Review of

DEEP OIL SPILL MODELING ACTIVITY SUPPORTED BY THE DEEPSPILL JIP AND OFFSHORE OPERATORS COMMITTEE

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Executive Summary

The DeepSpill JIP and Offshore Operators Committee recently sponsored two laboratory investigations, one field experiment, and three model comparison activities related to predicting the fate of oil spills from blowouts and pipeline ruptures. The following are the principal conclusions from these studies.

- 1. Jets of oil and gas (if present) will break up into droplets and bubbles, with diameters ranging from less than one mm to the approximate size of the discharge opening, or the maximum stable diameter (whichever is smaller). Break-up behavior is well understood for a single constituent released from an orifice, but more information is need when both oil and gas are discharged, or where release is from a pipeline rupture.
- 2. The buoyancy of the oil droplets and gas bubbles will form a buoyant plume with the gas providing the dominant source of buoyancy (if present). Basic plume features near the source can be described with conventional integral plume models, such as CDOG and DeepBlow.
- 3. Ambient currents (and perhaps stratification) will cause the oil and gas to separate from the entrained water at elevations of 100-200 m above the source. CDOG and DeepBlow treat this separation differently, but the differences are relatively unimportant in predicting the fate of oil released at depths of 800-1000 m.
- 4. Field experiments showed that some oil droplets rose to the surface faster than predicted based on the rise velocity of individual droplets, causing some oil to surface closer than expected to the release point. However, most oil was not recovered at the surface suggesting it was in the form of widely dispersed fine droplets. Slicks from submerged oil releases are thinner than those from surface spills allowing them to weather more rapidly.
- 5. At ocean depths below about 450m, natural gas hydrates are thermodynamically stable and their existence could reduce the rates of bubble dissolution and rise. However, lab studies suggest that hydrates may not actually form because of the presence of oil on the bubbles, and because plume dilution may limit background gas concentration and induction time. These conclusions are consistent with the DeepSpill field experiments (where hydrates were not observed). DeepBlow does not model the kinetics of hydrate formation; CDOG has a more detailed hydrate kinetic formulation, but the algorithm requires calibration.
- 6. Echo sounders provide efficient tracking of oil and gas releases in the field and showed that the gas was completely dissolved before it surfaced, suggesting it may be safe to operate machinery directly above the spill.
- 7. The models that were compared have evolved over time, at least in part because of the experimental studies and the model intercomparison. The value of the model comparison activities has been as much in spurring model development as in identifying the "best model".

The purpose of this report is to summarize conclusions from six recently sponsored activities of the DeepSpill JIP and Offshore Operators Committee: three experimental studies and three model comparison exercises. These include:

- 1. Laboratory studies of jet break-up, droplet size distribution and hydrate formation conducted at University of Hawaii
- 2. Laboratory studies of phase separation in multiphase plumes in the presence of stratification and crossflow conducted at MIT
- 3. DeepSpill field experiment conducted in the Norwegian Sea during June 2000 and documented in reports prepared by SINTEF
- 4. Results from the October 2001 workshop in New Orleans comparing subsurface blowout models.
- 5. Results from the April 2003 workshop in Seattle comparing integrated oil spill models
- 6. Intercomparison study of the SINTEF and Clarkson subsurface models.

These activities are reviewed in each of the first six sections of this report, while major conclusions are summarized in Section 7.

The goal is not to describe the activities fully. (More complete descriptions are provided in the references for each study, and the models themselves are best described in their most recent publications, since the models have evolved over time.) Rather, we provide a brief summary and then comment on how the conclusions from each activity help our understanding of the transport of oil released to the deep ocean via a blowout or pipeline break. As a reference for baseline discussion, we consider a release with the approximate characteristics of the DeepSpill field experiment as shown in Table 1.

Variable	Units	Magnitude
Water depth, H	m	844
Orifice diameter, D	m	0.12
Volume release rate of oil, Qo	m ³ /hr	60
Volume release rate of gas, Q _g	Sm ³ /s	0.6
Density of oil, p	g/cm ³	0.85
Viscosity of oil (diesel, crude), µ	g/cm/s	0.04, 0.8
Oil-water surface tension, σ	g/s^2	25
Large oil droplet slip velocity, w _{so}	cm/s	14
Gas bubble slip velocity, w _{sg}	cm/s	30

Table 1 Characteristics of a typical deep-sea spill used for discussion

1. Jet break-up, droplet size distribution and hydrate formation studies at University of Hawaii (UH)

Oil and gas released to the ocean at large flow rates will form a rising plume. As discussed under Section 2, during its ascent some or all of the oil may separate from the

plume due to effects of an ambient current and/or ambient stratification, with the separating oil rising to the surface as individual, diffusing, droplets. The rise behavior in both the plume and diffusion stages depends on the droplet size distribution that, in turn, depends on the mode of droplet formation. At sufficiently high pressure and/or low temperature (corresponding to seawater below a depth of about 450m), natural gas bubbles could react with seawater to form gas hydrates (Sloan, 1998). Solid hydrate particles of natural gas are much less buoyant than pure gas bubbles, and hence substantial hydrate formation would significantly reduce plume buoyancy. Even partial hydrate formation. Complicating matters is the fact that the tendency of natural gas bubbles to form hydrates could be influenced by the coating of oil on the bubbles. The above issues were explored in experiments conducted at UH and described in Masutani and Adams (2000), Tang et al. (2003), and Tang (2004).

Jet break-up and size distribution

The break-up of oil discharged through an orifice into water depends on the orifice velocity and diameter, U and D, the oil density and viscosity, ρ and μ , and the surface tension σ , as described by two dimensionless parameters: Reynolds number, Re = $\rho UD / \mu$ and Ohnesorge number, $Z = \mu / \sqrt{\rho \sigma D}$.

Using a range of tanks, orifice types and fluids (crude oils, liquid CO_2 and analog fluids—e.g., silicone fluids), UH ran 260 experiments over a wide range of Re-Z space. Each experiment was classified into one of the five modes of jet break-up—Rayeigh (laminar) instability, sinuous wave break-up, filament core break-up, wave atomization and full (turbulent) atomization—illustrated from left to right in **Figure 1**.



Fig. 1 Breakup modes of crude oil jets discharging into water. Jet velocity increases from left to right.

Results are plotted in **Figure 2** as a function of Re and Z. The dashed and dashed-dotted lines are best-fit boundaries for the laminar, transitional (middle three modes), and turbulent breakup modes, and correspond to

$$Z < \frac{5.5}{\text{Re}} \text{ (laminar) Rayleigh instability}$$
(1a)
$$Z > \frac{18}{\text{Re}} \text{ turbulent atomization}$$
(1b)

The significance of these relationships is that they are scale-independent, at least within a limited range, allowing one to predict characteristics of the initial droplet size distribution–monodispersion or polydispersion; coarse or fine droplets–for a wide range of flow scenarios.

Quantitative droplet size spectra assembled from Phase Doppler Particle Analysis (PDPA) measurements and digital video analysis supplemented the visual observations. Figure 3 shows representative droplet size distributions corresponding to the different breakup modes for a liquid CO_2 jet discharging through a 5 mm i.d. nozzle into water at about 6 MPa. Exit velocity (hence Reynolds number) increases from left to right. Measurements were performed about 70 cm above the nozzle and downstream of the breakup for all cases. Note the prevalence of large droplets (6-7 mm) along with some small droplets at the lowest velocity, a wide range of droplet sizes at intermediate velocity, and a tendency for only small droplets (less than 2 mm, with the majority between 0.3 and 0.6 mm) at highest velocity. Similar results were obtained with different fluids, orifice types and orifice diameters. In comparing experiments with different orifice diameters (not shown), the larger droplet sizes were correlated with the orifice diameter, while the smaller droplets were independent of orifice diameter. One explanation may be that since small droplets appear to be produced at the surface of the jet, the generation mechanism becomes relatively scale-independent once a threshold radius of curvature is exceeded.

From Eq. 1, and the definitions of Re and Z, we conclude that a continuous oil release will lead to laminar jet break-up, characterized by mainly large droplets (with diameters comparable to the orifice diameter), if $\rho O^2 / \sigma D^3 < 19$. However, droplets (or bubbles) larger than a critical size will be unstable and will split into smaller sizes (Clift, et al., 1978; see also discussion in Section 3). Turbulent atomization, consisting of mainly small droplets (diameters less than one or two mm), should occur if $\rho Q^2 / \sigma D^3 > 200$. And, curiously, oil viscosity drops out as an explanatory variable. Considering only the oil release characterized in Table 1 (i.e., $Q = Q_0$), we expect laminar conditions for an orifice diameter greater than about 80 cm and atomization for an orifice diameter less than about 36 cm. The nozzle used in the DeepSpill experiments had a nominal diameter of 12 cm, so one would expect to see atomization. However, the discharge contained both oil and gas, whereas the lab experiments had just one constituent, so this clearly complicates the picture. In addition, the diameter of the orifice in the field (12 cm) was significantly larger than the orifice in the lab (~0.5 cm), so any droplets formed within the laminar break-up mode (initial droplet diameter comparable to the orifice diameter), would be unstable and break up. Also, both the UH and DeepSpill experiments used idealized, circular nozzles; the release from a deep blowout might be similar, but the release from a pipeline rupture could be much more ragged.



Fig. 2 Liquid-in-liquid jet break-up regimes. Data points correspond to 175 oil and silicone fluid injection tests (upper two sets) and 85 liquid CO₂ injection tests (lower right hand corner).



Fig. 3 Liquid CO₂ droplet size spectra for the five breakup modes described in Figures 1 and 2. Velocity and Reynolds number increase from left to right.



Fig. 4 Sequence of video images showing the speed at which hydrate formation proceeds in the flowing water tunnel once nucleation and initial crystal growth has occurred. The left image indicates no hydrate formation. The middle image (taken 6 seconds after the first image) shows hydrate formation. The right image (taken 31 seconds after the first image) shows further hydrate growth by agglomeration.

Hydrate formation

Experiments were conducted under hydrate forming conditions to determine whether hydrates would actually form on rising natural gas bubbles and, if so, to determine the extent of formation and whether this was affected by the presence of an oil film on the bubble. Following a concept employed previously by Maini and Bishnoi (1981), clean and oily bubbles of various natural gas mixtures were injected into the high pressure UH vessel and stabilized in space by a downward flow of water inside a clear conical diffuser test section of a small, recirculating, counterflow water tunnel mounted vertically inside the vessel. **Figure 4** presents a sequence of video frames of hydrate formation on rising bubbles of a 70% CH₄/20% C₂H₆/10% C₃H₈ mixture at a pressure of 6.1 MPa and a water temperature of 3°C.

Experiments suggest that, if sufficient levels of dissolved CH_4 (and/or other paraffin hydrocarbons) exist in the water, hydrate formation on rising bubbles of natural gas can occur after a finite induction time (minutes or longer). Hydrate formation appears to be fostered by large bubbles and high gas loading and begins in the wake (downstream surface) of bubbles where a gas-rich diffusion layer may persist. If gas loading is high (i.e., the concentration of bubbles is high), then the hydrate film can grow, promoting bubble agglomeration and growth of the hydrate mass. The thickness of the hydrate film at the gas-water interface was difficult to determine. Since most of the hydrates that were detected appeared to be quite buoyant, it was presumed that the hydrate existed as a surface film that did not penetrate deeply into the gas, and hence would not significantly affect buoyancy.

The presence of oil at the gas-water interface was observed to exercise an inhibiting effect on the initiation and growth of hydrate films. **Figure 5** shows a video frame of a hydrate film growing on the surface of an oily bubble of a 70% CH₄/20% C₂H₆/10% C₃H₈ gas mixture slowly emerging from a small (0.57 mm i.d.) injector into water at 6.1 MPa and 3°C. In this and other tests, the hydrate film was observed to initiate on hydrate fragments attached to the end of the injector and move upward over the emerging bubbles. As the hydrate skin advances, it displaces the crude oil film. The oil eventually collects on the top of the bubble like a cap and prevents the hydrate layer from completely encasing the bubble.

Application of the UH results to a field scale deep oil spill suggests that hydrate formation on natural gas bubbles is probably not a significant consideration because 1) hydrate formation requires high concentrations of dissolved gas in the seawater and that is unlikely to happen in a large continuous flow of gas which forms a plume and hence tends to disperse the bubbles, diluting their concentration, 2) it was inferred that the hydrate formed in the lab was in the form of a thin coating shell surrounding the gas bubble; while this could affect mass transfer, the mass fraction of the solid shell would be too small to affect buoyancy, and 3) an oil film surrounding a gas bubble further impedes hydrate growth.



Fig. 5 Video frame of a hydrate film on the surface of an oily bubble emerging from the injector. The Neptune Spar oil film that originally encased the bubble has been pushed to the top by the hydrate that grows upward from the injector.

2. Phase separation studies at MIT

Mathematical models of oil and gas plumes—e.g. the Clarkson model (Yapa and Zheng, 1997, 1999; Chen and Yapa, 2003; Zheng et al., 2003) or the SINTEF model (Johansen, 2000, 2003)—are patterned after models of single-phase plumes such as those that result from the discharge of fresh water into seawater (e.g., a coastal sewage outfall) or from the discharge of warm water into cold water (e.g., a thermal discharge from an electric power plant). However, the presence of the dispersed phases (oil and natural gas) complicates the plume dynamics in several respects. Firstly, the dispersed phase *is* the source of buoyancy (with typical gas to oil ratios, the buoyancy is mainly contributed by the natural

gas) and secondly, the gas and oil will tend to separate from the plume due to the effects of ambient stratification and/or current. **Figure 6** compares a two-phase plume with a single-phase plume, illustrating the two modes of phase separation. Modeling studies at MIT (Masutani and Adams, 2000; Socolofsky, 2001; Socolofsky and Adams, 2002; Socolofsky and Adams, 2003) focused on characterizing the influence of a dispersed phase on plume dynamics and in particular, quantifying the nature of phase separation.

Effects of Ambient Stratification

In the presence of stratification, but not current, the primary variables characterizing a buoyant plume are its kinematic buoyancy, $B = g Q_o \Delta \rho / \rho$ (where Q_o is the dispersed phase flow rate, and $\Delta \rho$ is the difference between a reference ambient density, ρ , and the density of the dispersed phase fluid), and the ambient stratification frequency, $N = [(g / \rho)(d\rho / dz)]^{1/2}$. A single-phase plume will rise until it becomes trapped by the ambient stratification. A two-phase plume is similar except that some of the entrained water continues upward with the dispersed phase as a new plume is started. As seen in Figure 7, the influence of the dispersed phase is embodied in the dimensionless slip velocity, $U_N = w_s / (BN)^{1/4}$ where us is the droplet/bubble slip velocity. At values of $U_N \leq 1.5$ (Type 1*), the rising bubbles/droplets are relatively efficient at dragging fluid upward, the entrained water tends to peel at discrete elevations, and most of the entrained water is lost with each peeling event. Conversely, for $U_N \ge 2.4$ (Type 3), the process is less efficient and peeling tends to occur more continuously, starting at a lower elevation. Type 2 behavior is between Type 1* and 3, and Type 1 refers to the condition described by Aesada and Imberger (1993), but not relevant here, where the plume reaches the surface prior to peeling. Formulae for the fraction of plume water that peels, the trap height and the induced flow associated with the first peeling event are

$$f = 1 - 0.048 U_N^{-0.86} \tag{2a}$$

$$\frac{h_T}{\left(B/N^3\right)^{1/4}} = 2.8 - 0.27U_N \tag{2b}$$

$$\frac{Q_i}{\left(B^3 / N^5\right)^{1/4}} = 0.9 - 0.38 U_N^{0.24}$$
(2c)

The values of U_N calculated for oil droplets and gas bubbles (with the buoyancy flux of oil plus gas) for the reference spill in Table 1 are 1.3 and 2.7, suggesting a significant influence of droplets and bubbles on plume dynamics.



Fig. 6 Separation of plume phases due to ambient stratification (top) and current (bottom).



Fig. 7 Schematics of the various plume types with normalized slip velocity (U_N) increasing from left to right. *H* is the total depth relevant for a Type 1 plume and h_T is the intrusion depth (or trap height) of the first intrusion.

Effects of Ambient Current

The preceding results apply to multiphase plumes ascending in quiescent stratified environments. Crossflow was found to significantly impact plume behavior under certain conditions. **Figure 8** shows representative images from crossflow experiments conducted in a wave flume with no ambient stratification. In these tests, the plumes contained both oil droplets and air bubbles, and dye was injected to track the entrained

water. The solid lines show standard single-phase CORMIX (Cornell Mixing Zone; Doneker, 2002) model predictions of the composite plume centerlines. Analyses of the video records indicated that when the crossflows were weak (e.g., image on the left), the entrained fluid followed the buoyant bubble/droplet column from the injection point to the flume surface (though there was some loss of fluid, denoted by the dark color, at the lee of the plume), and CORMIX adequately predicted the centerline of the composite plume, suggesting that such plumes can be modeled similarly to single-phase plumes in a weak crossflow. On the other hand, strong crossflows (e.g., image on the right) resulted in significant separation between the dispersed phase(s) and entrained fluid, and CORMIX could not predict the trajectory of the bubbles or large oil droplets above the separation height.

The results of 41 crossflow experiments were employed to derive a relationship for the critical (separation) height. A least-squares fit to the data yields

$$h_s = \frac{5.1B}{(u_a w_s^{2.4})^{0.88}} \tag{3}$$

where u_a , is the ambient crossflow velocity.



Fig. 8 Crossflow experiments with no ambient stratification. The solid line represents the CORMIX prediction of the composite plume centerline.

Summarizing the observations of oil/gas plumes suggests the following progression of stages, starting at the release point:

- 1. Initially, the oil/gas mixture behaves as a coherent plume and, hence, is amenable to traditional integral plume analysis.
- 2. Higher, the oil/gas mixture continues to behave as predicted by integral models; however, entrained fluid begins to leak from the downstream side of the plume. This occurs, presumably, because the stripping current velocity overcomes the restoring entrainment velocity, which decreases with height (Davidson and Pun 1999).
- 3. Above a critical separation height h_s , the oil/gas mixture no longer behaves as a coherent mixture. Entrained water and fine oil droplets are lost downstream (or gas and large oil droplets are lost upstream), and the trajectory of the bubble column

follows more closely the vector addition of the group rise velocity of the bubbles and the crossflow velocity.

4. Finally, the separated mixture of entrained fluid and fine oil droplets continues to rise in the far field due to the momentum received before separation as well as buoyancy from the small oil droplets. This far-field plume (containing fine oil droplets) can be modeled as a single-phase plume, initiated at the separation height, h_S

A few experiments included both stratification and crossflow. The plumes exhibited a range of behaviors, depending on the relative strength of the stratification to the crossflow. When the trap height predicted for stratification, h_T , is much less than the separation height for the crossflow, h_{Sr} , the plume is stratification-dominated, and the crossflow can be neglected in the near field. Entrained fluid rises above the intrusion layer and peels as it does in the no-crossflow situation (albeit in the lee of the plume), then sinks to form an intrusion at height h_T . In the opposite case, where h_S is much less than h_T , separation will occur due to the crossflow and the plume is crossflow-dominated: stratification can be neglected in the near field of the plume. When the two separation heights are comparable, some fluid is stripped by the current and some fluid rises to the peel height, but the end result is that fluid intrudes in the lee of the plume at $h_T \approx h_S$.

For the reference spill described in Table 1, h_T is about 180 m, while for current speeds of 1.2, 2.5 and 5.6 cm/s, h_S ranges from 350 to 180 to 90m. These values of h_S are roughly 200%, 100% and 50% of h_T , suggesting that the release should be dominated by stratification for $u_a < 1$ cm/s, affected by both stratification and cross-flow for $1 < u_a < 6$ cm/s, and dominated by crossflow for $u_a > 6$ cm/s. The ambient currents measured 600 to 800 m below the surface at the start of the "diesel", "oil" and "natural gas" field experiments (see description in following section) were about 13 cm/s, 4 cm/s and 3 cm/s, while the average velocity measured over two days was about 10 cm/s. On this basis one would expect the plumes from DeepSpill to exhibit transitional to cross-flow dominated behavior, which is indeed consistent with the SINTEF observations.

3. DeepSpill field experiment conducted in the Norwegian Sea during June 2000 and documented in reports prepared by SINTEF

The DeepSpill experiment was conducted during 26-29 June 2000, at the Helland Hansen site in the Norwegian Sea (at 65° N, 4° 50' E) to test the behavior of accidental oil releases in deep water. The results of the experiments are summarized in a series of reports issued by SINTEF (Johansen et al., 2000a, b; Johansen et al., 2001) as well as a journal article (Johansen et al., 2003). The goals of the experiment were to

- 1. Obtain data for verification and testing of numerical models for simulating accidental releases in deep water
- 2. Test equipment for monitoring and surveillance of accidental releases in deep water
- 3. Evaluate safety issues for accidental releases of oil and gas in deep water.

Four experiments were successfully completed. In each case the release was at a depth of 844 m, through a single port diffuser giving an exit velocity of about 2 m/s. The releases were:

- 1. Nitrogen release: nitrogen gas (0.6 Sm³/s) and dyed seawater (60 m³/h) for 40 minutes
- 2. Diesel release: marine diesel (60 m³/h, non-emulsion forming) and LNG converted to compressed natural gas (0.6 Sm³/s) for 60 minutes
- 3. Oil release: crude oil (60 m³/h, emulsion forming) and LNG converted to compressed natural gas (0.7 Sm³/s) for 60 minutes
- 4. Natural gas release: LNG converted to compressed natural gas (0.7 Sm³/s) and seawater (60 m³/h) for 120 minutes

Measurements, monitoring, and surveillance were conducted using several systems. Three vessels were present: the supply ship (*Far Grip*), which stayed on station over the release site, and two research vessels, the *Håkon Mosby* and the *Johan Hjort*. Six measurement systems were utilized:

- 1. **ROVs:** ROVs made *in-situ* visual observations of the release infrastructure and plume, including measurements of the bubble and droplet size distributions. Because of the strong currents, only the ROV with a tether management system (TMS) was successful. Side-scan sonar on the ROV also showed promise for documenting the plume; however, electrical noise generated by the cryogenic pumps (both were operated from a common power supply) prohibited such measurements in the DeepSpill experiment.
- 2. Echo Soundings: Echo sounders on the two research vessels proved more successful in tracking the release than anticipated, especially when operating in the 38 kHz range.
- 3. **CTD and Carousel Water Sampler:** Water samples were collected from rosette CTD casts, guided mostly by the echo sounder imaging. A real-time fluorometer on the CTD, designed to measure *in-situ* aromatic hydrocarbons, did not work for unknown reasons.
- 4. **ADCP:** An acoustic Doppler current profiler (ADCP) was used to monitor ocean currents during the experiment. An acoustic modem relayed real-time current information to the *Håkon Mosby* for use by the SINTEF DeepBlow computer program to help predict the behavior of the experimental releases. Because the echo sounder data was so well resolved, real-time computer simulations were not necessary to track the plume.
- 5. Work Boats: Two work boats were run (one each from *Johan Hjort* and *Far Grip*) to collect oil thickness and emulsion samples and to measure oil concentrations using a flow-through fluorometer.
- 6. Aircraft: Airplane surveillance included photographic and scanned images of the surface slicks. These data helped guide the work boats and also were used to calibrate imaging techniques for determining slick thickness.

Data for model validation and testing

Each of the measurement systems identified above provide important data for models. By comparison to the data, the SINTEF DeepBlow model was nominally validated and shown to be successful at tracking the plume through the water column. (Further discussion of model validation is contained in the discussion of the two workshops, in Sections 4 and 5.) The experiment also resulted in important new knowledge about deep releases of oil and natural gas.

Measurements were made of droplet and bubble size distributions. Typical oil droplet diameters ranged from about 1 to 6 mm, with a few extending to 10 mm. A maximum rise velocity of about 14-15 cm/s is expected for droplets greater than about 5 mm. Typical gas bubble diameters ranged from 1-6 mm with a few up to about 8 or 9 mm. A maximum rise velocity of about 30 cm/s is expected for bubbles with diameter greater than about 2 mm. The distributions of both droplets and bubbles was flatter, and the typical diameters larger, than expected from the UH results for atomization mode. However, since the nozzle in the field discharged a mixture of oil and gas, the exit conditions cannot be truly comparable with those in the lab (where only one constituent was discharged).

The travel time for the first droplets released in the diesel and crude oil experiments to reach the surface was about one hour. This indicates a significantly faster rise time than predicted by the droplet rise velocity. (The water depth of 844 m divided by a maximum rise velocity of 14 cm/s is 1.7 hours.) This faster rise time could not be accounted for in the DeepBlow model by plume dynamics because of the relatively short height (hence duration) of the plume. As discussed earlier, density stratification and crossflows worked to arrest the plume rise within the first 100 to 200 m above the release, and the models assume that droplets rise as individuals above this point. Adams and Socolofsky (2001) offered a potential explanation for the rapid droplet rise: although a coherent plume may not form throughout the water column, group effects of rising droplet clouds and plume effects of sporadic re-started plumes could explain the higher rise velocity. Nonetheless, the conclusion of the DeepSpill experiment was that more research is necessary to address this question.

Although hydrates are thermodynamically predicted to form in these waters at depths below about 450 m, no hydrates were observed (gas bubbles were observed to be clear and glassy rather than foggy). This observation is consistent with the UH laboratory experiments that indicate that high concentrations of methane may be required for hydrates to form. In the open ocean, high methane concentrations are not likely to occur in the plume due to entrainment of ambient seawater and leakage of entrained fluid due to cross flows. Even at significant heights above the release, ROV observations showed no signs of hydrates.

The dissolution rate of natural gas in the water column was slower than predicted by theory (the bubbles rose to a higher level than predicted and a mass-transfer reduction factor of 0.25 was required to match the model to the experiments). Although hydrates may have been suspected of being responsible for the reduction in mass transfer from the

bubbles, no evidence for hydrate formation was observed. A possible explanation was that the bubbles were not dissolving into clean water, and that an oil film may have reduced the mass transfer. Another possibility is that when the mechanism for the enhanced rise velocity of the droplets and bubbles beyond their expected slip velocity is identified, this mechanism will account for a reduced dissolution rate with height. In any case, the DeepSpill experiment recommended further investigation through laboratory experiments.

Attempts were made to perform a mass balance on the diesel oil that rose to the surface (a similar balance would be difficult for the crude oil because its volume expands due to emulsification). Of the 60 m³ that were released, only between 1 and 17 m³ (lower and upper bound estimates) could be accounted for. The difference was ascribed to evaporation and natural dispersion, but it is also possible that much of the oil was contained in (much) smaller droplets whose diameters could not be determined with the ROV measurements. These droplets would not have left the primary plume along with the gas or larger droplets, but would have been carried much further by residual plume effects, and then would have risen to the surface much more slowly. An oil droplet with diameter of 0.5 mm, typical of those observed in the UH experiments under atomization, rises with a velocity of about 1 cm/s and hence would take about one day to surface. And with a current speed of 10 cm/s, it would be advected more than 8 km away from the point of discharge.

Monitoring and Surveillance

Aside from instrument malfunction, each of the observation methods described above was successful at tracking, monitoring, and measuring the DeepSpill releases. Echo sounder measurements, particularly in the 38 kHz range, were especially useful in tracking the oil and gas plumes; it was determined that real-time computer modeling was not necessary for that task. Traditional surface monitoring was also successful. The surface slick was thinner than if the oil had been spilled directly on the surface. As a result, the oil weathered quickly, and no combative measures were needed to clean up the releases. Emulsions were not observed to form at the release; however, stable emulsions were observed in the surface slick for the crude oil release (an emulsion forming oil). ROVs employing a TMS are recommended for deep observations as umbilicals experience significant drag due to currents at depth.

Safety Issues

A key safety issue related to regulations that prohibit activities directly above a deep ocean accidental release that involves natural gas due to explosion potential. The natural gas experiments conducted in DeepSpill indicate that this requirement may not be necessary under some circumstances. For this experiment, all of the released natural gas dissolved by within 150 m of the water surface. Although work boats did report observations of surfacing oil droplets, no bursting gas bubbles were observed. Allowing activity above the spill could significantly improve spill response since tracking and mitigation equipment could enter the spill zone immediately and because drill rigs and equipment would not have to be evacuated before addressing the leak.

Conclusions from field experiment

The DeepSpill experiment was successful at accomplishing its goals. The significant results are that:

- 1. Spill models are successful at predicting the fate of accidentally released oil and natural gas, given that initial conditions and currents are specified. Hydrates were not observed to form. Gas dissolution is slower than predicted theoretically, and oil droplets rise faster above the initial plume stage than expected from their slip velocity alone.
- 2. Further research is needed to determine why droplets surfaced faster than expected and why gas bubbles dissolved slower than expected.
- 3. Surface slicks formed locally to the spill, weathered rapidly, and were thinner than slicks resulting from surface spills.
- 4. Echo sounders are efficient at tracking oil and gas releases.
- 5. Released natural gas may dissolve completely within the water column if released from deep enough depth relative to the gas flow rate. Therefore, it may be safe to operate machinery directly above the spill without a danger of explosion.

4. Results from the October 2001 workshop in New Orleans comparing subsurface blowout models

The first of two workshops to compare deep-water oil spill models among themselves and to the DeepSpill data took place in New Orleans on 11-12 October 2001. The purpose of the workshop was to review existing models, understand their formulations and differences, compare their results to the DeepSpill data, develop an assessment of their accuracy, and identify areas of improvement. The workshop focused on the subsurface simulation, which tracks oil from the release to just below the water surface. The following summary was prepared, in part, from notes prepared in an October 15, 2001 memo by C. Cooper of ChevronTexaco.

Three models were considered:

- 1. DeepBlow, a comprehensive integral plume model developed by SINTEF
- 2. CDOG, a comprehensive integral plume model developed by Clarkson University
- 3. An MIT parametric model developed through correlations to the MIT laboratory experiments

The models were applied to a series of 21 test cases. In addition to the three oil/gas releases studied in the DeepSpill experiment, the cases tested sensitivity to oil and gas flow rates, oil density, temperature and droplet size, tendency for oil emulsification and gas hydrate formation, and ambient water depth, currents and density stratification. Results of the comparison are summarized in **Figure 9**, which depicts the time to the first surface oil (top), the distance to the first surface oil (middle), and the first plume trap height (bottom) for the three models (the MIT model only predicts the last quantity).



Fig. 9 Comparison of Clarkson (red or light gray), SINTEF (blue or dark gray) and MIT (white) models for 18 test cases. Time to first oil (top), distance to first oil (middle), trap height (bottom):

Based on the models, the experimental studies described in Section 2 and, to a limited extent, the DeepSpill experiment described in Section 3, an accidental release of oil and/or natural gas obeys the following staged pattern. Near the release, oil, gas and entrained seawater rise as a coherent buoyant plume. A few meters above a point-source release, ambient conditions begin to affect the plume: crossflows cause the plume to deflect in the downstream direction and stratification retards the upward plume motion by entrainment of ambient seawater. For cases similar to the DeepSpill experiment, at a height of order 100 m, these ambient effects arrest the plume, and cause the entrained seawater and the dispersed phases to separate. The arrest takes the form of a completely bent over plume in the case of a strong crossflow, or a trap height and intrusion in the case of a stratification dominated plume. At this terminal level, there is rapid spreading, either by advection from the crossflow or gravitational collapse of the intrusion layer, and the oil is distributed over a wide area. Above this trapping zone, the oil rises as individual droplets. In the DeepBlow and CDOG model, this post-plume stage is assumed to be a random-walk diffusion process governed by the slip velocity of the bubbles and the ambient currents. The MIT model does not simulate this stage.

Comparison of the DeepBlow and CDOG results to the DeepSpill data indicate that the rise time for the bubbles is over-predicted in the models by about 1 hour in 850 m depth of water. This fact suggests that the post-plume stage likely consists of some organized group flows that permit the oil droplets to travel faster their natural slip velocity. This may be in the form of subsequent intermediate plumes or merely group effects of rising bubbles, such as wake shadowing. Unfortunately, the physics of this stage is not well known, and the models can only rely on the droplet slip velocity for guidance.

To evaluate the performance of these, or any, subsurface models, a set of performance criteria was independently formulated as part of the workshop. In summary, subsurface models should be able to

- 1. predict the time it takes for oil to reach the surface to within an accuracy of order 1 hour and predict the downstream distance for surface expression of the oil to within 1 km. These "error tolerances" are based on oil spill response criteria.
- 2. predict the properties of oil when it surfaces, particularly thickness, weathering, and emulsification. These properties determine the need for spill mitigation response.
- 3. simulate the time series of these parameters for long-duration spills.

From the model intercomparison, the error tolerances were generally met by the model simulations. There were some simulations where surface expression differences were greater than 1 km, but these were attributed to differences in the assumed oil droplet size distribution at the source, and not due to model performance. In general, oil simulated by CDOG reached the end of the plume stage first, whereas, the SINTEF and MIT models predicted a longer plume stage. However, each model predicts a plume stage of the order of 10% of the total water column depth so that the post-plume stage dominates the results.

Because of the relative importance of the post-plume stage, for the simulated water depths, differences in simulations in the plume stage do not significantly impact the predictions for time to surface or surface expression. Open questions regarding the plume stage, however, include how and whether gas bubbles, gas hydrates or large oil droplets may leave the upstream edge of the plume due to the crossflow. A second concerns the chemistry of hydrate formation itself. DeepBlow does not include hydrate kinetics, and hence, under hydrate forming conditions, the model predicts solid hydrate particles. Not only is the mass transfer from such particles slower than from gas bubbles, but also hydrate density is closer to that of water than that of natural gas, substantially reducing plume buoyancy. Because the DeepSpill experiment did not observe any hydrate formation, the hydrate sub-model in DeepBlow was turned off. CDOG does include a kinetic formulation and simulates hydrates occurring as a thin film surrounding natural gas bubbles; this film reduces gas dissolution but has a negligible effect on bubble buoyancy. With their hydrate formation turned on, the CDOG simulations matched the dissolution times of the natural gas release (Exp. 4) very well. With hydrate formation turned off, an ad hoc dissolution reduction factor of 0.25 was needed to match the experimental data.

None of the models examined predicts the mass of hydrocarbons dissolved in the water column due to dissolution as the oil droplets rise to the surface. Prediction of dissolution of hydrocarbons would be useful in the damage assessment process as a means of assessing the potential for exposure of organisms in the water column to oil components. Accurate knowledge of droplet size is expected to be important for accurate predictions of dissolution.

The most important parameter in the models is the initial size distribution of the oil droplets. Experiments at the University of Hawaii (UH) described in Section 1 provide guidance for releases from idealized circular orifices, but it is unknown how the size distributions may change for an accidental release involving complicated source geometry. Clarkson was asked to include a sub-model similar to the DeepBlow algorithm for automatically calculating the size distribution from the release conditions. This sub-model was based largely on the UH data.

Because of the importance of the post-plume stage, it was suggested that more research should be focused on understanding and predicting the behavior in this stage. In particular, what conditions are required to have a post-plume dominated release? At the depth of 850 m, the uncertainties about group effects and the under-predicted rise velocity did not stop the simulations from being within the desired error tolerance. For deeper releases, however, the time to surface expression may not be adequately reproduced. Because dissolution will depend heavily on rise time and the ambient conditions in the immediate vicinity of the oil droplets, the behavior in this region will have to be better understood before it will be possible to predict the mass left in the water of major oil constituents.

5. Results from the April 2003 workshop in Seattle comparing integrated oil spill models

The follow-up meeting for the model intercomparison was conducted on 3-4 April 2003, in Seattle, Washington. This meeting compared the subsurface models of the New Orleans meeting, as well as a new plume model from ASA. In addition, each model was also coupled with a traditional surface spill model (Clarkson's CDOG was coupled with NOAA's GNOME model, while SINTEF and ASA had their own surface models). The integrated models were compared using a series of 13 test cases similar to those used at the New Orleans workshop, but with a few additional environmental variables such as wind speed and time variable current. As with the previous section, the following summary was prepared, in part, from notes provided in an April 14, 2003 memo by C. Cooper of ChevronTexaco.

This meeting confirmed many of the conclusions of the New Orleans meeting and helped to focus the modeling efforts on those items that make the biggest difference for oil spill response.

Among the key findings was again the result that the terminal level of the plume stage varied significantly in each model, but the overall simulation results were dominated by the post-plume stage. Differences in rise heights for the plume stage are due to local differences in the simulated plumes. Each model uses a different algorithm for hydrate formation (ASA assumes no hydrates) and for separation between the entrained fluid and the dispersed phase(s). Although these differences can results in a factor of three difference for the plume stage height, time to surface and slick formation were much less affected because, for the simulated water depths, the plume stage is relatively short. This is clear from **Figure 10** which summarizes the surface oil footprint, as simulated at three times with each of the three models, for the base case scenario.

Similarly to the previous model comparison activities, it was emphasized that the oil droplet size distribution was a key parameter for predicting the fate of the oil using these models. From the ASA results, it was also concluded at the details of the plume stage are insignificant to the overall model prediction for a deep spill. This was because the ASA model does not provide for the momentum jet, separation, or detailed hydrate chemistry.

Although the unknown processes in the post-plume stage do not limit these models from predicting the time to surface and surface expression for the 850 m spill, a deeper spill may have difficulties. Group effects in the post-plume stage must be understood to develop a truly robust post-plume model.



Fig 10. Simulated footprint of surface oil at three times using three models and the base case scenario

6. Intercomparison study of the SINTEF DeepBlow and Clarkson CDGO subsurface models

As a result of the two modeling workshops (New Orleans and Seattle) SINTEF and Clarkson completed a detailed model intercomparison report involving 8 test cases designed around conditions in the Gulf of Mexico (Yapa, et al., 2003). A total of 24 simulations were presented: eight test cases with each of the two models (the Clarkson model CDOG and the SINTEF model DeepBlow), and 8 extra simulations using CDOG with the gas separation option turned off. Many of the conclusions are similar to those summarized for the two workshops and revolve around the two basic differences between models: their handling of gas and oil separation and their handling of hydrates.

The models have very different algorithms for crossflow separation among the entrained fluid, gas bubbles, hydrate particles, and oil droplets. Although data from the MIT experiments are available, the data are not adequate to choose between the separation algorithms in the two models, in part because there can be several dispersed phases.



Fig. 11 Comparison of plume profiles for base case scenario with gas separation turned off in CDOG (top) and with gas separation turned on in CDOG (bottom)

The models also differ in their treatment of hydrates. The DeepBlow model assumes that, when thermodynamic conditions (pressure and temperature) are favorable for hydrate formation, gas is converted completely and almost instantaneously into solid hydrate grains, which shred from the surface of the gas bubbles. Because of the flakes' near neutral density and small size, the slip velocity of hydrate is assumed to be negligible and the hydrate particles do not separate from the plume. CDOG takes a more detailed, kinetic approach to hydrate formation. As illustrated in **Figure 11**, these model differences are important for predicting the extent of the plume stage and for predicting the ultimate fate of the released natural gas. However, for deep water conditions the differences in separation and hydrate formation are not very important for predicting the time to surface and surface expression of the oil.

7. Conclusions

The following has been learned from the six activities described above, in reference to the fate of oil spilled in the deep ocean.

- 1. Jets of oil and gas (if present) will break up into droplets and bubbles, respectively. The mechanism of breakup depends on the source conditions, and could result in a wide range of diameters ranging from less than one mm to the approximate size of the discharge opening, or the maximum stable diameter (whichever is smaller). Laboratory studies have not been conducted to examine droplet size distributions when both oil and gas are discharged, and guidance is needed to relate lab results to field conditions when exit conditions are less idealized, such as in a pipeline rupture.
- 2. The buoyancy of the oil droplets and gas bubbles will form a buoyant plume with the gas providing the dominant source of buoyancy (if present). Near the point of release, this plume will behave like a single-phase plume. Though slight leakage of entrained seawater and fine oil droplets can be expected in the lee of the plume, basic plume features in this near source region can be easily described with conventional integral plume models.
- 3. Above a certain height, ambient stratification and/or ambient currents will conspire to separate the dispersed phase(s) from the entrained water. Above a current speed of roughly 2.5 cm/s, the current is the major factor and separation can be expected at elevations of order 180 m or less. The CDOG and DeepBlow models treat this separation somewhat differently. However, as the plume stage is short compared with the water depth, differences in plume dynamics are relatively unimportant in determining the fate of oil released at depths of 800-1000 m.
- 4. Above the point of separation, gas bubbles and large oil droplets rise toward the surface, while small oil droplets continue with the entrained seawater as a buoyant jet. The latter can be simulated with traditional integral plume models, while the former must be simulated as diffusing buoyant droplets (and bubbles). DeepSpill experiments show that some of the oil surfaces more rapidly than expected based on the individual rise velocity of the fastest rising (largest) oil droplets, suggesting some group or secondary plume effects. The greater than expected rise velocity means that the oil will surface closer to the release point. However, the fact that

only a small fraction of the diesel oil was recovered at the surface suggests that much of the oil could have been contained in the form of much finer droplets that are much more widely dispersed. Slicks from a submerged oil release are thinner than those resulting from surface spills allowing them to weather more rapidly.

- 5. At ocean depths below about 450m, natural gas hydrates are thermodynamically stable. Hydrates could form as thin skins surrounding gas bubbles, which would reduce the bubbles' rate of dissolution, or as solid hydrates, which would significantly reduce bubble buoyancy. However, the UH laboratory studies suggest that hydrate formation requires relatively high background gas concentration, as well as significant induction time, neither of which are likely to occur due to the dilution caused by plume entrainment. The UH results suggest that the presence of oil on the bubbles can further impede hydrate formation. These conclusions are consistent with the DeepSpill field experiments (where hydrates were not observed), but not the model predictions. DeepBlow does not model the kinetics of hydrate formation (if hydrates are thermodynamically stable, solid hydrates are presumed), so SINTEF turned off the hydrate sub-model based on their observations. CDOG has a more detailed hydrate kinetic formulation, allowing it to predict a thin hydrate film; with such films Clarkson was able to match observed bubble rise heights in the DeepSpill experiments, but possibly for the wrong reason.
- 6. Echo sounders provide efficient tracking of oil and gas releases in the field and showed that the gas was completely dissolved before it could surface. This suggests that it may be safe to operate machinery directly above the spill without a danger of explosion.
- 7. The models that have been compared in these studies have evolved over time, at least in part because of the experimental studies and the model intercomparisons. As such the value of the last three (model comparison) activities has been as much in spurring model development as in identifying the "best model".

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