2014 INTERNATIONAL OIL SPILL CONFERENCE

Modeling Subsurface Dispersant Applications for Response Planning and Preparation

Deborah Crowley, Daniel Mendelsohn, Nicole Whittier Mulanaphy, Zhengkai Li and Malcolm Spaulding

RPS ASA, 44 Village Square Drive, South Kingstown, RI 02879, USA
Tel: 1 401 789 6224 ~ Fax: 1 401 789 1932

Deborah.Crowley@rpsgroup.com, Daniel.Mendelsohn@rpsgroup.com
Nicole.Mulanaphy@rpsgroup.com, Zhengkai.Li@rpsgroup.com,Malcolm.Spaulding@rpsgroup.com

ABSTRACT 300204:

The increase in oil and gas development activity at increasing water depths has highlighted the need for modeling tools to evaluate the unique aspects of accidental deepwater releases, one aspect being the need to assess the impact of subsurface dispersant application to a deepwater blowout. In response to this need, the effect of subsurface dispersant application has been implemented within RPS ASA's blowout model OILMAPDeep. OILMAPDeep was developed to simulate deepwater blowout releases; it predicts the evolution and characteristics of the subsurface plume and estimates the oil droplet size distribution associated with the release. The droplet size distribution dictates the vertical transport of oil within the water column, and impacts the relative volume anticipated to either surface or remain trapped in the water column. Droplet sizes are primarily a function of the energy of the release and the oil-water interfacial tension. The energy of the release is characterized by a reference velocity, typically the exit velocity, and the oil-water interfacial tension as a function of the oil properties. Dispersants mixed with oil reduce the oil-water interfacial tension, which in turn reduces the droplet sizes associated with treated releases serving to delay or eliminate surfacing oil. The present model implementation takes advantage of recent studies that have quantitatively assessed the relationship between the dispersant to oil ratio and surface tension.

Here we present a background of the OILMAPDeep module, the governing physical processes of droplet formation, and the relationship between dispersant-to-oil ratio (DOR) and droplet size formation as characterized in the model. A description of the model implementation including model inputs and outputs are provided. Furthermore a set of scenarios are presented that demonstrate the model's capabilities for planning and preparing response activities in the event of a potential oil well blowout. This paper shows how the implementation of subsurface dispersant application within OILMAPDeep provides an effective means of evaluating potential response activities associated with subsurface dispersant application to a deepwater blowout. This includes evaluating the effect of subsurface dispersant application on droplet size distribution, and the ultimate impact on the timing, location and the relative volume of surfacing oil.

INTRODUCTION:

The progression of oil and gas development technologies has resulted in an increase in deepwater well development. This in turn has necessitated tools to evaluate the impact of potential accidental releases of oil and gas from a deepwater well blowout, and furthermore to assess the efficacy and effects of spill response activities such as subsurface dispersant application. To accommodate this need a subsurface dispersant feature was added to OILMAPDeep within the OILMAP model system.

OILMAPDeep is an integrated component within the OILMAP modeling system. OILMAPDeep is a blowout model that evaluates and connects near field blowout dynamics with OILMAP's far field transport and weathering calculations to estimate (or predict) surface, subsurface and shoreline oiling. This paper describes the blowout model algorithms including the incorporation of the subsurface dispersant feature and also presents case studies of a subsurface blowout. The case studies evaluate several accidental blowout releases and presents the model predictions associated with (1) high and low volume of dispersant applied to released oil, (2) partial treatment of oil with dispersant, and (3) an untreated release of oil. Section 2 presents the model algorithms, Section 3 contains the case studies and Section 4 contains conclusions.

MODEL DESCRIPTION:

OILMAPDeep comprises two sub-models, a plume model and a droplet size model. The plume model predicts the evolution of plume position, geometry, centerline velocity and oil and gas concentrations until the plume either surfaces or reaches a terminal height at which point the plume is trapped. The droplet model predicts the size and volume (mass) distribution of the oil droplets. The near field blowout model results calculated in OILMAPDeep define the initial conditions for far field simulations in OILMAP3D, where the oil mass is initially released at the plume trap height in droplets defined by the calculated size distribution. The near-field model is on the timescale of seconds and length scale of hundreds of meters, where the far-field model is on the scales of hours/days and kilometers. Once the oil reaches the plume trap height the transport of the oil droplets is dominated by their own buoyancy and environmental conditions, rather than the blowout specifics. Thus, when modeling the potential impacts of an oil well blowout the near field predictions are an input to the far field model.

The OILMAPDeep blowout model is based on the work of McDougall (gas plume model, 1978), Fanneløp and Sjøen (1980a, plume/free surface interaction), Spaulding (1982, oil concentration model), Kolluru, (1993, World Oil Spill Model implementation), Spaulding et.al. (2000, hydrate formation) and Zheng et.al. (2002, 2003, gas dissolution). A simplified integral jet theory is employed for the vertical as well as for the horizontal motions of the gas-oil plume. Oil and gas buoyancy are incorporated based on their respective densities and, for gas, include the effects of compression based on methane characteristics. The necessary model parameters defining the rates of entrainment and spreading of the jet are obtained from laboratory studies (Fanneløp and Sjøen, 1980a). The gas plume analysis is described in McDougall (1978), Spaulding (1982), and Fanneløp and Sjøen (1980a). A hydrate formation and dissociation model is formulated based on a unique equilibrium kinetics model developed by R. Bishnoi (1989) and colleagues at the University of Calgary.

Oil droplet size distribution calculations are based on the methodology presented by Yapa and Zheng (2001b) and Chen and Yapa (2007) which uses a maximum diameter calculation and the associated volumetric droplet size distribution. The maximum diameter can be determined using Hinze (1955), Wang and Calabrese (1986) (adopted by Johansen et al (2013), or Boxall et al. (2012). The droplet size distribution can be described utilizing either Rosin-Rammler (1933) or any other user-defined distribution function. The maximum droplet size estimate considers the continuous phase properties of the receiving fluid in terms of density and interfacial tension (IFT) as well as the conditions of the release in terms of the release velocity.

The gas dissolution algorithm is a function of gas bubble size, the appropriate gas saturation depending on the temperature and the estimated water column concentration of dissolved gas in the plume water. Formulations, originally from Johnson et al. (1969) and Clift et al. (1978), are used to develop general formulations for mass transfer coefficients of bubbles in contaminated liquids based on three different size ranges for use in the gas dissolution calculations. The bubbles are approximated as spheres for small size, ellipsoids for intermediate size, and spherical-caps for large size. Consistent with Zheng (2003) the critical diameter is 5 mm between small and intermediate size ranges and 13 mm between intermediate and large size ranges.

Subsurface dispersant application was implemented in the model through incorporation of a reduced IFT associated with the dispersant treatment. IFT reduction is based on experimental studies presented by Khelifa (2009, 2011), Venkataraman et. al (2013) and Johansen et. al (2013). Details of the subsurface dispersant module are provided in Section 2.1.

Subsurface dispersant treatment:

Subsurface dispersant treatment is incorporated in the OILMAPDeep module. The module allows temporally-varying partial or total plume treatment with dispersant. Throughout the simulation, the treatment conditions can vary as (a) being treated or untreated, (b) the percentage of the plume treated, and (c) the dispersant-to-oil ratio (DOR) of the treated fraction. This results in time-varying droplet size distributions which are seamlessly incorporated in the far-field OILMAP simulation.

The OILMAPDeep droplet size algorithm employed for the case studies is described and the methodology to quantify the effect of IFT reduction on oil dispersion is discussed, along with a comparison of alternative size distribution calculations.

Droplet size distribution algorithm:

Many natural and engineered processes of multiphase releases have indicated that the droplets/particles/bubbles associated with such releases vary in sizes which can be described by standard mathematical distributions. Each distribution function typically has a reference size (e.g. d_{50}, d_{95} or d_{max}) and the shape coefficients that determine the spread and skewness of the distribution. The characteristic diameter d_{95} represents the size at which 95% of the volume (mass) can be found in droplets equal to or smaller than that size. To provide case examples this paper presents an analysis using a d_{95} (d_{max}) calculation based on the Hinze (1955) d_{max} formulation and the Rosin-Rammler (1933) distribution function; Hinze approximated d_{max} to be equivalent to d_{95}. This formulation requires two coefficients, which define the maximum droplet size and subsequent distribution, respectively. The coefficients vary depending on the continuous phase of the receiving fluid, based on the estimated regime calculated as a function of the

localized gas to oil ratio (GOR). OILMAPDeep employs variable coefficients depending on the flow regime in a similar manner as presented by Yapa and Chen (2007).
The maximum droplet size is calculated as:

$$d_{max} = kD_o We^{-0.6}$$

where

k = maximum droplet diameter coefficient

d_{max} = maximum droplet diameter

D_o = release opening diameter

$We = \frac{v_0^2 \, D_0 \rho}{\sigma}$ = Weber number

v_o = plume exit velocity

σ = interfacial tension

ρ = density

The plume exit velocity is calculated from the total volumetric release rate based on the oil release and local GOR (compressed at depth) considering reservoir properties, release depth and the cross sectional area of the release opening. The density of the continuous phase and IFT between fluids are defined depending on the regime (high or low GOR), with water density typically in the range of 1,025 kg/m^3 and gas density calculated as a function of depth. The oil-gas IFT is approximately 5 mN/m and the oil-water IFT varies typically between 15-30 mN/m, depending on the oil type and weathering conditions. The resulting droplet sizes are calculated as even increments of the maximum size based on the number of size classes (bins) desired and the volume fraction of each bin is calculated with the Rosin-Rammler distribution as follows:

$$Vol(d_b) = 1 - exp\left[-2.996 \left(\frac{d_b}{d_{max}}\right)^n\right]$$

where

$Vol(d_b)$ = volume fraction of droplet diameter bin d_b

d_b = bin droplet diameter

d_{max} = maximum droplet diameter

n = droplet diameter class number

The coefficients suggested by Chen and Yapa (2007) and Johansen (2002) are summarized in Table 1 along with those implemented in OILMAPDeep.

Table 1: Coefficients k and n used in d_{max} and Rosin-Rammler distribution calculation

Regime	Coefficient	Chen & Yapa [1]	SINTEF[2]	OILMAPDeep[3]
High GOR	*k*	4	4	4
High GOR	*n*	2.5	2.5	2.5
Low GOR	*k*	20-27.5	20	20
Low GOR	*n*	1.6	2.5	1.6

1 – Chen and Yapa (2007) and Clarkson Deepwater Oil and Gas Model (CDOG)
2 – Johansen (2002) based on the DeepSpill (2000) data
3 – Low GOR for *n* is from CDOG because it assumes the shape of the distribution would be different for the high and low GOR cases. Low GOR *k* is from SINTEF as it was from comparison to data.

The droplet size distribution is stored in the model and the appropriate mass fraction in each size is released at every model time step at the location of plume trap height as calculated by the plume model.

Subsurface dispersant:

Subsurface dispersant was implemented to allow for spatially and temporally varying treatment of the subsurface plume in the model simulation. Treatment can vary throughout the simulation, limited only by the far field model timestep (on the order of minutes). Dispersant treatment includes start and end time of treatment, fraction of the plume treated and the volumetric rate of dispersant used for each treatment period. The DOR and associated IFT reduction for the treated fraction are calculated and the corresponding droplet size distribution is calculated for both the treated and untreated fraction of the release. The two distributions are then combined to appropriately reflect their weighted fraction. Throughout the far field simulation oil mass is released seamlessly within the appropriate size distribution based on the applicable treatment definition for the time step. The droplet size distribution for both treated and untreated fraction utilize the formulation presented in Section 2.1.1, with the treated fraction using an adjusted IFT based on the treatment definition. The IFT is calculated based on the dispersant to oil ratio (DOR) which is defined as follows:

$$DOR = \frac{Q_{dispersant}}{Q_{oil} * PTF}$$

where

$Q_{dispersant}$ is the volumetric rate of dispersant

Q_{oil} is the volumetric rate of oil

PTF is the treated fraction of the plume [0 to 1]

IFT reduction as a function of DOR have been estimated empirically by Khelifa (2009 and 2011), Johansen et. al (2013), and Venkataraman et. al (2013). Findings from these studies are presented in Figure 1. The figure shows that all groups observed similar trends of the dispersant effect on IFT reduction, yet differing absolute results exist across studies, presumably owing to variation of mixing energy and mixing time and the method for the application of dispersant to oil (e.g., premix versus side-injection). In all cases the IFT is reduced from the initial value with increasing DOR, and then reaches a minimum after which point increasing DOR does not decrease IFT but actually causes a slight increase. The relationship between IFT and DOR is understood in the trend but not well quantitatively established. OILMAPDeep provides two options to evaluate this relationship; the user can either define the reduced IFT or alternatively can select a proxy curve of IFT vs. DOR defined in the model. In the following case studies the proxy curve used was based on the average values reported by Khelifa and So (2009).

CASE STUDY:

A case study is presented to demonstrate the use of the model by performing comparisons of simulations of a subsurface release of oil and gas varying subsurface dispersant treatment options. The case study evaluates four different scenarios; an untreated release, treatment of the entire plume with a 1:40 DOR, treatment of the entire plume with a 1:100 DOR, and partial plume treatment with 50% of the plume treated with a 1:40 DOR.

Case study scenario definition:

The case study evaluated four different dispersant treatment options of a hypothetical 15 day subsurface release of oil and gas at a location west of the Shetland Islands located at the merger of the Atlantic Ocean and North Sea. The release conditions are summarized in Table 2. The environmental characteristics used to force the far field model included a water column temperature and salinity profile, wind fields, and local currents. The water column temperature and salinity profile was obtained from the World Ocean Database 2001 (WOD01) based on work from Levitus (1982) and Conkwright et al (2002). Winds were obtained from output of the U.S. Navy Operational Global Atmospheric Prediction System (NOGAPS), and the 3D currents were acquired from the HYCOM (HYbrid Coordinate Ocean Model) 1/12 degree global simulation assimilated with NCODA (Navy Coupled Ocean Data Assimilation) from the U.S. Naval Research Laboratory (http://www.hycom.org). The model was run for 15 days over an arbitrary chosen period. The scenarios were identical with the exception of the dispersant treatment characteristics. A summary of the four different case scenarios is provided in Table 3.

Table 2: Release Characteristics

Oil Type	Release rate (bbl/day)	Duration (days)	GOR (scf/stb)	Density (kg/m^3)	IFT (mN/m)	Opening Dia. (m.)	Depth (m)	Temp. (^{o}C)
Claire Crude Oil	20,000	15	2,000	910	27.5	0.305	1,040	37.78

Table 3: Scenario dispersant treatment characteristics

ID	Description	Percent Treated (%)	Dispersant Rate (gallons/day)	Treated Fraction DOR	Dispersant Pump Rate (gallons/min)
1	Untreated	0	0	N/A	N/A
2	All treated, high DOR	100	21,000	1:40	14.583
3	All treated, low DOR	100	8,400	1:100	5.833
4	Partially Treated, high DOR	50	10,500	1:40	7.292

Case study model results:

The four scenarios were run in OILMAP utilizing the near field module with subsurface dispersant, OILMAPDeep, and the far field module, OILMAP3D. The near field and far field results are presented below.

Case study near field results:

OILMAPDeep provides output of release plume trap height and droplet size distribution. The dispersant treatment characteristics do not alter the trap height predictions, and the four cases were all predicted to trap at approximately 260 m above the release, 750 m below the water surface. Individual droplet size distributions at each DOR and the cumulative droplet size distribution for each scenario are shown in Figure 2 and 3 respectively. The results show that for these release conditions the untreated oil has maximum droplets of 8400 um, the 1:100 DOR treatment has maximum droplets of 244 um and the 1:40 DOR treatment has maximum droplets of 22 um. These variable size ranges have significantly different free rise velocities, which have significantly different times to surface. Both the 1:40 and 1:100 DOR have free rise velocities less than 1 cm/s where the untreated range from less than 1 cm/s up to approximately 12 cm/s. The resulting time to surface as a function of droplet size for this release scenario is shown in Figure 4. This figure shows that based on free rise velocity only, the untreated droplets surface on the order of one to tens of hours, the 1:100 DOR treated surface on the order of days to weeks and the 1:40 DOR treated surface on the order of months to years.

Case study far field results:

The OILMAPDeep results described in Section 3.1.1 define the initial conditions for far field simulations in OILMAP3D, where the oil mass is released at the plume trap height in droplets defined by the calculated size distribution. Table 4 provides a summary of the far field modeling results. The non-treated and the partially treated cases rise to the surface within 2 hours; the timing is the same given that the high end of the droplets in the partially treated case are the same size as the non-treated oil due to the volumetric averaging for the partial treatment case. The low DOR (1:100) case takes over 3 days for the oil to reach the surface whereas the high DOR (1:40) case does not reach the surface 15 days after the initial release. The partial treatment and the low DOR (1:100) cases have comparable percentages of oil on the surface and in the water column; 19% less oil rises to the surface for the low DOR (1:100) case because the droplet size distribution for the partial treatment contains larger oil droplets for 50% of the volume released.

Figure 5 displays the footprint of the surface and subsurface 15 days after the initial release. There is a clear difference between the treated oil with high DOR (1:40) and the non-treated oil cases. The non-treated oil quickly rises to the surface and produces a surface oiling footprint primarily due to the wind, whereas the high DOR (1:40) case does not reach the surface and is only transported by currents and natural dispersion. The low DOR (1:100) oils a larger extent with subsurface oil, when compared to the other cases, because the smaller oil droplets have more time to transport and disperse within the water column as they rise to the sea surface. The non-treated scenario results in the greatest thickness of surface oil because this scenario has the largest oil droplets, thus the greatest amount of oil reaches the surface. The partially treated oil has two distinct plumes, the non-treated oil that rises to the surface rapidly and the plume that is treated with a 1:40 DOR that reduces the oil droplet size such that it does not surface in 15 days.

The surface oil thickness and subsurface oil concentrations 15 days after the initial release are shown in Figures 6 and 7 respectively. Note that these figures represent one snapshot during the model simulation, the oil footprint varies spatially throughout the 15 days of modeling (i.e. graphic does not display swept area). The non-treated oil and the partially-treated cases have comparable surface oiling footprints; as one would expect the non-treated case does result in thicker oiling. The low DOR (1:100) contains patchy surface oiling and the high DOR (1:40) has no surface oiling as no oil reaches the surface within 15 days. Figure 7 displays the vertical maximum subsurface oil concentration. This footprint represents both entrained surface oil and subsurface oil ascending in the water column subject to advection and dispersion. The surface entrained oil is northwest of the well site and results in lower hydrocarbon concentrations, approximately <1 mg/m^3. The subsurface oil ascending in the water column from the well site has relatively higher concentrations (greater than 1 mg/m^3); this is localized within 50 km east and 150 km northwest of the well site. Concentrations of subsurface oil due to the entrainment of the surface oil are comparable in all cases, with the exception of the high DOR (1:40) case because it does not surface. The greatest subsurface oil concentration, in the far field, result from the high DOR (1:40) scenario due to the increased retention of subsurface oil. The subsurface oil represented in this paper reflects oil droplets and dissolved components, for simplification dissolution of aromatics were not incorporated. The output from OILMAPDeep could be simulated using RPS ASA's spill impact module (SIMAP) to incorporate dissolution; if this was incorporated the quantity of oil reaching the surface would be slightly reduced as the soluble components of oil would dissolve in the water column as it rises to the surface.

Table 4. Summary of mass balance and surfacing results.

Case Examples	**Time to Reach Surface (hrs)**	**Percent of Oil 15 Days After Initial Release**			
		Shoreline Oiling	**Surface Oil**	**Subsurface Oil**	**Evaporated**
No Treatment	2	0%	72%	2%	26%
1:40 100% Treatment	NS[1]	0%	0%	100%	0%
1:100 100% Treatment	82	0%	12%	80%	8%
1:40 50% Treated	2	0%	31%	51%	18%

1 – Oil does not surface within the 15 day simulation.

CONCLUSIONS:

Implementation of subsurface dispersant treatment within OILMAPDeep has been developed. The module allows temporally-varying dispersant treatment of a simulated release of oil and gas from a subsurface origin. Partial or full plume treatment is possible, which can vary in both fraction treated and treatment DOR throughout the simulation. The model allows for incorporating subsurface dispersant treatment by defining the reduced IFT or calculation of the reduced IFT based on the treatment DOR. The model is capable of predicting the droplet size distribution from partial treatment of an oil plume by appropriately weighting the treated and non-treated fractions of each portion of the plume. Seamless integration within the far field OILMAP3D model is achieved through temporally varying release of oil in droplets of the appropriate distribution depending on the release time.

A case study of variable dispersant treatment was included in this study. OILMAPDeep predicted droplet size distributions for four different scenarios. OILMAP3D provided an efficient means of determining the relative difference in far field impacts including surface, waters column and shoreline oiling associated with the variable dispersant treatment options. This information used in combination with logistical constraints, such as available dispersant volume, blowout oil release rate and dispersant pumping capacity, aids in selecting an appropriate response approach.

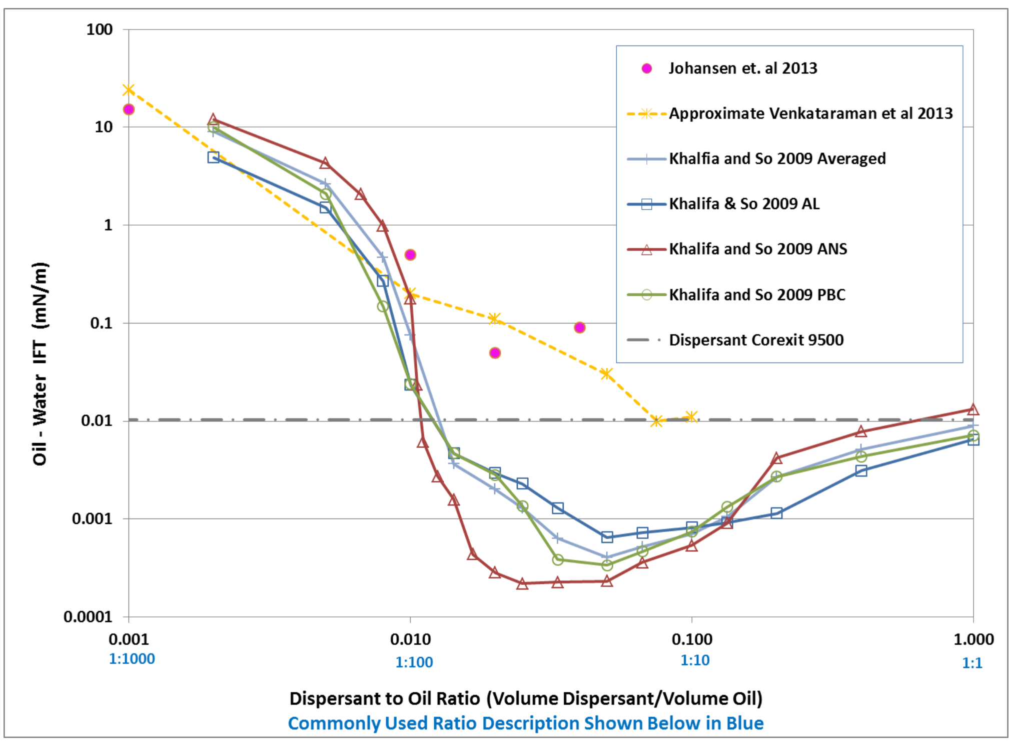

Figure 1 Estimates of IFT vs DOR from various sources. Y-axis shows the IFT as a function of different treatment intensities.

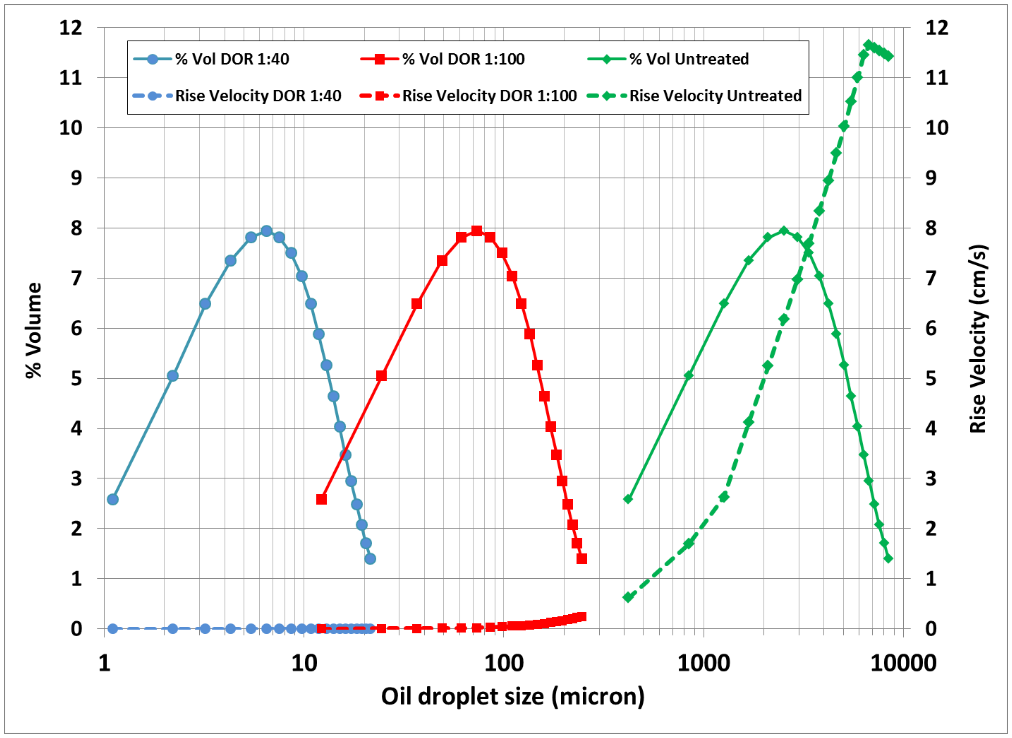

Figure 2 Droplet size distributions and associated droplet free rise velocity for 1:40 DOR, 1:100 DOR, untreated and 50% partially treated plume at 1:40 DOR associated with the release scenarios.

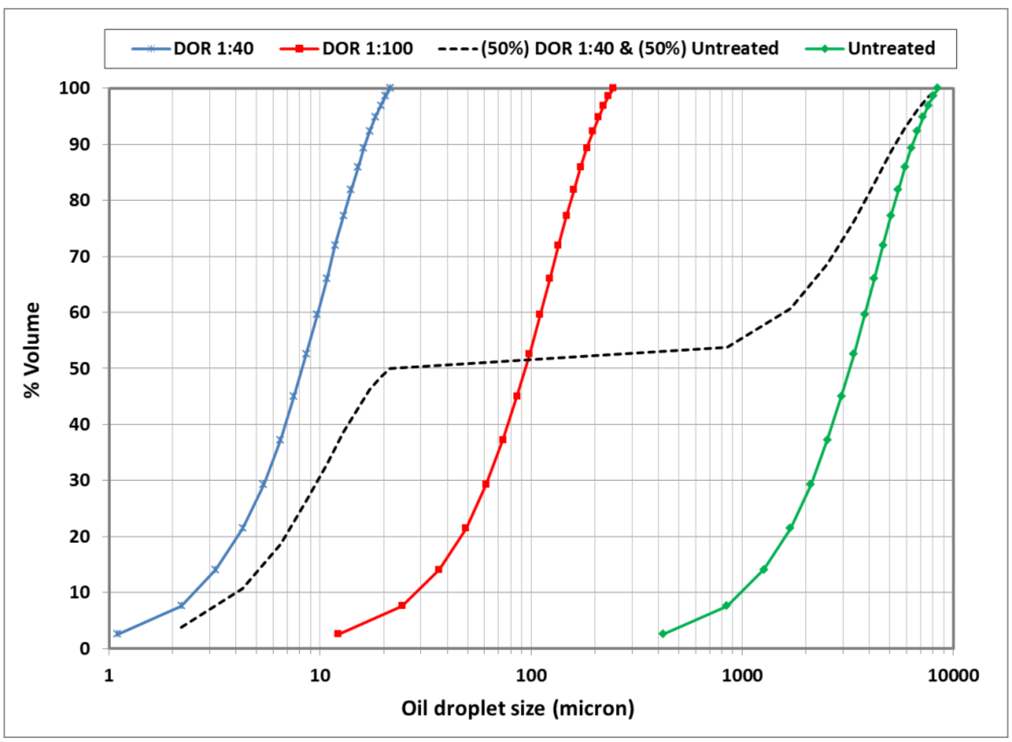

Figure 3 Cumulative droplet size distributions for 1:40 DOR, 1:100 DOR, untreated and 50% partially treated plume at 1:40 DOR associated with the release scenarios.

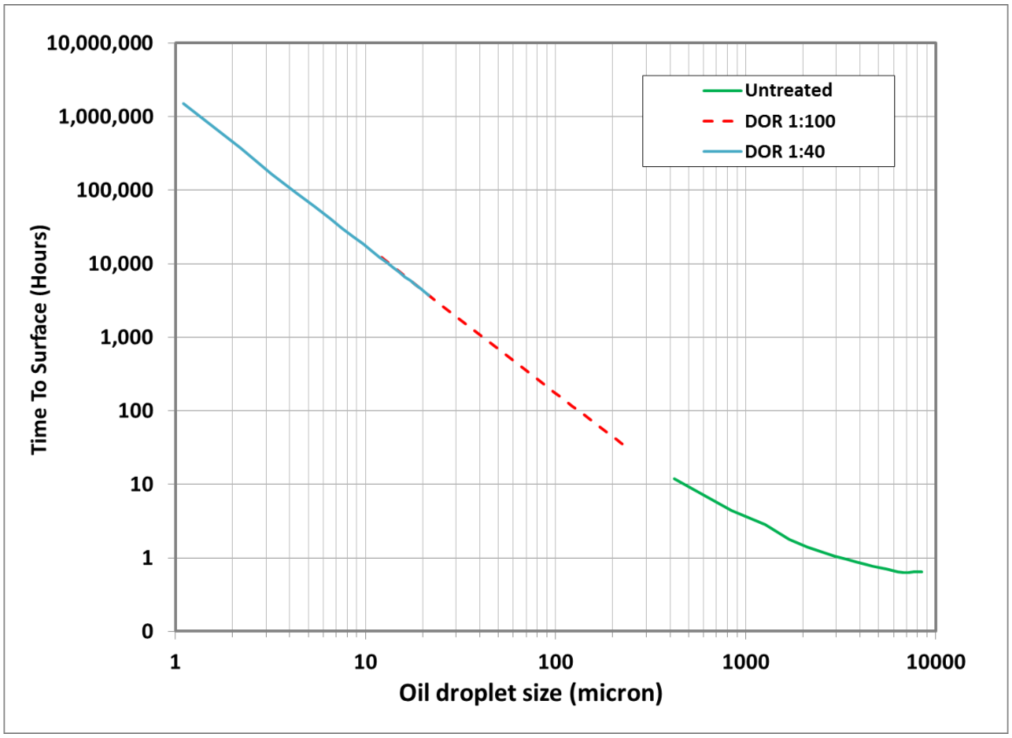

Figure 4 Free rise surfacing times based on initial release at 750 m below the surface for 1:40 DOR, 1:100 DOR and untreated oil associated with the release scenario.

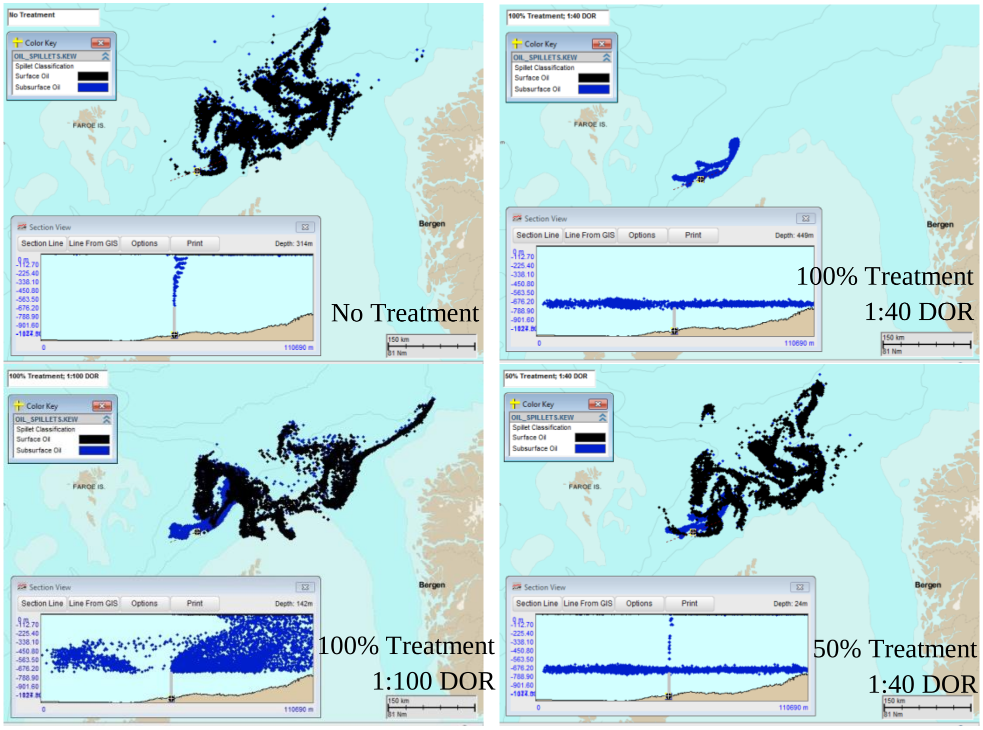

Figure 5 Surface and subsurface oil 15 days after initial release.

(Upper Left = no treatment; Upper Right = 100% treatment with 1:40 DOR; Lower Left = 100% treatment with 1:100 DOR; Lower Right = 50% treatment with 1:40 DOR. Black = surface oil, blue = subsurface oil, and gray = near-field portion of plume.)

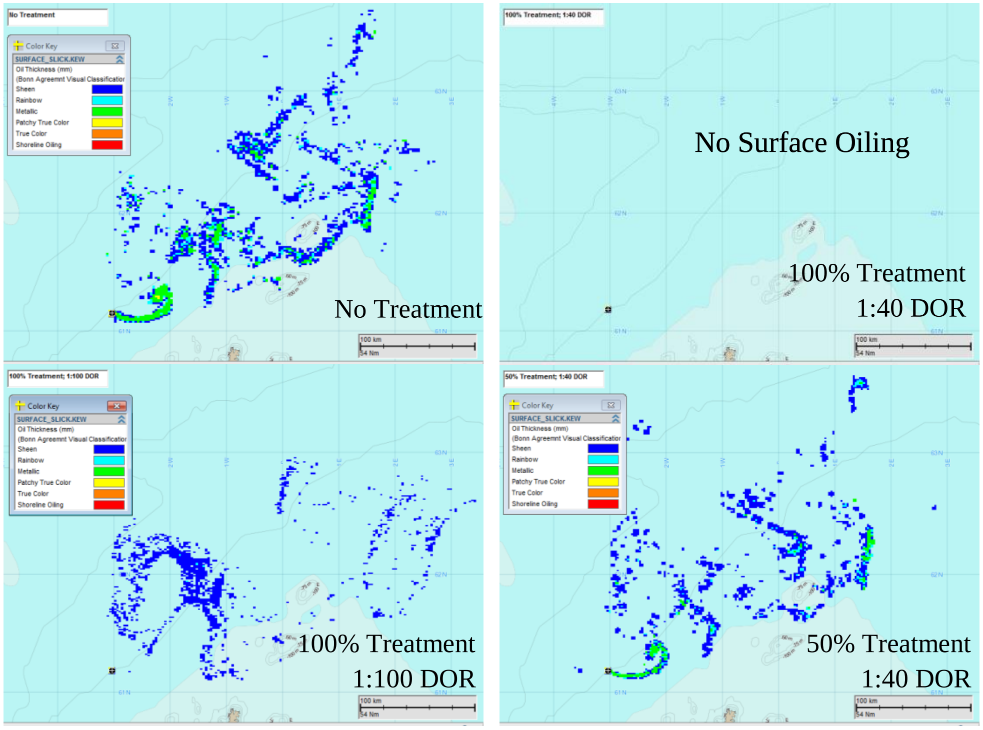

Figure 6 Surface oil thickness contours, 15 days after initial release.
(Upper Left = no treatment; Upper Right = 100% treatment with 1:40 DOR; Lower Left = 100% treatment with 1:100 DOR; Lower Right = 50% treatment with 1:40 DOR. Colors displayed on map correspond to visual representation of oil: Yellow = patchy true color; Green = metallic; Turquoise = rainbow; Blue = Sheen.)

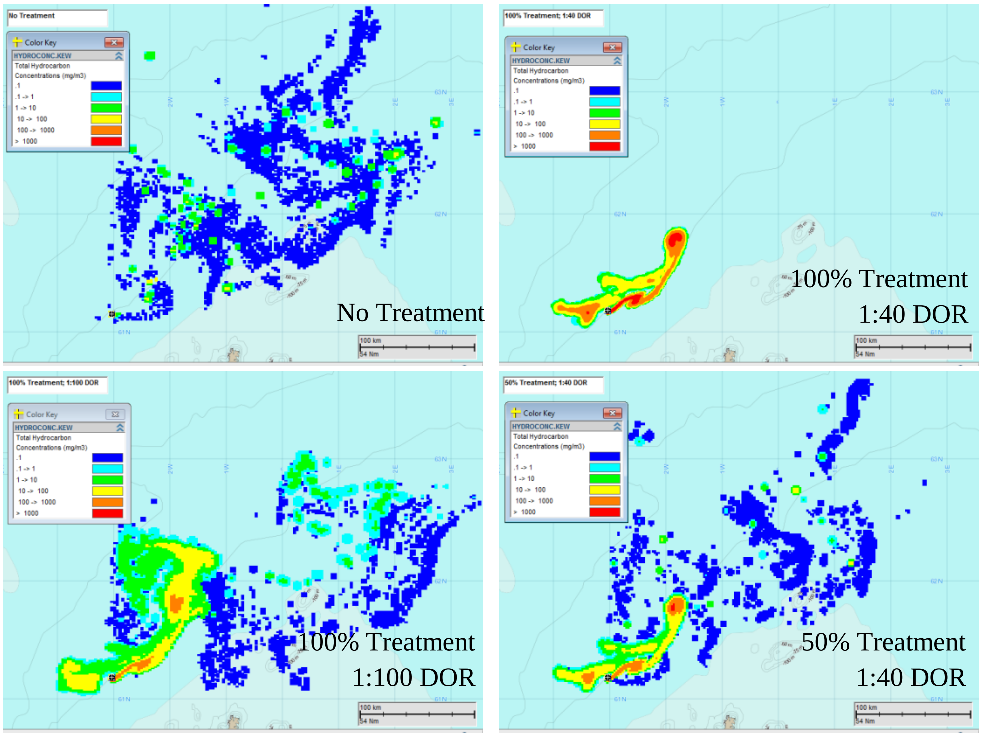

Figure 7 Subsurface total hydrocarbon concentrations, 15 days after initial release.

(Upper Left = no treatment; Upper Right = 100% treatment with 1:40 DOR; Lower Left = 100% treatment with 1:100 DOR; Lower Right = 50% treatment with 1:40 DOR. Color contours on map represent total hydrocarbon concentration (as mg/m^3): Blue = <0.1; Turquoise = 0.1 to 1; Green = 1 to 10; Yellow = 10 to 100; Orange = 100 to 1,000; and Red = > 1,000.)

REFERENCES:

Bishnoi, P. R., Gupta, A. K., Englezos, P., Kalogerakis, N., 1989. Fluid Phase Equilibria, 83, 97.

Boxall, J. A.; Koh, C. A.; Sloan, E. D.; Sum, A. K.; Wu, D. T., 2012. Droplet size scaling of water-in-oil emulsions under turbulent flow. Langmuir 28, 104−110.

Chen, F.H. and P.D. Yapa. 2007. Estimating the Oil Droplet Size Distributions in Deepwater Oil Spills. Journal of Hydraulic Engineering, Vol. 133, No. 2, pp. 197-207.

Clift, R., Grace, J.R., and Weber, M.E., 1978. Bubbles, Drops and Particles. New York, NY. Academic Press, Inc.

Conkright, M.E., J.I. Antonov, O., Baranova, T. P., Boyer, Garcia, H.E., Gelfeld,mR., Johnson, D., Locarnini, R.A., Murphy, P.P., P.P., O'Brien, P.P., Smolyar, I., Stephens, C., 2002: World Ocean Database 2001, Volume 1: Introduction. Ed: Sydney Levitus, NOAA Atlas NESDIS 42, U.S. Government Printing Office, Washington, D.C., 167 pp.

Fanneløp, T.K. and K. Sjoen, 1980a. Hydrodynamics of underwater blowouts, AIAA 8th Aerospace Sciences Meeting, January 14-16, Pasadena, California, AIAA paper, pp. 80-0219.

Fanneløp, T. K. and K. Sjoen, 1980b. Hydrodynamics of underwater blowouts, Norwegian Maritime Research, No. 4, pp. 17-33.

Hinze, J. O. 1955 Fundamentals of the hydrodynamics mechanisms of splitting in dispersion process. AIChE J. 1, 289–295.

Johansen, O., Brandvik, P., Farook, U., 2013. Droplet breakup in subsea oil releases – Part 2: Predictions of droplet size distributions with and without injection of chemical dispersants. Mar. Pollution Bull., 73, 327–335.

Johansen, O., 2002. "Estimates of Droplet Size from Subsea Oil and Gas Leaks or Blowouts," SINTEF document.

Johnson, A. I., Besik. F.. and Hamielec, A., 1969. Mass Transfer from a Single Rising Bubble. A. E.. Can. J. Cheril. Eng. 47. 559-564.

Levitus, S., 1982: 2011. 2 Climatological Atlas of the World Ocean, NOAA Professional Paper 13 U.S. Gov. Printing Office, Rockville, M.D., 190 pp.

Khelifa, A. and So, L.L.C., 2009. Effects of chemical dispersants on oil-brine interfacial tension and droplet formation. In: 32nd Proceedings of Arctic and Marine OilSpill Program Technical Seminar, Environment Canada, Ottawa, Canada, pp. 383-396.

Khelifa A, Charron D.M., Tong, T. & Singh N.R., 2011. Effects of chemical dispersants on oil-brine interfacial tension and droplet formation: New results using new high resolution imaging setup and weathed oils. In: 34nd Proceedings of Arctic and Marine OilSpill Program Technical Seminar, Environment Canada, Ottawa, Canada, pp. 865-879.

Kolluru, V.S., 1993. Oil blowout model, Applied Science Associates, Inc., Narragansett, RI 02882.

McDougall, T.J., 1978. Bubble plumes in stratified environments, Journal of Fluid Mechanics, Vol. 85, Part 4, pp. 655-672.

NCEP (National Centers for Enviornmental Prediction). Global Forecast System (GFS) Model Products Inventory. http://www.nco.ncep.noaa.gov/. 2013

Rosin, P. and E. Rammler, 1933. The Laws Governing the Fineness of Powdered Coal, Journal of the Institute of Fuel 7: 29–36

Spaulding, M.L., 1982. User's manual for a simple gas blowout plume model, Continental Shelf Institute, Trondheim, Norway.

Spaulding, M.L., P.R. Bishnoi, E. Anderson, and T. Isaji, 2000, An Integrated Model for Prediction of Oil Transport from a Deep Water Blowout.

Venkataraman, P., Tang, J., Frenkel, E., McPherson, G.L., He, J., Raghaven, S.R., Kolesnichenko, V., Bose, A., John, V.T., 2013. Attachment of a Hydrophobically Modified Biopolymer at the Oil−Water Interface in the Treatment of Oil Spills. ACS Applied Materials & Interfaces.

Wang, C. Y. & Calabrese, R. V. 1986b Drop breakup in turbulent stirred-tank contactors. Part 2: Relative influence of viscosity and interfacial tension. AIChE J. 32, 667–676.

Yapa, P. D., and Chen, F. H. 2003. CDOG 2 Clarkson Deepwater Oil and Gas Model Users Guide. Dep. Civ. And Env. Eng., Clarkson University, Potsdam, NY.

Yapa, P. D., Zheng, L., and Chen, F. H. 2001a. ‘‘A model for deepwater oil/gas blowouts.’’ Mar. Pollution Bull., 43, 234–241.

Yapa, P. D., Zheng, L., and Chen, F. H. 2001b. Clarkson deepwater oil & gas ~CDOG model. Rep. No. 01–10, Dept. of Civil and Environmental Engineering, Clarkson Univ., Potsdam, N.Y.

Zheng, L. and Yapa, P.D., 2002. Modeling Gas Dissolution in Deepwater Oil/Gas Spills,Journal of Marine Systems, Elsevier, the Netherlands, March, 299-309

Zheng, L., Yapa, P.D. and Chen, F.H., 2003. A Model for Simulating Deepwater Oil and Gas Blowouts - Part I: Theory and Model Formulation, Journal of Hydraulic Research, IAHR, August, Vol. 41(4), 339-351