



## RESEARCH

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

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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<sup>3</sup> of oil and 10,000 standard m<sup>3</sup> 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.

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**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

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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<sup>3</sup> oil and 10,000 standard m<sup>3</sup> 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 determine the dispersal characteristics of oil and gas in deep water. Second, to determine the impact of deep water releases on the environment. The study was conducted in the Norwegian Sea, 125 km offshore of the coast of Norway, at a depth of 844 m. The study 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.

### ***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.

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 supply vessel, and the research vessel *Johan Hjort* of the Marine Research Institute (IMR) and the *Håkon Mosby* of the University of Bergen (UB) (see Figure 1). The 7 m autonomous underwater vehicle (AUV) *de e c*. A 43 cm diameter, 1 m long JIP pipe was used to discharge the oil.

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* airbase and coordinated the operations.

**Field operations**

The *Far Grip* and *Håkon Mosby* arrived at the site of 25 June 2000 at 07:00.

A 24-hour offshore Bore (Figure 2). The release rate of the *Johan Hjort* was 1 m<sup>3</sup>/h. Meanwhile, the *Far Grip* and *Håkon Mosby* discharged the oil and gas at a rate of 844 m<sup>3</sup>/h.

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 *Håkon Mosby* (see Figure 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.

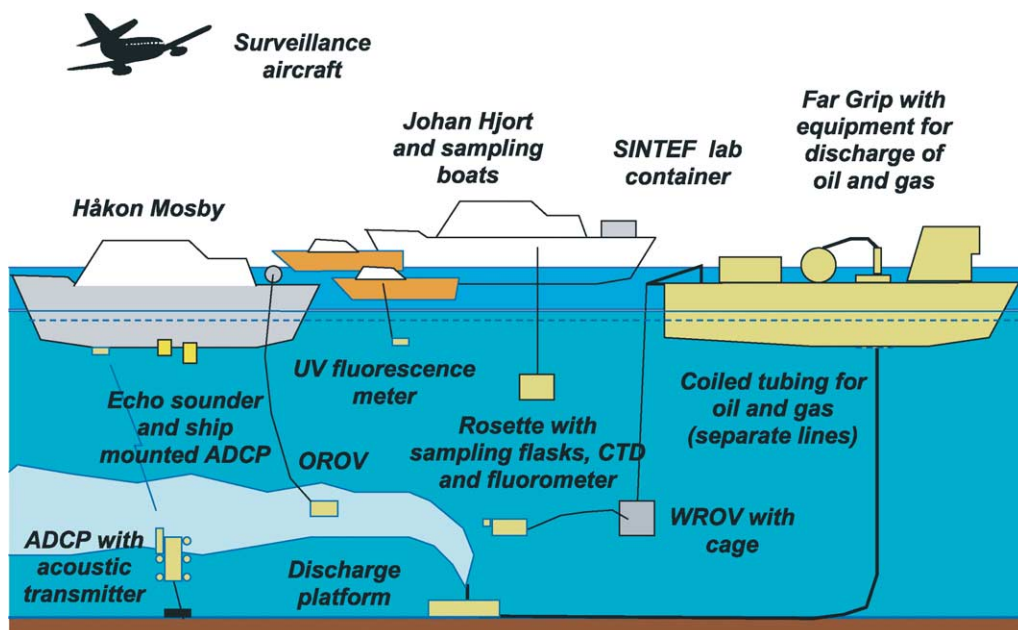
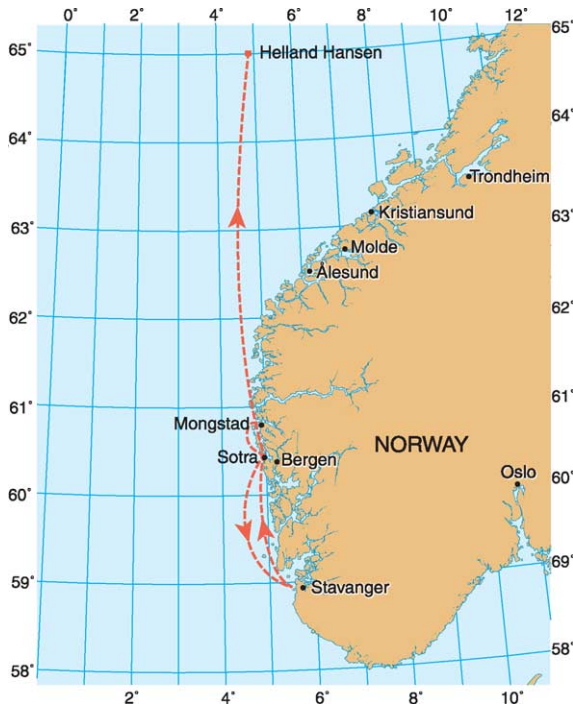


Fig. 1 Schematic overview of participating units at the DeepSpill experiment. The role of each vessel is indicated in terms of equipment and instrumentation operated by the vessels.



**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

Discharge	Duration (min)	Gas release (kg)	Water release (kg)
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* was used to monitor the discharge.

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* concluded.

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 used to monitor the discharge of LNG and sea water. The ROV was used to monitor the discharge of LNG and sea water. The ROV was used to monitor the discharge of LNG and sea water. The ROV was used to monitor the discharge of LNG and sea water.



**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

Observation	Method	Sampling	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 level data available for face
Observation of oil droplets, gas bubbles and transition to hydrate	Visual video recorded by work ROV	During discharge periods	Conductivity, temperature, salinity, density, turbidity, fluorescence, chlorophyll, and dissolved oxygen measurements
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 data available
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	Salinity, temperature, density, surface oil thickness, and surface oil properties
Extent of surface slick	SLAR, UV and IR imaging from aircraft	Subsequent to oil discharges	SLAR, UV, and IR data available (June 27). Oil slick data available (June 29)
Sea surface temperature	Sea surface temperature sensor on research vessel	Periodic	Conductivity, temperature, salinity, density, and surface oil thickness measurements by specialists from NINA and IMR

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**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* c a e ed f f e de a e e. T e ROV ed abe c e ec e a d de c d .

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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<sup>3</sup> of the same type of crude released on the sea surface (Lewis *et al.*, 1995). A e ec ed, e d e e d d a f e f a . H e e, e c de f ed e ad a a c ea e f 30% a e

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Aerial surveillance of the oil slicks gave supplementary information on the slick shape and amounts of oil (Daling *et al.*, 1999). T e e a e ed ee c a e ed bec de ab a e a ea e ea ed (60<sup>3</sup>), e ad a e a e a f e a 1<sup>3</sup> a a f 17<sup>3</sup>. T e de e c ed a ed e e ed d d ec bab de e a d d e f ed ee e e a e c b a e ac .

**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* de de e ed b SIN-

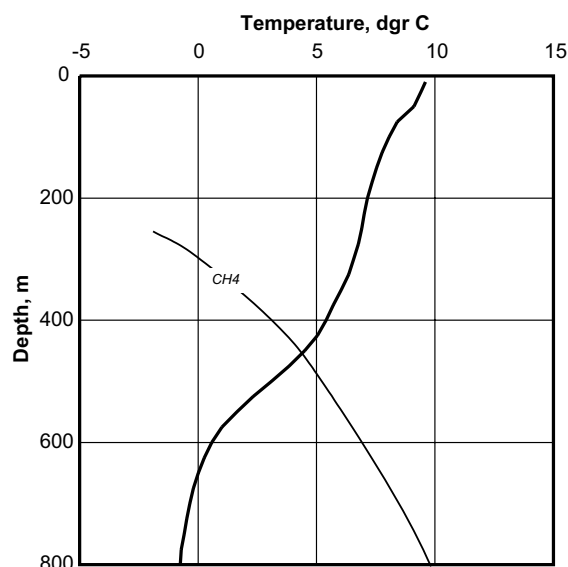


Fig. 5 Vertical temperature profile measured at the experimental site (thick line). The thin line represents the equilibrium line for hydrate formation from methane gas (Sloan, 1990). The line is adjusted for the freezing point depression of 1.8 °C due the salinity of sea water.



Discharge starting Jun 27 06:30 UTC

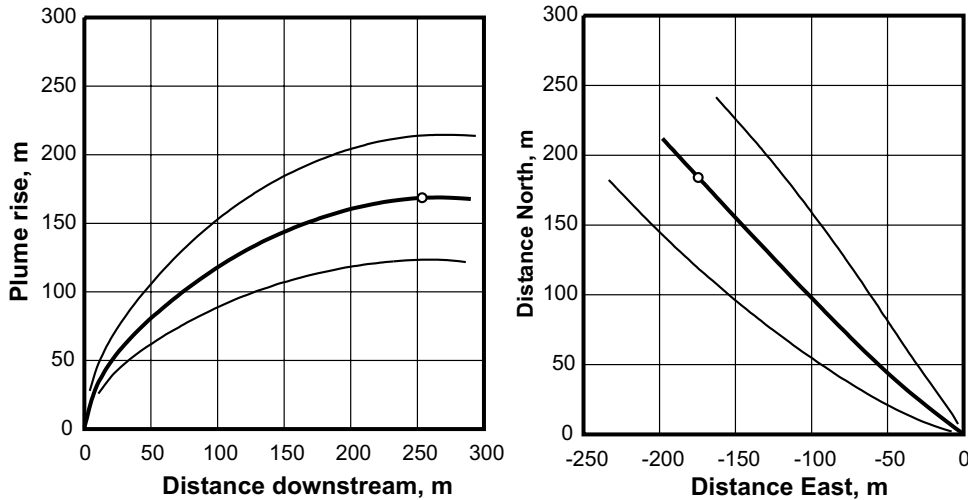


Fig. 6 Plume path calculated with the DeepBlow model for the diesel experiment. A marker on the plume centerline indicates the termination point of plume rise. The computed rise time to this point was 36 min.

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e (J a e , 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

June 27 07:01 - 08:04 UTC

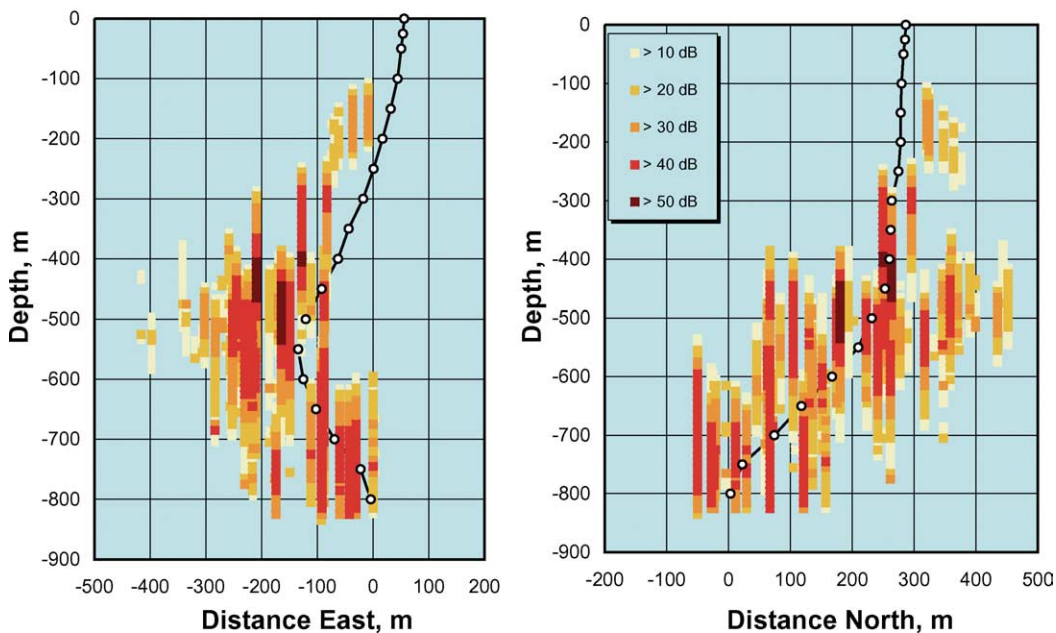


Fig. 7 Rise of oil droplets for the diesel experiments one hour after start of discharge. Black curve denotes the mean path of the droplet cloud computed with the model, while colored data points indicate echo-sounder data from Håkon Mosby.

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 *Deep-Blow* de d c e a e a a F . 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

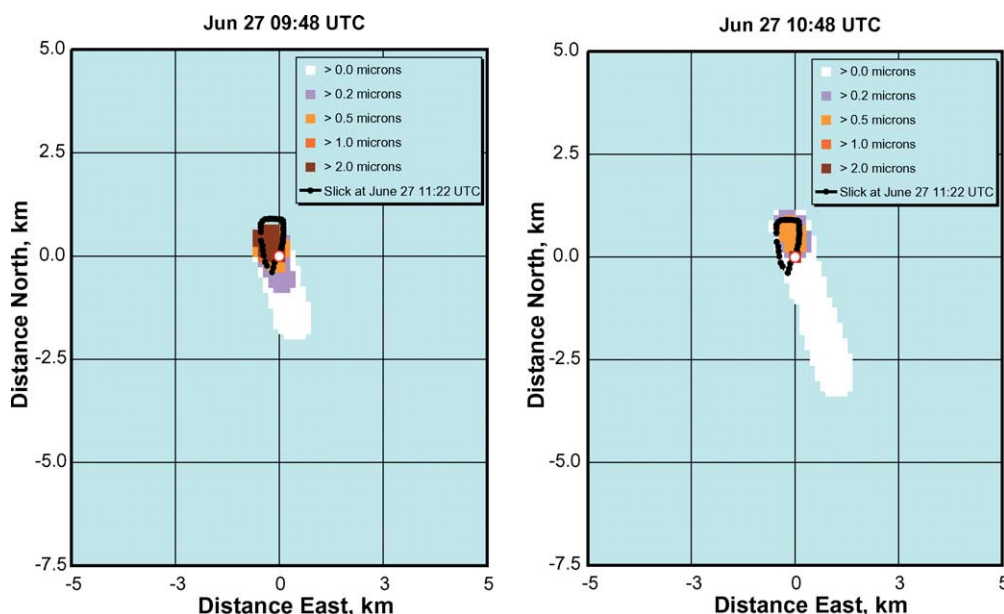


Fig. 8 Simulations of the development of the surface slick from the diesel experiment. Top: 3 and 4 h from start of discharge. Observed slick contours from adjacent times are drawn on the same plots for comparison.



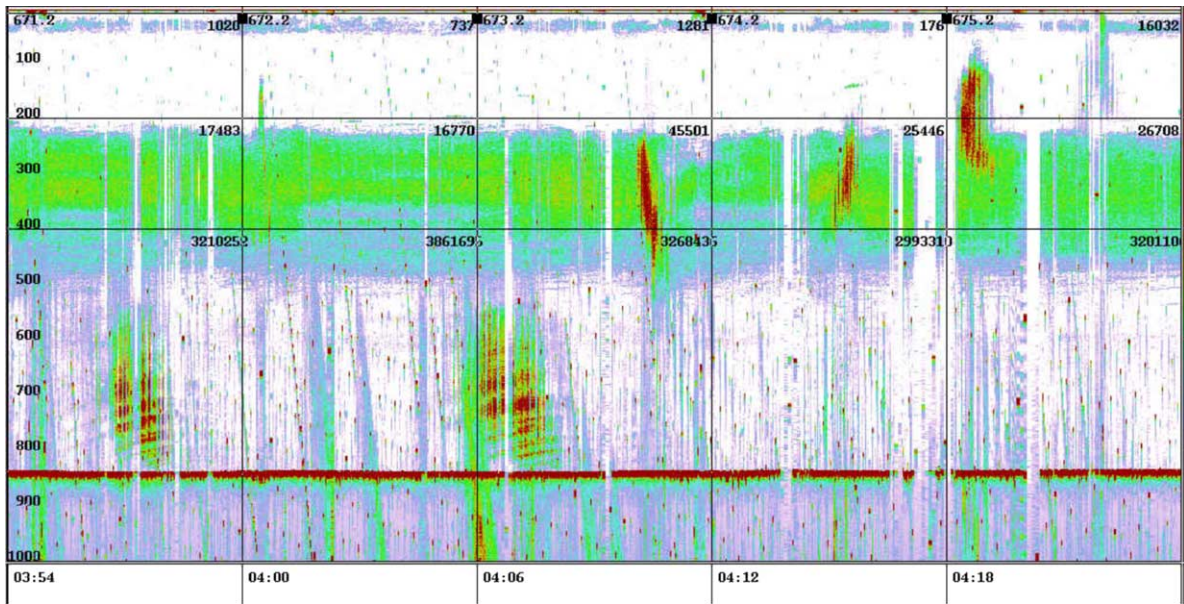


Fig. 9 Echo sounder image as observed on the Håkon Mosby during the crude oil discharge June 29. The horizontal axis indicates time (hours and minute), with markers at 6 min intervals. The vertical axis indicates depth, with the seabed visible at 840 m. The green colored stratum between 200 and 400 m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

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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* de be ea - ed e e e e . W e ac - a a d e e a e e ea e e ed add a e , ac ea - e c - e dee a e e ed de e fac e a d e fa ac c de . T de ed be e e e e e e e e

During the present sea trial, three ships were used—one in a fixed position (*Far Grip*) and two in a barge position. The diesel oil was released from a fixed position (*Far Grip*) and two in a barge position.

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**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

reach the surface, it is possible to take preventive measures. The sea trial was conducted in the North Sea. The diesel oil was released from a fixed position (*Far Grip*) and two in a barge position. The diesel oil was released from a fixed position (*Far Grip*) and two in a barge position.

**Conclusions and Recommendations**

The *DeepBlow* (Johansen, 2000) model is a Lagrangian plume model for deep water blowouts. The model is a Lagrangian plume model for deep water blowouts. The model is a Lagrangian plume model for deep water blowouts.

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 than 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.

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