Pergamon

Spill Science & Technology Bulletin, Vol. 8, Nos. 5–6, pp. 433–443, 2003

Printed in Great Britain
1353-2561/$ - see front matter

doi:10.1016/S1353-2561(02)00123-8

RESEARCH

DeepSpill—Field Study of a Simulated Oil and Gas Blowout in Deep Water

ØISTEIN JOHANSEN†*, HENRIK RYE†,[1] & CORTIS COOPER‡,[2]
†*SINTEF Applied Chemistry, Enviromental Engineering, S.P Andersens vei 15A, Trondheim, N-7465 Trondheim, Norway*
‡*ChevronTexaco Petroleum Technology Co., 6001 Bollinger Canyon Road, Rm L-4240, San Ramon, CA 94583, USA*

With the world's increasing demand for oil and gas and dwindling onshore reserves, the need to exploit oil and gas has moved into deep water. This move brings with it the potential of accidental releases from well blowouts and pipeline or riser ruptures. While there is a low risk of such accident thanks to today's technology, the oil industry has to be prepared. To better understand how oil and gas would behave during a deep water release, the DeepSpill experiment was conducted in the Norwegian Sea at the Helland Hansen site (65°00′N, 04°50′E) in 844 m of water roughly 125 km off the coast of central Norway. Four controlled discharges of oil and gas were made during late June 2000 amounting to a total of 120 m^3 of oil and 10,000 standard m^3 of natural gas. The main objectives of the experiments were to calibrate numerical models and to test methods of subsurface surveillance.

Extensive observations were made of wind, currents, water density, surface and subsurface oil concentrations, and chemical and biologic samples in the water column. Results showed that the oil started reaching the surface about an hour after the release began and within a few hundred meters of the release site. Oil continued to surface for several hours after the release stopped. No gas hydrates were formed even though thermodynamic equilibrium suggested they should have. No gas bubbles reached the surface indicating that gas dissolution was complete but not as quickly as predicted by standard algorithms. The echo sounders on-board the research vessels were able to track the oil/gas plume as it rose through the water column. In general the surface slick was much thinner than a slick initially released at the surface would have been. Emulsified oil was observed at the surface after the crude oil discharge, with water content increasing with time after the oil came to the surface. An integral plume model [Spill Science and Technology Bulletin 6 (2000) 103] did a reasonable job of predicting the time to surface and the location of the slick though some tuning of the bubble/droplet sizes, gas dissolution rate, and hydrate formation were needed. Finally, the results showed that all gas was dissolved well beneath the surface suggesting that today's safety restrictions governing surface vessel activity could possibly be revised.

Keywords: **Oil spills, deep water, oil and gas blowout, experimental releases, field study, plume modeling, model verification**

Introduction

With the world's increasing demand for oil and gas and dwindling onshore reserves, the need to exploit oil and gas has moved into deep water. For example, in the last decade, Gulf of Mexico oil production in water of 300 m or greater has increased to 30% of total Gulf production. Similar trends are occurring offshore Norway, Brazil, West Africa, and Australia. This

*Corresponding author. Tel.: +47-73-59-12-21; fax: +47-73-59-70-51.
E-mail addresses: oistein.johansen@sintef.no (Ø. Johansen), henrik.rye@sintef.no (H. Rye), cortcooper@chevrontexaco.com (C. Cooper).
[1] Tel.: +47-73-59-13-19; fax: +47-73-59-70-51.
[2] Tel.: +1-925-842-9119; fax: +1-214-545-5316.

move to deep water brings with it the potential of accidental releases from well blowouts and pipeline or riser ruptures. While there is a low risk of such accident thanks to today's technology, the oil industry still has to be prepared. To do that, the operators need to understand how the oil will disperse as it moves up through the water column, how to track it as it moves through the water column, and how to clean it up once it reaches the surface.

Comparisons of models with field experiments in shallow water (e.g. Zheng & Yapa, 1998) suggest a good understanding of what goes on in shallow water, however, similar efforts have not been conducted in deeper water. There are a number of factors that can complicate the situation in deep water. The water is much colder and at higher pressure, and currents and thermal stratification tend to be more complicated. Some people have conjectured that the oil may not come to the surface for days and could travel hundreds of miles away from the source underwater.

In response to these challenges the oil industry together with governmental agencies began planning the DeepSpill joint industry project (JIP) in 1999 with the aim of conducting a field experiment to simulate a deep water release. After about one year of planning and preparations, the DeepSpill JIP culminated in June 2000 in a field study involving the controlled releases of 120 m^3 oil and 10,000 standard m^3 of gas in 844 m about 125 km offshore Norway. SINTEF Applied Chemistry acted as the main contractor in the project that was funded by a group of 21 oil companies along with the US Minerals Management Service, the federal agency in charge of offshore leasing in the US.

The DeepSpill JIP had two primary goals (Johansen *et al.*, 2001). First, to collect the first comprehensive data set from a deep water release. Such information would provide a valuable one-time view of oil fate in an important oil-producing region of the world but, more importantly, it would provide baseline data for model validation and tuning. The second goal was to investigate various methods to track the subsurface oil.

Planning and preparations

The study plan was to conduct a series of four experiments in June 2000 at one of either two sites in the Norwegian Sea. The site depth was chosen to be at least 700 m, well below the 450 m where thermodynamic equilibrium predicted gas hydrate would form. The month of June was chosen because the weather is relatively mild and there was no known migrations of marine life near the area at that time of year. A second site was considered in order to provide an alternative in case of poor weather conditions but was later dropped because it was too close to sensitive coastal biological resources.

The experiments were planned for two days. The first day involved the discharge of nitrogen gas only to test the equipment. It was followed by a second release with diesel and natural gas. The second day involved release of the medium crude and natural gas followed by a fourth experiment with natural gas only. Three vessels were involved: a supply vessel equipped for transport and discharge of the oil and gas and deployment of an ROV, and two research vessels one with another ROV. In addition, two 7-m sampling boats operated from the supply vessel were to be used to sample the surface slick.

A condensate that would not form water-in-oil emulsion was proposed for the first oil/gas experiment, while emulsion-forming crude was proposed for the second. In the actual experiment marine diesel was used as a substitute for the condensate because of the cavitation potential of the supply pump in the presence of condensate. The natural gas was transported to the experimental site in liquid state in cryogenic tanks. The liquefied natural gas (LNG)—which is composed primarily of methane (≈99%), with smaller amounts of other hydrocarbon gases—was pumped through a seawater-heated evaporator mounted on the vessel and transported as pressurized gas to the seabed in coiled steel tubing. A separate coiled tubing line was to be used for the oil discharge.

The overall plan evolved considerably during the six months leading up to the experiment. Changes were driven by equipment availability, contractor input, and especially safety considerations. Two safety workshops (HAZOPs) were held and they resulted in a number of changes. These workshops were facilitated by specialists from the Norwegian maritime classification company Det Norske Veritas.

One of the most important aspects of planning the project was in assessing the potential negative environmental impacts of the spilled oil. A very thorough assessment was done by running SINTEF's deep water plume model and state-of-the-art subsurface and statistical oil spill model (Johansen, 2000; Johansen & Skognes, 1994). The results indicated that the plume would be trapped at 100–200 m above the sea bed, with the oil droplets carried to the surface by their own rise velocity, forming surface slicks with a thickness in the order of 100 μm. Statistical oil drift simulations based on this initial film thickness and historical wind data for the region of concern indicated that the potential area of influence of such spills would be very limited, with practically no possibility for hitting coastlines.

An application for discharge permit was submitted to the Norwegian Pollution Control Authority (SFT), the Norwegian equivalent of the US Environmental

Protection Agency. The permit was forwarded to about a dozen Non-Government organizations and Governmental organizations for review and comment. SFT issued a permit in May 2000 with some additional, but easily met provisions.

Participating units

The experiment involved three vessels: The *Far Grip*, a 74.5 m long supply vessel, and two research vessels—the 65 m long *Johan Hjort* from the Institute of Marine Research (IMR) and the 47 m long *Håkon Mosby* from the University of Bergen (UiB) (see Fig. 1). Two 7 m long sampling boats were used to collect samples of surface oil and monitor the water column under the slick. A total of 43 scientists, specialists and JIP representatives participated in the experiment on the three vessels.

The Norwegian Clean Sea Association (NOFO) provided the necessary clean-up capability for the DeepSpill experiment. NOFO's oil-on-sea trial involved three oil recovery vessels and two towing vessels. Seven airplanes from several European countries were involved in aerial surveillance of the oil slicks. A dedicated flight commander was stationed at the *Kristiansund* airport to organize this activity and secure videotapes and pictures taken during the flights.

Field operations

The *Far Grip* and the *Håkon Mosby* arrived at the experiment site on the afternoon of 25 June 2000 after a 24-h transit time from Bergen (Fig. 2). The other research vessel (the *Johan Hjort*) arrived early the next morning. Meanwhile, the *Far Grip* and the *Håkon Mosby* had completed the deployment of the discharge platform at the seabed at 844 m depth.

Four experimental discharges were conducted as summarized in Table 1. The first experiment was initiated at 10:00 Monday June 26 (local time). However, it was delayed several hours due to mechanical problems. This forced the second experiment into Tuesday. Unfortunately the weather forecast from the Norwegian Meteorological Institute (DNMI) for Tuesday was poor with winds forecasted to increase to 25 knots by the afternoon. Given the worsening forecast it was decided to proceed as quickly as possible.

At 07:40 on Tuesday, the safety officer reported that everything was ready for the second experiment. Diesel and natural gas began to flow by 08:30 after some minor pumping problems. The discharge was stopped after one hour as planned. About that time (09:35), the first traces of diesel were observed on the sea surface Northeast of the *Far Grip*, and the sampling boats started surface and underwater sampling (see Fig. 3).

By 10:00 the wind had increased to 25 knots making conditions difficult for the sampling boats. However, they continued to operate as did the various surveillance airplanes. The first surveillance aircraft (LN-SFT) arrived on site at 10:12 and stayed for about half an hour, followed by the other surveillance airplanes and finally, the UK aircraft, which visited in the afternoon.

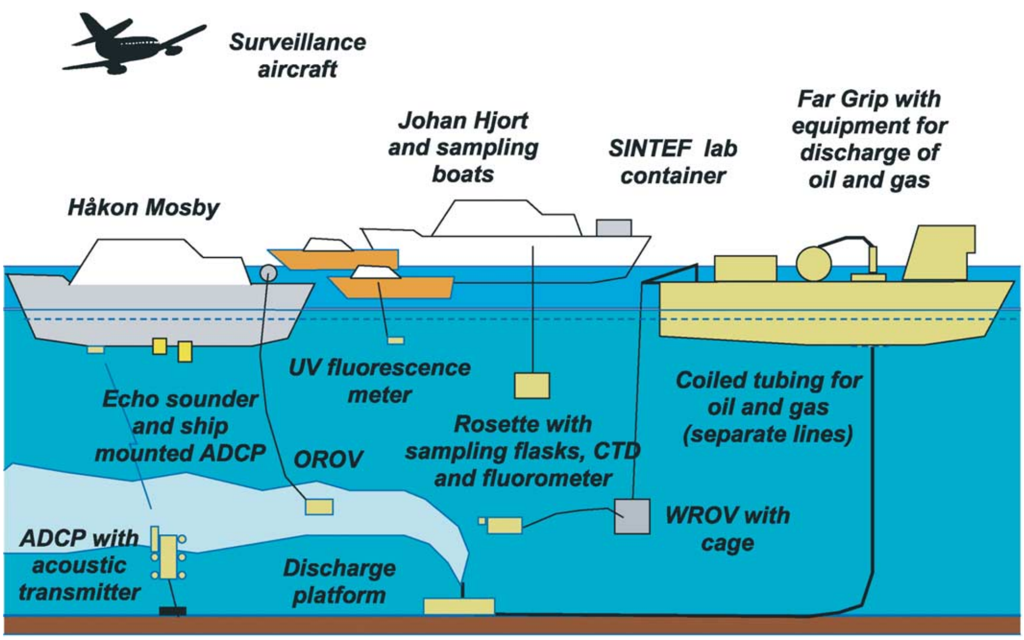

Fig. 1 Schematic overview of participating units at the DeepSpill experiment. The role of each vessel is indicated in terms of equipment and instrumentation operated by the vessels.

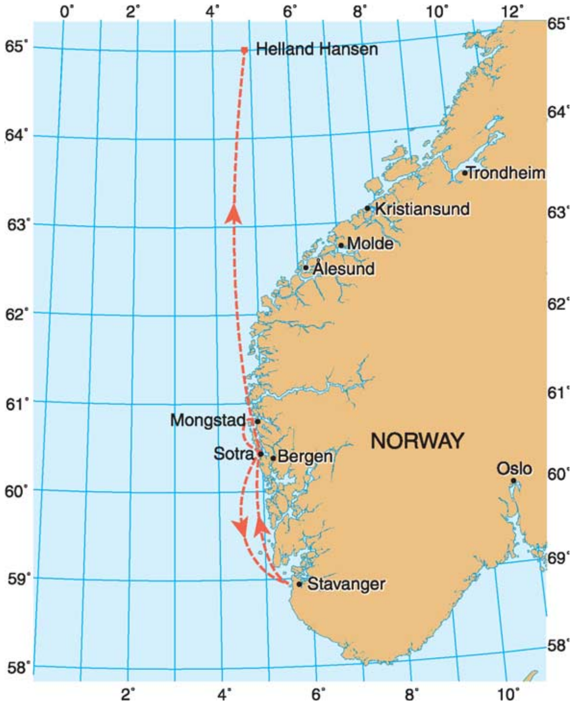

Fig. 2 Sailing route for the discharge vessel (Far Grip) to the experiment site (Helland Hansen). The vessel was chartered at Mongstad and sailed to Stavanger to mobilize equipment and personnel. Next stop was at Sotra outside Bergen to load crude oil and LNG.

Table 1 Summary of four experimental discharges

Experiment	Duration (min)	Gas rate (Sm^3/s)	Water/oil rate (m^3/h)
Nitrogen and dyed sea water	40	0.6	60
Marine diesel and LNG	60 (oil)	0.6	60
Crude oil and LNG	50 (oil)	0.7	60
LNG and sea water	120	0.7	60

Fig. 3 Aerial image of surface slick from diesel discharge. Picture taken from the Norwegian surveillance aircraft June 27. The vessels seen on the picture are (from left to right): Far Grip, Håkon Mosby and Johan Hjort. The two small boats are sampling boats. The ROV on the *Håkon Mosby* proved ineffective in the current conditions. Fortunately the echo sounders on both research vessels provided clear images of the rising plume of oil/gas. The real-time echo sounder images also helped guide the water samplers directly into the plume of rising droplets.

The crude oil discharge was planned as the first of two experiments to be conducted on Wednesday. However, the experiment had to be postponed another day due to poor weather. Preparations were made for discharge of the oil/gas at 06:00 on Thursday but the strong swell prohibited launching of the ROV. With the forecast for worsening weather for the next few days, it was decided to commence the experiment anyway without the ROV. Discharge of crude oil began at 07:20 and the release continued at a constant rate until 08:10. Close to 1 h after initial release, the first sighting of oil on the sea surface was observed.

At about 09:00 the SFT surveillance aircraft arrived at the site and guided the sampling boat through the surface slick. At this time, this was the only aircraft available since the other surveillance airplanes had left to attend to prior commitments. The SFT aircraft stayed in the area about 1.5 h on the first flight and returned at 16:00 for a final surveillance. At 16:30 the pilots on the SFT aircraft concluded that the remaining surface slick would dissipate in a short time and represented no serious threat to the marine environment. On that basis the JIP manager decided that no attempts to recover the oil would be required. The SFT representative onboard the *Far Grip* concurred.

The fourth experiment involving the natural gas discharge was started at 09:40 on Thursday. By that time seas had calmed somewhat and the ROV from *Far Grip* was launched. discharge of LNG and seawater continued for about 2 h. During this period, the ROV took video shots of the rising bubble plume and close ups of the gas bubbles (see Fig. 4). At the same time the *Håkon Mosby* circled the discharge vessel to monitor the plume with its echo sounder. After the gas discharge was finished, the *Håkon Mosby* assisted the

Fig. 4 Picture taken from the ROV of the discharge platform showing the gas bubble plume from the LNG experiment.

Table 2 Overview of measurements and observations

Objective	Methods	Sampling interval	Comments
Documentation of experimental conditions	Weather station on research vessel. CTD operated from research vessel. Two ADCPs, one mounted on research vessel and the other on the seafloor connected with acoustic link to research vessel	Wind and current data sampled at 10 min intervals. Sea temperature and salinity profiles measured minimum once a day	Wind measured 10 m above sea level Ocean currents sampled at 25 m intervals from 50 m above seabed to 25 m below sea surface Sea temperature and salinity measured at 1 m spacing from surface to seabed
Observation of oil droplets, gas bubbles and transition to hydrate	Visual video recorded by work ROV	During discharge periods	Clouds of gas bubbles pictured from outside of plume. Close up of oil droplets and gas bubbles inside plume
Mapping of plume trajectory	Video, sonar, UV-fluorometer, methane detector mounted on observation ROV. Remote operated sampling flasks (rosette sampler) deployed from research vessel. Echo sounders operated from research vessels	During and after each discharge period	No measurements obtained from the observational ROV due to operational problems Echo sounder images used to guide the rosette sampler into the rising plume of gas bubbles and oil droplets
Surfacing of oil droplets, thickness and properties of surface oil	UV-fluorometer, sampling pads and flasks operated from two sampling boats	Subsequent to oil discharges	Sampling boats guided into surface slick by aircraft
Extent of surface slick	SLAR, UV and IR imaging from aircraft	Subsequent to oil discharges	Surveillance shared by six airplanes during diesel experiment (June 27). Only one aircraft available during crude oil experiment (June 29)
Supplementary information	Sea bird surveillance. Sampling and surveillance of marine organisms	Prior to and during field trials	Carried out from *RV Johan Hjort* by specialists from NINA and IMR

Far Grip in the recovery of the discharge platform while the *Johan Hjort* recovered the ADCP (current meter) mooring from the seabed. The vessels departed the site on Thursday June 29 at 16:25.

Measurements and observations

Table 2 summarizes the measurements made during the experiments. Most of the measurements were carried out according to the original plan. One exception was the ROV on the *Håkon Mosby* which was equipped for monitoring of the underwater plume. The ROV proved unable to cope with the current and depth conditions.

Fortunately, the second ROV on the *Far Grip* performed well. Also, the echo sounders on both research vessels were able to profile the underwater oil and gas plumes quite clearly. The sampling of the water column carried out with the rosette sampler on the *Johan Hjort* provided additional data on plume behavior. These three sources compensated to a large extent for the ROV failure.

Analysis of water samples taken with a rosette sampler revealed how the composition of the crude oil and diesel changed on its way to the sea surface due to dissolution of the water soluble components into the ambient water.

The echo sounder images indicated that the LNG did not reach the sea surface, disappearing at about 150 m depth. The disappearing gas was almost certainly due to the dissolution of the gas into the ambient water. Both the crude oil and the diesel releases did reach the sea surface though the rise time was somewhat shorter than predicted by the model.

Concentrations in the upper water column were monitored with UV-fluorometers lowered from sampling boats. The sampling boats were also used to sample the crude oil and diesel slicks and to measure the thickness of these slicks. Analysis of oil samples from the surface slicks provided a time history of the loss of volatile components (evaporation), increases in water content (water-in-oil emulsion), and changes in physical properties (viscosity).

The surface oil film thickness observed from the two oil releases was significantly different. Typical thickness of the diesel slick was of order of 1 μm while within the thicker emulsified parts of the crude oil slick the thickness reached order of 1 mm. This is considerably thinner than the 2–9 mm thickness observed in emulsified patches in a previous field experiment conducted in the North Sea with 20 m^3 of the same type of crude released on the sea surface (Lewis *et al.*, 1995). As expected, the diesel did not show any sign of emulsion formation. However, the crude oil formed emulsion gradually with an increase from 30% water measured in samples taken 1/2 h after surfacing of the oil up to a maximum of 75% after 5 h on the surface (water content determined with Karl Fischer Titration method). Samples with the maximum water content were found to be stable emulsions in the sense that no water separated from the emulsion within a 24 h settling period at ambient temperature (10 °C). This development in water content and stability of the emulsion with time resembles the development observed in the North Sea field experiment mentioned above, where the same oil type was discharged on the sea surface. It is thus likely that the emulsion was formed after the oil had surfaced.

Aerial surveillance of the oil slicks gave supplementary information on the slick shape and amounts of oil (Daling *et al.*, 1999). The remaining volume in the diesel slick was reported to be considerably smaller than the amounts released (60 m^3), with the minimum and maximum estimates ranging from less than 1 m^3 up to a maximum of 17 m^3. The diesel slick showed a limited extension in the downwind direction probably due to the rapid dispersion of the diesel into the upper water column by wave action.

Results and Discussion

Verification or validation of models

The data collected form a good basis for comparison with numerical simulation models of deep water releases. As a part of the analysis of the experimental observations the *DeepBlow* model developed by SIN-

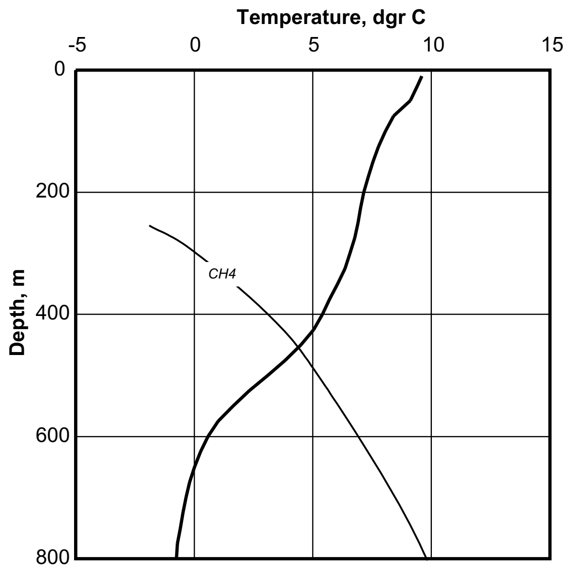

Fig. 5 Vertical temperature profile measured at the experimental site (thick line). The thin line represents the equilibrium line for hydrate formation from methane gas (Sloan, 1990). The line is adjusted for the freezing point depression of 1.8 °C due the salinity of sea water.

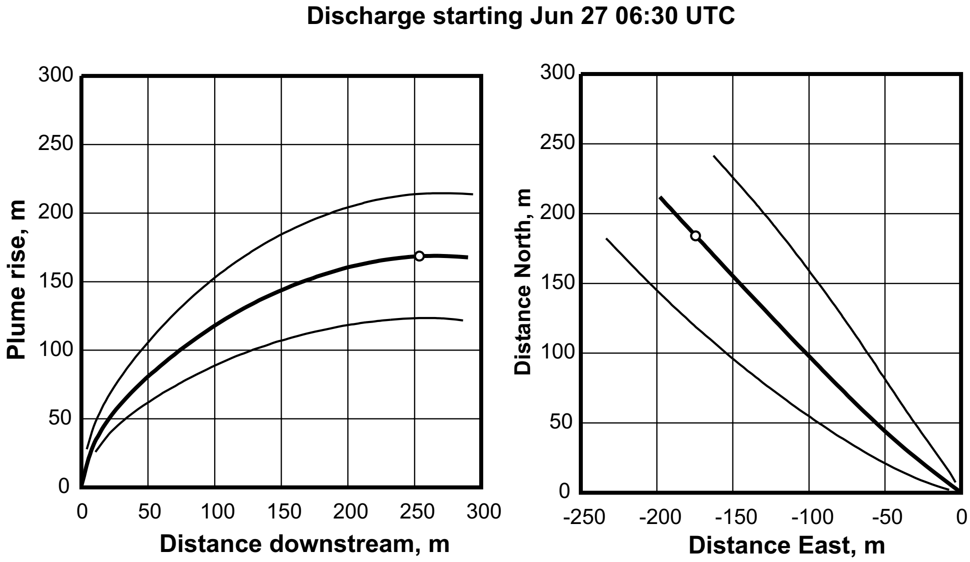

Fig. 6 Plume path calculated with the DeepBlow model for the diesel experiment. A marker on the plume centerline indicates the termination point of plume rise. The computed rise time to this point was 36 min.

TEF was compared with the field data. This model is designed to include effects of hydrate formation, gases dissolution, cross currents, trapping of the underwater plume, and escape of gas bubbles from a bent-over plume (Johansen, 2000).

Different sub-models were used to represent the ascent of oil droplets from the trapped plume to the sea surface, the formation and thickness of the slick on the sea surface, and finally the dissipation of the surface slick due to wind/wave action.

The model was run using the actual release conditions including the ambient currents and density stratification. Under the prevailing conditions at the experimental site, methane gas was expected to form stable hydrates at 450 m and lower (Fig. 5) based on thermodynamic equilibrium. However, no hydrate formation was observed during the experiments. The simulations with and without hydrate formation predicted nearly identical plume trap height of 170 m. In the case with hydrate formation, the plume trap height

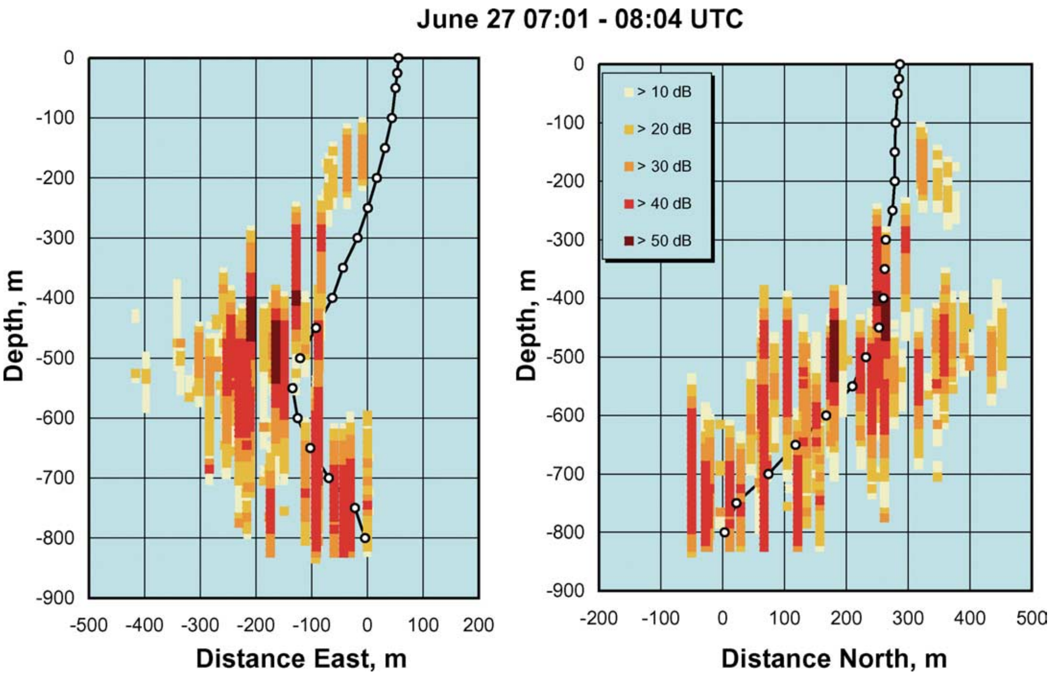

Fig. 7 Rise of oil droplets for the diesel experiments one hour after start of discharge. Black curve denotes the mean path of the droplet cloud computed with the model, while colored data points indicate echo-sounder data from Håkon Mosby.

was controlled by conversion of gas into hydrate. In the case where hydrate formation was turned off, the trap height was controlled by gas dissolution and gas bubbles leaking out of the plume as the ambient current deflected it. Thus in both cases the plume was deprived of the high buoyancy gas bubbles.

No direct measurements of the plume of entrained water could be made during the experiments although observations with the video camera mounted on the ROV showed clouds of rising bubbles (and oil droplets) up to at least 100 m above the discharge point. Moreover images from the echo sounders during the LNG discharge tracked gas bubbles to a depth of 150 m beneath the surface.

These findings contradict calculations based on empirical mass transfer coefficients from chemical engineering literature (Hughmark, 1967). These calculations indicate that gas bubbles with an initial diameter corresponding to the observed maximum bubble size (10 mm) would be dissolved completely after a rise of about 200 m from the exit point. In order to produce the observed bubble rise, a reduction factor of 0.25 had to be applied to the empirical mass transfer coefficient. With this modification, the *DeepBlow* model produced a plume path as shown in Fig. 6.

One potential explanation for the reduced dissolution rate could have been formation of a hydrate shell on the surface of the bubbles. However this explanation seems unlikely for several reasons. First this shell would likely have melted as the gas bubbles ascended above the hydrate thermodynamic equilibrium line (indicated as 450 m in Fig. 6). Subsequently, the gas bubbles would have had to survive a further rise of at least 300 m without the protecting hydrate shell. Moreover, close up video images of gas bubbles made from the ROV for the initial 100 m ascent showed transparent bubbles with no sign of a hydrate shell.

The apparent lack of hydrate formation also remains an unresolved issue. According to Sloan (1990) the formation of nuclei is likely to occur at the gas–water interface when the thermodynamic conditions for hydrate formation are present as they were in the DeepSpill case. Perhaps one explanation is that the local water was probably not gas saturated. There are strong suggestions in a recent series of high-pressure laboratory studies (Masutani & Adams, 2000) that hydrate formation first required methane saturation of the local water at pressures of 650 m.

In the two experiments with discharges of oil, the oil was first reported on the surface close to one hour after the start of the experiments. Based on close-up video images from the ROV during the diesel experiment, the maximum droplet diameter was 8–10 mm. This is greater than the critical diameter where the rise velocity no longer increases with droplet size (Hu & Kintner, 1955). Thus the largest droplets would be expected to rise at 0.13–0.15 m/s. If we presume free rise of oil droplets from the exit point, this would imply a minimum rise time of 90 min, rather than the reported 60 min. However, by taking into account the added rise velocity of the plume, the calculated rise time is reduced to 75 min. Still, this is 15 min longer than the observations indicate. This might imply that

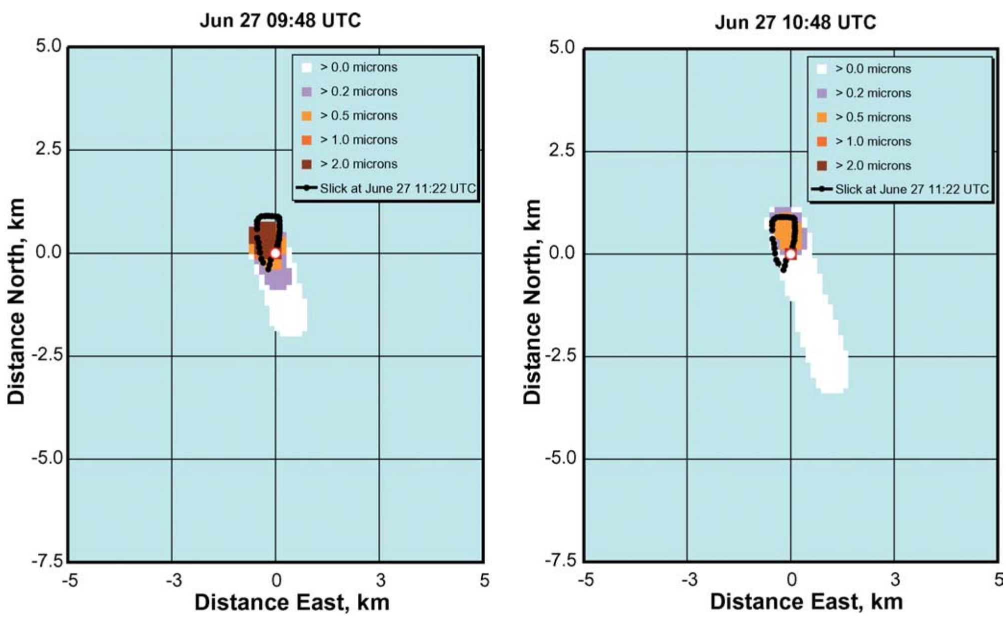

Fig. 8 Simulations of the development of the surface slick from the diesel experiment. Top: 3 and 4 h from start of discharge. Observed slick contours from adjacent times are drawn on the same plots for comparison.

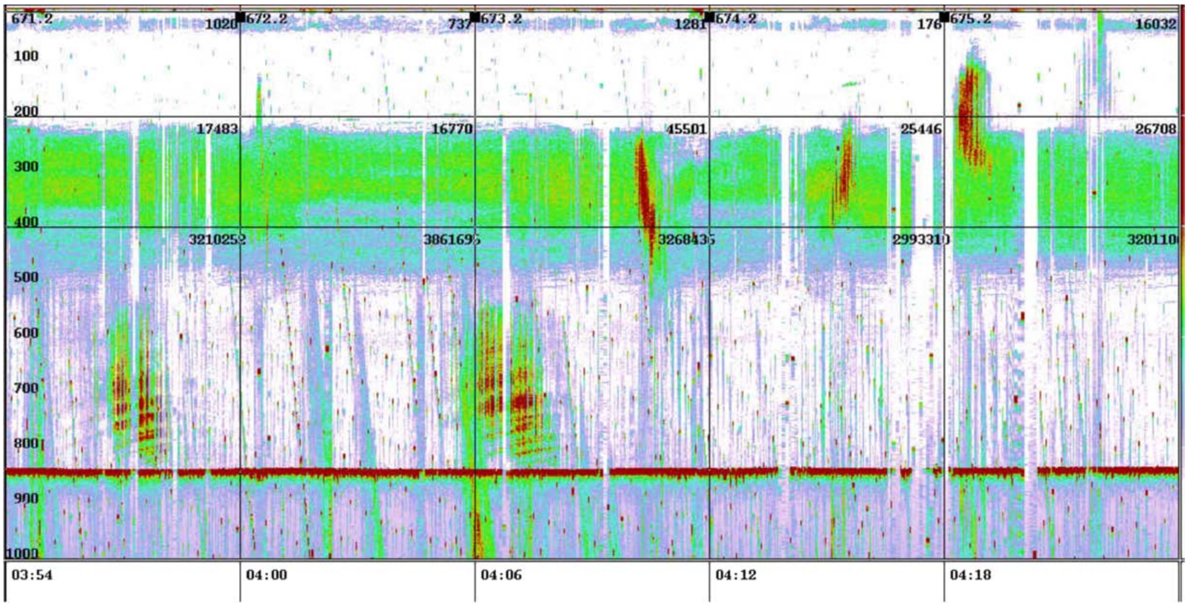

Fig. 9 Echo sounder image as observed on the Håkon Mosby during the crude oil discharge June 29. The horizontal axis indicates time (hours and minute), with markers at 6 min intervals. The vertical axis indicates depth, with the seabed visible at 840 m. The green colored stratum between 200 and 400 m depth is related to plankton situated within the perennial thermocline.

the rising gas bubbles enhances the rise of the oil droplets in some way.

Aside from the discrepancy mentioned above, the calculated paths of the rising clouds of oil droplets and gas bubbles were in good agreement with the images obtained from the echo sounders. The mean path of the rising droplet clouds was computed from the observed droplet size distribution and the observed current profile at the start the discharge periods. These paths were found to be centered well within the observed echo-sounder signal, and to terminate inside the first observed surface slicks (Fig. 7).

The calculated surface slick also compared well to that observed although some differences in the shape and extension of the slicks were noted (Fig. 8). For this calculation, loss of surface oil due to natural dispersion and evaporation was lumped together in a first order decay model with the rate represented by a half-life parameter (time corresponding to 50% reduction). In order to reproduce the diesel discharge, a half-life of 5 min was used, while the crude oil discharge required a considerably longer half-life (3 h). This difference in half-life is consistent with the difference in evaporation and the formation of water-in-oil emulsions for the crude oil slick.

Monitoring lessons learned

The ROV operated from the *Far Grip* generally performed well although heavy swell prevented launching of the ROV during one of the experiments (the crude oil discharge). A key ingredient to the success of this ROV was that it had sufficient power (maximum 75 HP distributed on six thrusters), and it used a "garage" arrangement. The garage and ROV were lowered within about 100 m of the ROV destination and then the ROV was deployed from the garage. This avoided the large current drag that results on a long umbilical going all the way to the surface and also minimized tangling problems. For exactly the opposite reasons, the other ROV operated from the *Håkon Mosby* proved inoperable because it was much less powerful (15 HP distributed on five thrusters), and used an umbilical all the way to the surface.

The echo sounders on the research vessels proved to be effective for imaging of the gas bubbles and oil droplets (Fig. 9). Both vessels were equipped with Simrad EK500 scientific echo sounders that were capable of operating with 18, 38, 120 or 200 kHz transducers. The transducers were mounted on a retractable keel in order to obtain high quality data during potentially severe weather conditions. The most useful data for tracking the plume came from the 38 kHz transducer.

Vertical profiles of sea temperatures, salinity and ocean currents were made in real time during the field trial. This information allowed the *DeepBlow* model to be run in real-time during the experiment. While acquiring salinity and temperature profiles in real time required no additional effort, acquiring real-time currents in deep water required deployment of a current mooring and use of an acoustic modem. This modem turned out to be quite sensitive to vessel engine noise so to retrieve data, the vessel had to stop directly over the current meter, and shut down engines. In hindsight the ship echo sounders proved to be so efficient at tracking the rising plume that real-time modeling was probably not essential.

During the present sea trial, three ships were used—one in a fixed position (*Far Grip*) and the other two were mobile. This proved to be an efficient arrangement that allowed good sampling along with some redundancy and safety backup.

Implications for safety

One of the goals of the sea trial was to see if gas bubbles from a blowout might reach the surface. Clearly if one knows in advance that the gas will *not* make it to the surface this eases safety constraints for vessels trying to cope with a major blowout. Today's North Sea standards prohibit anyone onboard the drilling unit (that was drilling at the time of the blowout) or vessels from working directly over a blowout. This requirement seriously complicates and slows the logistics of the response thus allowing more hydrocarbon to escape. Theoretical considerations suggest that NG is highly dissolvable at the high pressures and low temperatures found in deep water. Indeed, the results from *DeepSpill* support the theory. During the crude oil and diesel releases, the observers in the sampling boats could see oil droplets "bursting" at the sea surface but no sign of gas bubbles. In addition the echo sounder images showed that the NG-only plume vanished 150 m beneath the surface. In short, all indications are that for the conditions in this experiment, it would have been safe to operate directly above the blowout. However, this problem needs to be studied more closely before any regulatory changes are made. In particular a better understanding needs to be gained about the dependency on volume of gas, ocean thermal stratification, and current conditions.

Conclusions and Recommendations

The *DeepBlow* model (Johansen, 2000) predicted the rise time to the surface and the centerline track of the plume quite nicely once a few adjustments were made. The two surprises were that hydrates failed to form and the NG dissolved more slowly then predicted by standard algorithms. Verification runs with other models would reveal if this is a model specific problem or a more generic one.

While the surfacing times of oil from the diesel and the crude oil experiments were similar, the persistence of the oil on the surface was found to differ significantly. The rapid decay of the diesel oil was most probably due to the fact that the diesel evaporates much more readily then the oil and did not form water-in-oil emulsions like the crude oil. In the crude oil experiment, an emulsion with maximum water content of 75% formed gradually as the oil was exposed to wave action.

Measurements of the thickness of the surface slick from the diesel experiment showed values of order 1 μm while measurements in the crude oil slick were up to the order of 1 mm in the emulsified oil patches. In general the initial surface slick in both cases was thinner and more dispersed than if the oil had been released as a point source at the surface. This may have some implications on the effectiveness of mechanical clean-up and dispersant application.

In certain regions like the North Sea, response vessels are prohibited from working above a blowout because of the potential for explosion. Such restrictions are based largely on shallow-water blowout experience and generally slow the initial response. Results from DeepSpill suggest they may not be necessary although clearly further study is needed in order to substantiate this claim.

Acknowledgements—A complex, expensive project like this would not have been possible without the help of many including the subcontractors at Argus Remote Systems, Det Norske Veritas (DNV), Institute of Marine Research (IMR), JM Consult, Krytem GmbH, MARINTEK, Norwegian Institute of Nature Research (NINA), Oceaneering A/S, Schlumberger Norge, and Seabrokers Chartering. Special thanks go to SFT and NOFO for their cooperation. We would like to acknowledge the exceptional technical contributions from participants at Chevron, Norsk Hydro, Statoil, Shell, and Exxon-Mobil. We also acknowledge the excellent cooperation and support from the funding companies: AGIP, BHP, BP, Conoco, Chevron, Devon, Dominion, EEX, El Paso, Exxon-Mobil, Kerr-McGee, Mariner, Marathon, MMS, Murphy, New Field, Norsk Hydro, Shell, Statoil, Texaco, Total-Fina-Elf, and Unocal.

References

Daling, P.D., Lewis, A., Ramstad, S., 1999. The use of Colour as a Guide to Oil Film Thickness—Main Report. SINTEF Report SFT66 F99082,SINTEF, Trondheim, Norway, 93p.

Hu, S., Kintner, R.C., 1955. The fall of single liquid droplets through water. AIChE Journal, 42–48.

Hughmark, G.A., 1967. Liquid–liquid spray column drop size, holdup, and continuous phase mass transfer. I&EC Fundamentals 6, 408–413.

Johansen, O., 2000. DeepBlow—a Lagrangian plume model for deep water blowouts. Spill Science & Technology Bulletin 6, 103–111.

Johansen, Ø., Skognes, K., 1994. Statistical Oil Drift Model for Environmental Risk Assessments. OCEANOR Report P-22890, Oceanographic Company of Norway, Trondheim, Norway, 26p.

Johansen, Ø., Rye, H., Melbye, A.G., Jensen, H.V., Serigstad, B., Knutsen, T., 2001. DeepSpill JIP—Experimental Discharges of Gas and Oil At Helland Hansen, June 2000, Technical Report. SINTEF Report STF66 F01082, SINTEF Applied Chemistry, Trondheim, Norway, 159p.

Lewis, A., Strøm-Kristiansen, T., Brandvik, P.J., 1995. The behaviour of sture blend crude oil spilled at sea and treated with dispersant. Proceedings of the 18th Arctic and Marine Oil Spill Program (AMOP) Technical Seminar. Edmonton, Alberta, Canada June 1995, pp. 453–469.
Masutani, S.M., Adams, E.E., 2000. Experimental Study of Multiphase Plumes with Application to Deep Ocean Oil Spills. Report to Minerals Mgt. Service, Contract 1435-01-98-CT-30964, Herndon, VA, 88p.
Sloan Jr., E.D., 1990. Clathrate Hydrates of Natural Gases. Marcel Dekker Inc, New York, p. 641.
Zheng, L., Yapa, P.D., 1998. Simulations of oil spills from underwater accidents, II: Model verification. Journal of Hydraulic Research, IAHR 36, 117–134.