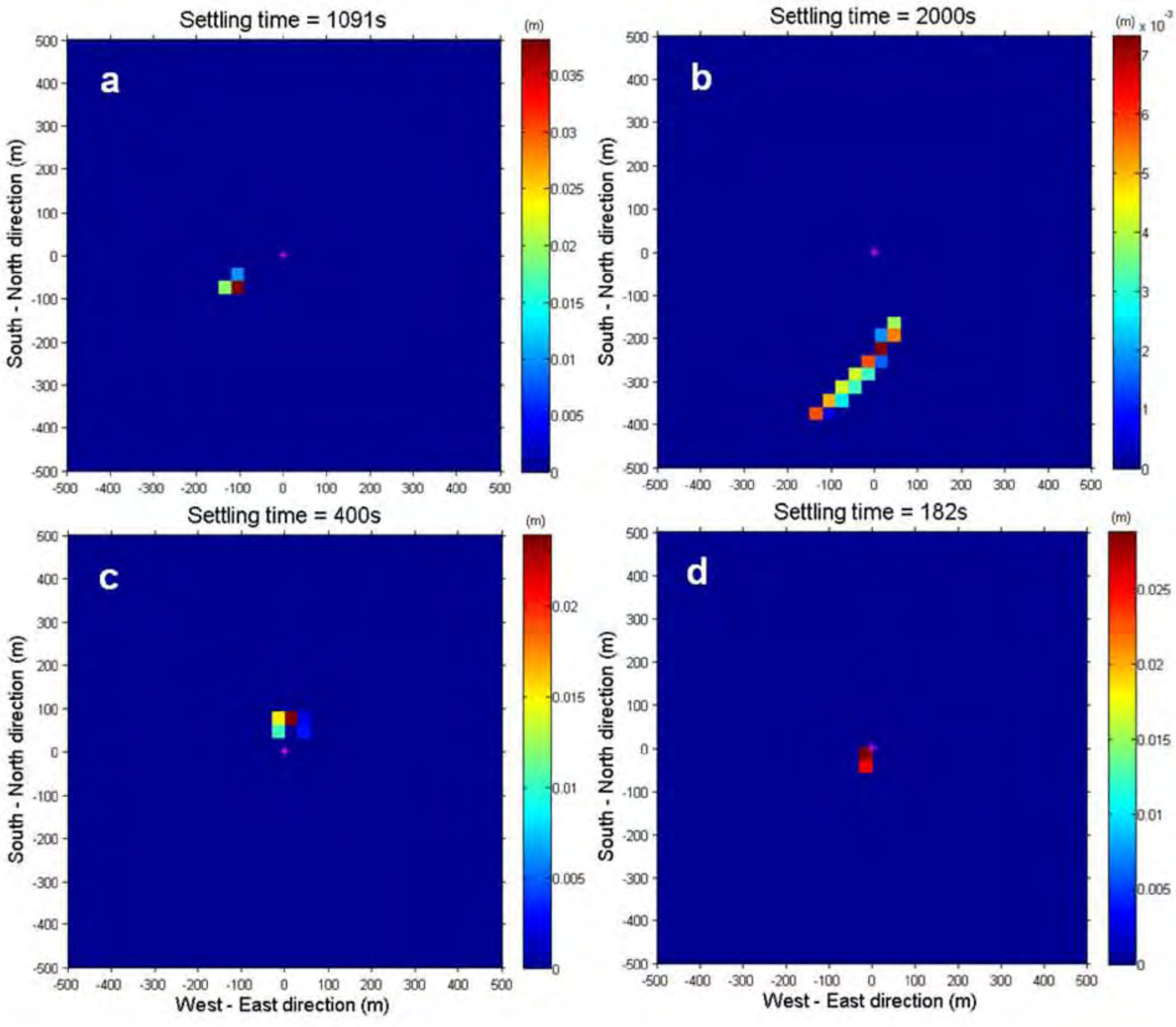
The footprint areas, and the associated footprint lengths, are expected to be associated with the period over which the SBM is released, the fall velocities, as well as the variability of the currents over that period and the settling period.

The largest footprint areas were found for the first riser flex joint scenario, which had the lowest fall velocity and the longest release period of 3 h. The single largest spill area in this scenario was observed in the winter season, and represented an area spanning approximately 579 m long by 40 m wide. Since the SBM was dispersed over a large area, the average layer thicknesses were much lower for this dispersion scenario compared to the other three.

The majority of the spill footprints were 1800 m^2 or smaller, corresponding to spill areas measuring 30 m by 60 m. The smallest footprints (30 m by 30 m) were predicted for the

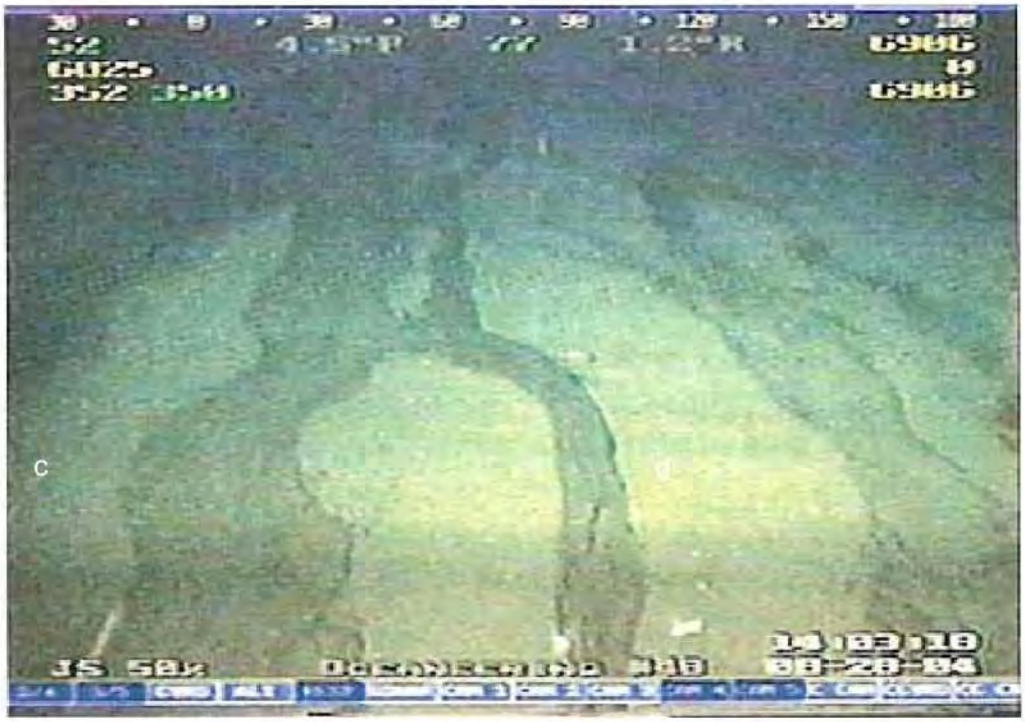
BOP disconnect scenarios, which exhibited a combination of low height above sea bottom, relatively quick release time (1 h), and high fall velocities.

Typical realizations of the spill footprints for the four selected modes of release are shown for the winter season in Figure 3-3. In the context of these descriptions of the footprint areas and thicknesses, it should be noted that these are only preliminary dimensions of the projected landing area for the SBM droplets, and the estimated SBM layer thickness if the full spill volume landing in each model cell were to be equally distributed within that cell. The subsequent fate and the footprint are likely to evolve in a less predictable fashion, as the negatively buoyant SBM droplets are expected to coalesce into streams or pools, and flow under the influence of gravity and the local bathymetric features, as evidenced by the photographic images of the seafloor taken following the Marathon SBM spill event offshore Nova Scotia in 2004 (Figure 3-4).



Note: a) surface low-speed jet release; b) subsea high-speed jet – low fall velocity; c) subsea high-speed jet – high fall velocity; d) subsea low-speed jet (BOP disconnect)

Figure 3-3 Example Realizations for the Four Modelled Release Scenarios in Winter



Source: Marathon Oil Corporation for CNSOPB (2005)

Figure 3-4 Synthetic-based Mud (dark ribbons) on the Sloping Seafloor as Seen on Remotely Operated Vehicle Video Footage at the Marathon Oil Spill Site, Offshore Nova Scotia

3.5 Synthetic-based Mud Dispersion Model Sensitivity Tests

Two alternative sets of model scenario parameters were derived for sensitivity testing of the model outcomes, based on the observed relationships between the physical parameters and the model outcomes in the main model runs. The first one involved increased fall velocities (by 1 cm/s for all scenarios), while the second one involved release periods with twice the length of the original model runs. The results, shown in Figure 3-3 and Figure 3-4 reveal further the influence of these parameters on the model outcomes, as well as the cases in which they make the largest difference to the outcomes.

An increase in the fall velocities by 1 cm/s (Figure 3-3) resulted in smaller footprint areas and lengths in all scenarios, but the difference was most pronounced for the first flex joint failure scenario, in which the original fall velocity was 1 cm/s. In this instance, doubling the fall velocity cut the footprint areas in half, and similarly reduced the footprint distances from the site of release. This resulted in an increase in the average SBM layer thicknesses, as more of the material was distributed within a smaller area on the seafloor. The other scenarios showed similar effects, but to a lesser degree, as a fall velocity change of 1 cm/s represented a smaller percentage of the original fall velocity for those scenarios.

Table 3-4 Sensitivity Testing for all Fall Velocities Increased by 1 cm/s: Synthetic-based Mud Dispersion Modelling Results for All Scenarios

SBM Dispersion Scenario		Distance from Release Site (m)		Footprint Length (m)		Footprint Area (m^2)		SBM Layer Thickness (cm)	
		max	med	max	med	max	med	max	mean
Surface Tank Rel.	Winter	969	182	95	46	4,500	1,800	6.7	4.5
	Spring	417	150	77	45	3,600	1,800	6.7	4.7
	Summer	626	124	100	46	4,500	1,800	6.7	4.6
	Fall	774	192	124	49	4,500	1,800	6.7	4.2
Riser Flex Joint I	Winter	510	95	304	95	11,700	3,600	5.4	1.6
	Spring	234	90	247	97	9,900	3,600	5.4	1.6
	Summer	437	67	435	98	17,100	3,600	5.4	1.5
	Fall	391	120	428	118	17,100	4,500	5.4	1.3
Riser Flex Joint II	Winter	175	42	121	52	5,400	1,800	5.4	3.1
	Spring	95	30	102	52	5,400	1,800	5.4	3.1
	Summer	162	30	165	53	7,200	1,800	5.4	3.1
	Fall	150	42	163	59	7,200	1,800	5.4	2.6
BOP Disc.	Winter	95	30	45	34	3,600	900	5.4	5
	Spring	67	30	42	34	2,700	900	5.4	5
	Summer	95	30	52	34	2,700	900	5.4	4.9
	Fall	85	30	53	35	2,700	900	5.4	4.8

The second sensitivity test (Table 3-5) showed that doubling the time period over which the SBM is discharged increases the average and maximum footprint areas by approximately a factor of two, while the distances of the footprints from the site of release were changed to a much lesser degree. These tests illustrate the fact that all other factors being equal, lengthening the period of release presents the opportunity for the overall volume of SBM to be exposed to ocean currents that might change drastically and therefore, substantially change the expected trajectory of SBM droplets at the end of the release, compared to that at the beginning of the spill event. However, the tradeoff is that the larger footprint will result in a lower average SBM layer thickness at the seafloor, compared to the case where a smaller area receives a larger portion of the SBM.

Table 3-5 Sensitivity Testing for all Release Periods Increased by a Factor of Two: Synthetic-based Mud Dispersion Modelling Results for All Scenarios

SBM Dispersion Scenario		Distance from Release Site (m)		Footprint Length (m)		Footprint Area (m^2)		SBM Layer Thickness (cm)	
		max	med	max	med	max	med	max	mean
Surface Tank Rel.	Winter	1,060	201	207	73	8,100	2,700	6.7	2.7
	Spring	458	162	157	71	6,300	2,700	6.7	2.9
	Summer	677	134	219	72	9,000	2,700	6.7	2.8
	Fall	824	212	284	81	11,700	2,700	6.7	2.5
Riser Flex Joint I	Winter	969	192	919	237	42,300	11,700	5.0	0.5
	Spring	433	175	637	247	36,900	11,700	5.1	0.5
	Summer	836	150	1,406	249	65,700	12,600	4.3	0.5
	Fall	750	234	1,128	308	54,900	16,200	3.6	0.4
Riser Flex Joint II	Winter	190	42	208	71	9,900	2,700	5.4	1.9
	Spring	108	30	151	73	9,000	2,700	5.4	1.8
	Summer	190	30	305	74	15,300	2,700	5.4	1.8
	Fall	175	60	250	86	11,700	3,600	5.4	1.5
BOP Disc.	Winter	108	30	46	34	2,700	900	5.4	4.9
	Spring	67	30	44	34	3,600	900	5.4	4.9
	Summer	108	30	53	34	3,600	900	5.4	4.8
	Fall	85	30	55	35	3,600	900	5.4	4.8

4.0 SUMMARY

It is anticipated that certain stages of the drilling operations in the development of the WREP will involve the use of SBMs, due to their unique performance characteristics, as well as their low toxicity and relatively low environmental effects compared to OBMs.

As part of the environmental assessment process, to characterize possible accidental SBM releases, a review was conducted of the latest scientific literature and industry spill databases from Atlantic Canada and the US OCS to determine the most probable modes of accidental release. Four potential release spill scenarios were selected as being most representative for the WREP:

- Surface tank discharge
- Riser flex joint failure (two scenarios, for two fall velocities)
- BOP disconnect

Subsequently, a numerical dispersion modelling study was conducted to predict the potential seasonal footprints of SBM spills on the seafloor for each of the four scenarios.

The comparison of regional and local spill statistics from 1997 to 2011 (published by the C-NLOPB, CNSOPB and the BOEMRE) showed that the modes of accidental discharges of SBMs are similar between regions, with surface spills being the most frequent, while subsea spills due to leaks or failures in the mud circulation system or emergency events are less frequent, but tend to result in bigger amounts of spilled volumes. However, it is notable that drilling operations offshore Newfoundland and Labrador have generally resulted in smaller spill amounts compared to other jurisdictions, which could be at least partly explained by the fact that drilling operations on the Grand Banks are conducted on the continental shelf in relatively low water depths (on the order of 100 m), compared to the developments offshore Nova Scotia and in the Gulf of Mexico (on the order of 2,000 m). The lower water depths generally imply that lower amounts of drilling mud are required for the drilling operations, as the total length of components in the mud circulation system are shorter and of smaller overall capacity.

The SBM planned for use during drilling operations in the WREP will be based on the synthetic drilling fluid Puredrill IA-35LV (65 percent by volume), and will exhibit a total density of 1,350 kg/m^3. The SBM is therefore negatively buoyant and immiscible in water, and is expected to form droplets of varying sizes that will fall toward the seafloor upon being discharged in the marine environment. The fall velocities of droplets resulting from the most frequent modes of accidental SBM spills have been measured in an experimental laboratory study commissioned by the BOEMRE, and conducted by the SwRI (2007). These experimental results formed the basis for the numerical SBM dispersion model developed by AMEC, in which four different release scenarios were represented during each season, resulting in a total of 16 spill model scenarios.

The numerical model used a full-year time series derived from ADCP current measurements at White Rose from 2008 to the end of 2010, with approximately 13,000 model realizations being simulated in each seasonal scenario per release mode. The total spill footprint area, length and distance from release site, as well as projected initial

SBM layer thickness on the seafloor, were estimated for each simulated event, and seasonal median, maximum and average values were derived.

The distance from the release site at which most of the SBM droplets will land appears to be largely dependent not only on the height of release above the sea bottom and the droplet fall velocity, but also on the variability of the seasonal currents. Overall, there was no strong tendency for the spills to land in a particular direction from the spill site in any given season.

The maximum predicted distances from the release site are those for the winter surface dispersion scenario and the first riser flex joint scenario (high-speed jet, low fall velocity), where the maximum concentrations of the footprint are found at 1,061 and 1,008 m from the release site, respectively. For the other dispersion scenarios, the spill footprints remain within a maximum distance of 201 m (second riser flex joint scenario, high fall velocity), and 108 m (BOP disconnect scenario). These maximum distances are expected to occur if a spill occurs during periods when the current magnitudes are at the seasonal maximum. However, this does not necessarily imply that the spill footprint would be larger than normal, only that the footprint would be shifted horizontally with respect to the release location.

The footprint areas, and the associated footprint lengths, are expected to be associated with the period over which the SBM is released and the fall velocities, as well as the variability of the currents over the release and settling periods. The largest footprint areas were found for the first riser flex joint scenario, which had the lowest fall velocity and the longest release period of 3 h. The single largest spill area in this scenario was observed in the winter season, and represented an area spanning approximately 579 m long by 40 m wide. Since the SBM was dispersed over a large area, the average layer thicknesses were much lower for this dispersion scenario compared to the other three.

The majority of the spill footprints were 1,800 m^2 or smaller, corresponding to spill areas measuring 30 m by 60 m. The smallest footprints (30 m by 30 m) were predicted for the BOP disconnect scenarios, which exhibited a combination of low height above sea bottom, relatively quick release time (1 h) and high fall velocities.

The interpretation of the predicted footprint areas and thicknesses should take into account that these are only preliminary dimensions of the projected landing area for the SBM droplets, and the estimated SBM layer thickness if the full spill volume landing in each model cell were to be equally distributed within that cell. The subsequent fate and the footprint are likely to evolve in a less predictable fashion, as the negatively buoyant SBM droplets are expected to coalesce into streams or pools, and flow under the influence of gravity and the local bathymetric features. As there is a tradeoff between the area covered by the spill and the thickness of the spill, it can be expected that an area of the seafloor that is relatively flat and with few roughness features is likely to result in a thinner and widely distributed SBM layer, while a localized depression in the seafloor could retain the received SBM as a thicker layer within a smaller area. While the weathering properties for the SBM considered in the present study are not precisely known, it is expected that the biodegradation of the SBM on the seafloor would take place over periods on the order of several weeks. This timescale far exceeds the duration of the spill and settling of SBM to the floor; therefore, the SBM is considered to be stable during the entire duration of the physical dispersion of the droplets in all modelled scenarios.

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6.0 ACRONYMS

Term	Description
ADCP	Acoustic Doppler Current Profiler
BOEMRE	Bureau of Ocean Energy Management, Regulation and Enforcement
C-NLOPB	Canada-Newfoundland and Labrador Offshore Petroleum Board
CNSOPB	Canada-Nova Scotia Offshore Petroleum Board
h	hour
kg/m^3	kilograms per cubic metre
m/s	metres per second
OWTG	Offshore Waste Treatment Guidelines
OBM	Oil-based mud (a type of drilling mud)
OCS	Outer Continental Shelf (ref. to United States)
s	seconds
SBM	synthetic-based mud (a type of drilling mud)
SwRI	Southwest Research Institute
WBM	water-based mud (a type of drilling mud)
WREP	White Rose Extension Project

7.0 GLOSSARY

Word	Definition
ADCP	An instrument designed to measure water flow by making use of the acoustic Doppler effect
Bathymetry	The measurement of depths of water in oceans, seas and lakes; also the information derived from such measurements
Drilling Mud	A special mixture of clay, water and chemical additives pumped down the wellbore through the drill pipe and drill bit to cool the rapidly rotating bit, lubricate the drill pipe as it turns in the wellbore, and carry rock cuttings to the surface; may have a **water base** or a **synthetic oil base** fluid
Fall Velocity	The vertical speed at which particles or negatively buoyant droplets fall through the water column
Roughness features	Seafloor irregularities, including ripples, dunes, channels, localized elevations and depressions
Rayleigh instability	The flow perturbation responsible for the tendency of streams and droplets to break up into smaller droplets under laminar flow in a stagnant fluid
Oil-based Mud (OBM)	A **drilling mud** in which the continuous phase consists of diesel or mineral oils that are refined from crude oil
Synthetic-based Mud (SBM)	A **drilling mud** in which the continuous phase is a synthetic fluid
Water-based Mud (WBM)	A **drilling mud** in which the continuous phase is water
Water Column	The vertical dimension of a body of water (i.e., the water between a reference point or area on the surface and one located directly below it on the bottom)

Note: Bolded **words within a definition are themselves defined**