Fate and Behavior of Deepwater Subsea Oil Well Blowouts in the Gulf of Mexico

for

Minerals Management Service

by

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1. Study Scope

Oil exploration in the Gulf of Mexico is moving further offshore into very deep waters. If a subsea oil and gas blowout were to occur during drilling, oil could rise through the water column and reach the surface. The objective of this study was to answer the following questions:

- *What properties are expected of the oil once it reaches the surface, such as slick thickness, area, and dispersibility?*
- *Are there any major differences in oil spill behavior between a blowout in relatively shallow water and one in very deep water?* and
- *What cleanup measures are available and appropriate to deal with the spill?*

2. Background

The focus is an oil well blowout situation in which the drilling platform moves off site or is destroyed during the accident. In this case the discharging oil and associated gas emanate from a point on the sea bed and rise through the water column to the water surface. An example of this kind of subsea blowout was the 1979 *Ixtoc 1* oil-well blowout in the Bay of Campeche, Mexico, which took place in 50 meters of water. The behavior of such blowouts has been investigated and modeled by several researchers. No subsea oil well blowouts have occurred in very deep water, but some research has been done on the subject. Before discussing deepwater blowouts (>300 m of water), it is useful to quickly review knowledge on subsea blowouts in less deep water.

2.1 Subsea Blowouts in Water Depths less than 300 Meters

Fluid Dynamics: Oil-well blowouts generally involve two fluids, namely crude oil (or condensate) and natural gas. The volume ratio of these two fluids is a function of the characteristics of the fluids and the producing reservoir. The natural gas, being a compressible fluid under pressure at reservoir conditions, provides the driving force for an uncontrolled blowout. As the well products flow upwards, the gas expands, finally exiting at the well-head at very high velocities. At this point the oil makes up only a small fraction of the total volumetric flow.

Oil and gas released from a subsea blowout pass through three zones of interest as they move to the sea surface (Figure 1). The high velocity at the well-head exit generates the jet zone which is dominated by the initial momentum of the gas. This highly turbulent zone is responsible for the fragmentation of the oil into droplets ranging from 0.5 to 2.0 mm in diameter (Dickins and Buist 1981). Because water is also entrained in this zone, a rapid loss of momentum occurs a few meters from the discharge location. In the buoyant plume zone, momentum is no longer significant relative to buoyancy, which then becomes the driving force for the remainder of the plume. In this region the gas continues to expand due to reduced hydrostatic pressures. As the gas rises, oil and water in its vicinity are entrained in the flow and carried to the surface.

Although the terminal velocity of a gas bubble in stationary water is only about 0.25 m/sec, velocities in the center of blowout plumes can reach 5 to 10 m/sec due to the pumping effect of the rising gas in the bulk liquid. That is, the water surrounding the upward moving gas is entrained and given an upward velocity, which is then increased as more gas moves through at a relative velocity of 0.25 m/sec. When the plume becomes fully developed a considerable quantity of water containing the oil droplets is pumped to the surface.

In the surface interaction zone the upward flow of water turns and moves in a horizontal layer away from the center of the plume. The influence of the surface water current causes this radial flow to turn downward forming a parabolic surface influence as seen in Figure 1. This surface influence carries the oil down-current and spreads it over the surface up to the point where this flow no longer influences the surface water motion (between 1 to 1.5 slick widths down-current). At this point the oil moves with the prevailing currents and spreads as any batch spill of oil would behave. The gas exits from the centre of the plume and causes a surface disturbance or "boil zone" identified by the arrows in the top view of Figure 1.

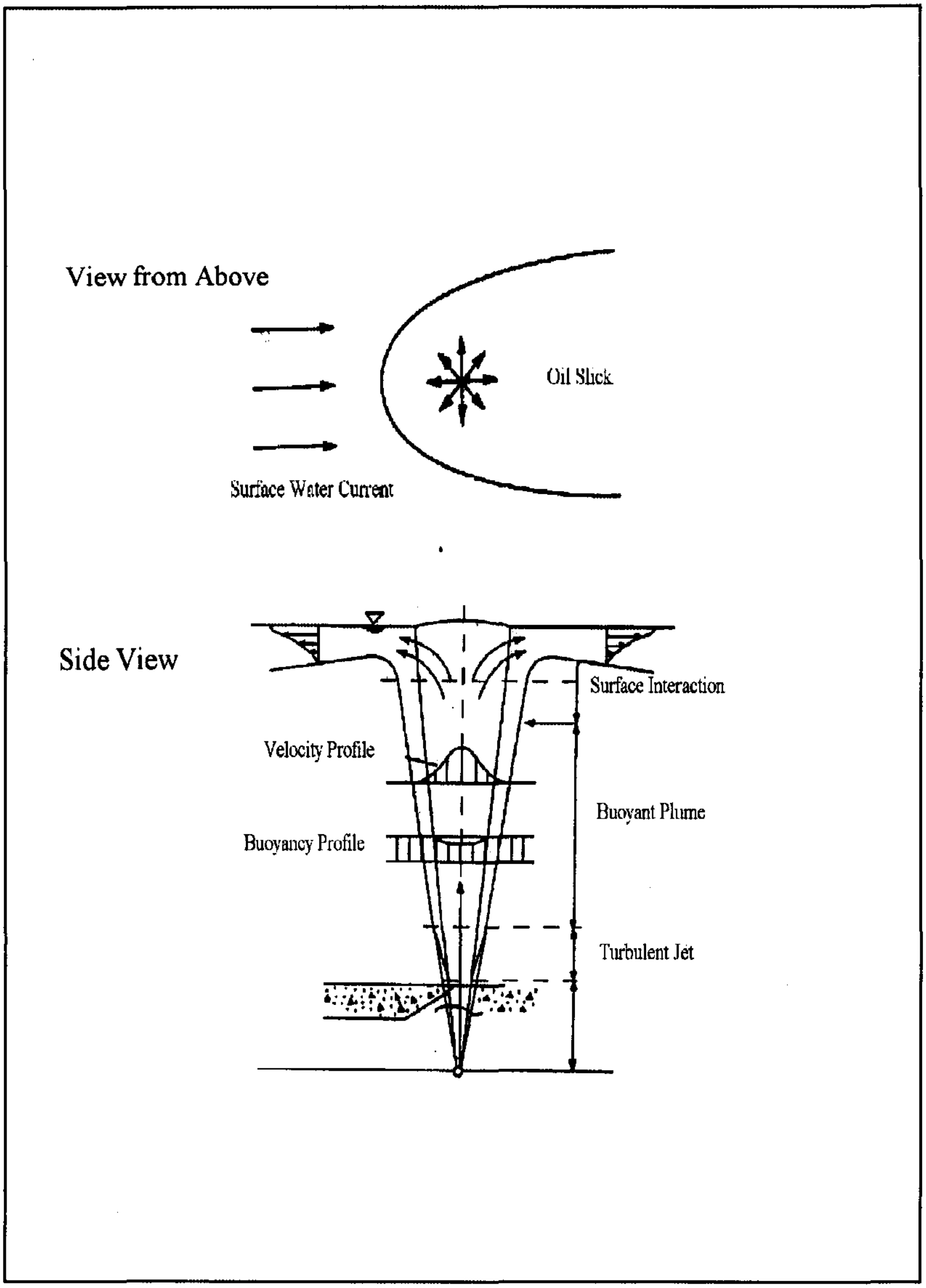

Figure 1: Subsea Blowout Schematic

At the surface the oil coalesces in this outward flow of water and is spread into a slick at a rate much faster than conventional oil diffusion or spreading rates. The resulting slick takes on a hyperbolic shape when subjected to a natural water current, with its apex pointed up-current (Figure 1). The sizeable quantity of gas released during these blowouts enters the atmosphere from a turbulent bubble area that forms above the plume.

2.2 Subsea Blowout Behavior in Deep Water (>300 m)

As noted above, the initial dimensions of oil slicks from shallow water blowouts are mostly determined by the flow of gas that is released with the oil. The gas, rising to the surface as a column of bubbles, acts as a large-scale pump to quickly transport oil droplets to the surface. Because the normal ocean currents are small compared to the vertical rise velocities in the plume, they have little influence on the oil. This may be different when considering a subsea oil well blowout in deep water. In this situation the high pressure and low temperatures may cause the natural gas to combine with water to form a solid, ice-like substance known as hydrates. The gas volume may also be depleted through dissolution into the water. With the loss of gas through either or both of these processes, the driving buoyancy of the rising plume may be completely lost, which will result in the oil droplets rising slowly under gravity forces alone. The movement of the oil droplets will now be affected by cross currents during their rise. This will result in the separation of the oil droplets based on their drop size. The large diameter oil drops will surface first and smaller drops will be carried further down current prior to reaching the surface. Oceanic diffusion processes will result in additional separation of the oil drops due to their varying residence times in the water column.

The remainder of this report reviews the environmental and oceanographic conditions that exist in the vicinity of the deep well drilling activities in the Gulf, the physical-chemical processes that will affect the behavior of oil and gas releases from deepwater locations, the likely fate of the oil from such releases, and possible cleanup activities to deal with the oil.

3. Gulf of Mexico Oceanographic Summary

The behavior of the oil and gas released from a seabed rupture will depend on the depth of the rupture and the temperature, salinity and velocity of the water that the materials pass through. All of these parameters vary widely through the Gulf of Mexico and precise information on them is generally not available for most of the Gulf. Ranges of likely or common values for these parameters have been gathered and used in this assessment.

3.1 Depth of Possible Release Points

A summary of the water depths where exploration and/or production are occurring or could occur in the near future has been provided by MMS. Table 1 summarizes this information by field name. Figure 2 shows the general location of each of these fields. From this information it is clear that blowouts could occur in waters up to 2000 meters deep. MMS considers any drilling over 305 meters (1000 feet) to be deepwater drilling.

Table 1: Summary of water depths at deepwater exploration and production sites in the GOM

Field Name	Depth (ft)	Depth (m)
Green Canyon	1300-4300	400-1310
Mississippi Canyon	1000-7500	305-2290
Viosca Knoll	700-3300	215-1010
Ewing Bank	900-1800	275-550
Garden Banks	900-3600	275-1100
Aliminos Canyon	4900-7200	1500-2200
Keathley Canyon	4900-7200	1500-2200
East Breaks	3500-4400	1070-1340

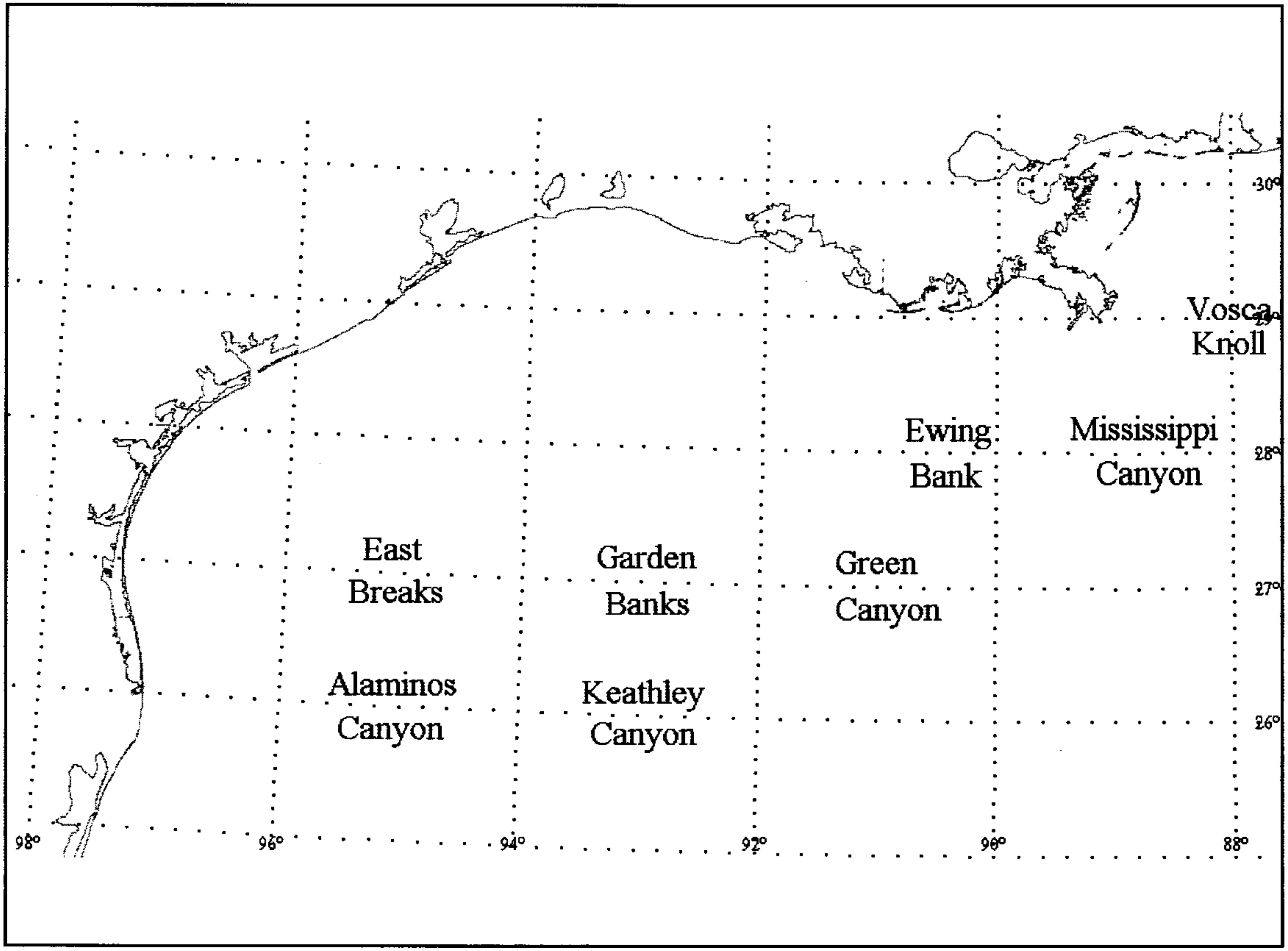

Figure 2 : Location of Deepwater Exploration and Production Fields in the Gulf of Mexico

3.2 Water Temperatures

Near surface water temperatures in the Gulf range between 25 to 32°C. Water temperatures typically drop to about 18-19°C at the 150 meter water depth and then to 5°C at 1000 m and deeper. Figure 3 graphically depicts this water temperature variation with depth. Water temperatures will deviate from this "typical" representation both by location and by time but this generic temperature profile is suitable for the estimation of the behavior of deepwater oil and gas discharges. Figure 4 shows the temperature profile taken along a transect through a Loop Current eddy. Similarities and differences between this measured temperature field and the idealized profile are evident.

3.3 Water Salinity

Waters near shore and within the influence of the Mississippi River can have salinities less than 20 ppm. The salinity of the deep offshore waters range between 29 - 32 ppm. This small difference in the deepwater areas will not significantly affect the behavior of oil or gas rising from a deepwater blowout.

3.4 Water Velocity Profile

As with the other environmental parameters reviewed above, the water velocities in the Gulf are variable both spatially and temporally. Water velocities are probably the most variable and least understood of these parameters. The movement of water in the Gulf is driven by the Loop Current, which is a branch of the Gulf Stream that enters through the Straits of Yucatan, circulates clockwise through the Gulf and exists through the Florida Straits. This general circulation pattern is further complicated by localized wind and pressure systems, the Mississippi outflow and the formation of large eddies that periodically detach from the Loop and move through portions of the Gulf. We have again chosen to use a representative water velocity profile to estimate oil and gas behavior from deepwater blowouts. Figure 5 shows the water speeds present along the northern edge of the Loop as measured during a survey in 1985. Surface water speeds ranged from 115 to 170 cm/s and were

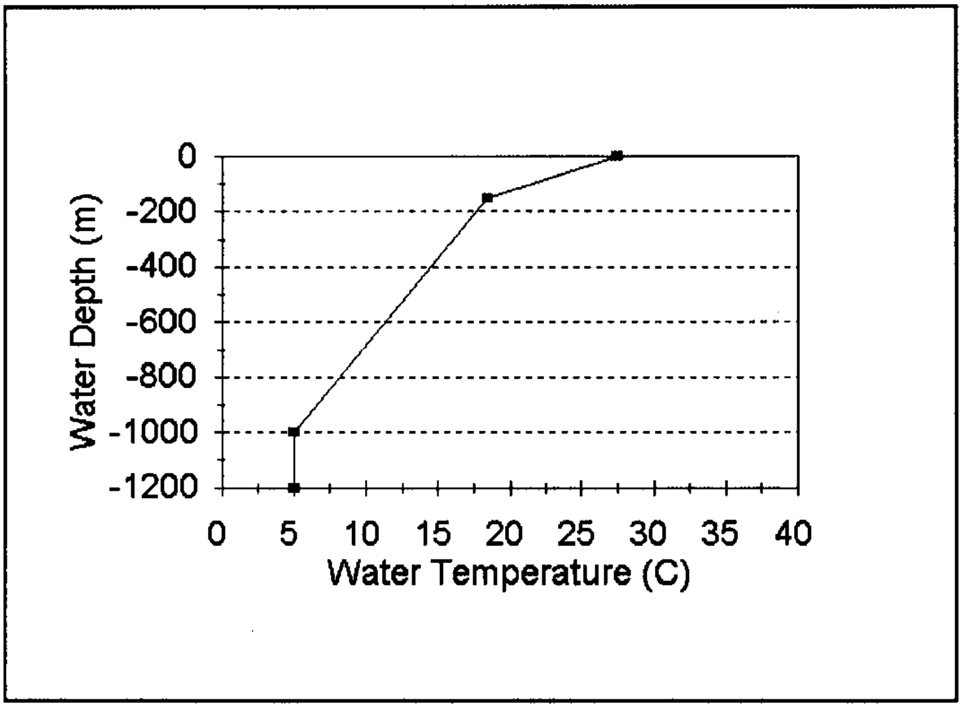

Figure 3 : Typical Water Temperature Profile in the GOM

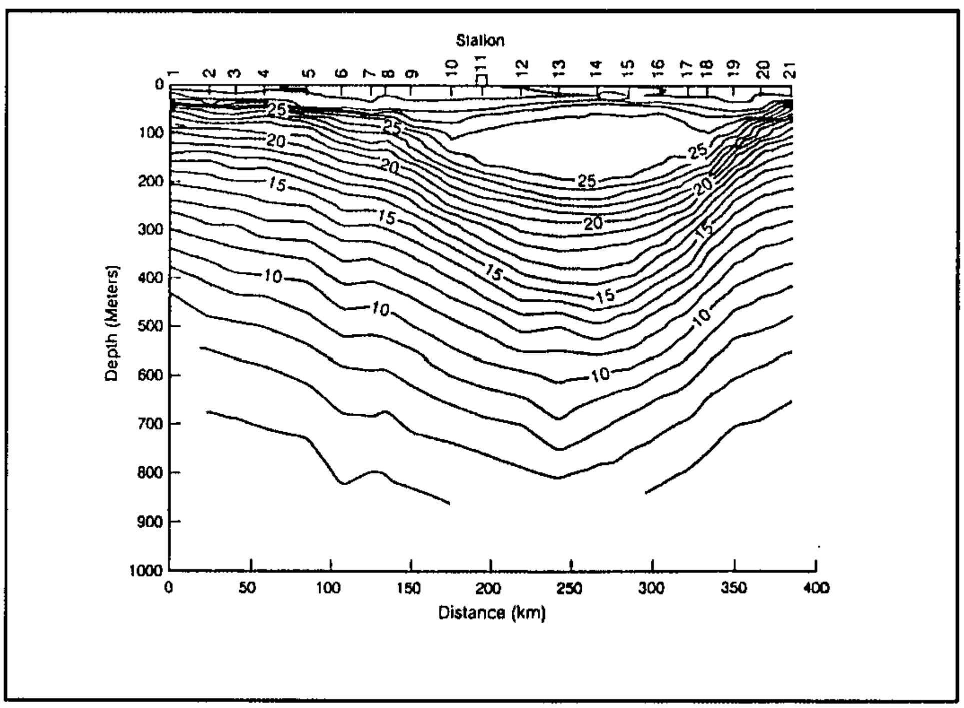

Figure 4 : Measured Water Temperature Profile (Forristall, 1985)

relatively constant over the upper 100 meter depth. The water speed dropped off linearly to about 75 cm/s at a depth of about 200 m and then again dropped linearly to 2 to 5 cm/s at 1000 m. Other reports (Forristall et al 1992, Hamilton 1992, Johnson et al 1992, Scott et al 1993) have surface water currents varying from 30 to 200 cm/s. Mean deepwater currents measured by Hamilton (1990) can be seen in Figure 6. These currents range from about 2 to 3 cm/s and are in general agreement with the deepwater currents of Figure 5. We have used the velocity profile of Figure 5 in our assessment of oil and gas fate from deep well blowouts. As was the case for the other environmental parameters, this represents a reasonable velocity distribution for the Gulf. The significance of different velocities in the eventual fate of the oil and gas is discussed later in this report.

4. Near-Source Blowout Behavior in Deep Water

4.1 Oil Behavior: Oil Droplet Formation

As previously discussed, the oil and gas released from a shallow subsea blowout passes through an initial turbulent zone created by the high velocities of the gas exiting from the well-head. This high exit velocity is driven by the expansion of the liquid natural gas (at reservoir pressures) as it flows upwards and the pressure falls to the ambient pressure at the release point. This situation will also exist for the deep well blowout cases being considered in this study since the hydrostatic pressure, at even the deepest well, is lower than the pressure necessary to maintain the natural gas in liquid form at the reservoir temperatures. However, the higher exit pressures associated with deep well blowouts will result in denser and lower volumes of gas exiting compared to releases in shallow waters.

The turbulent zone created at the release point causes the oil to fragment into droplets. Although the droplet sizes will surely vary as a function of the exit conditions and velocities, very little information is available on the subject. The only drop-size data for oil and gas releases at the seabed come from an experimental field program completed in the Canadian Arctic by Dome Petroleum (Dickins and Buist, 1981) and a small laboratory study completed by Topham (1975). The drop size distributions generated from these experimental oil and gas discharges can be seen in Figures 7 and 8. Without

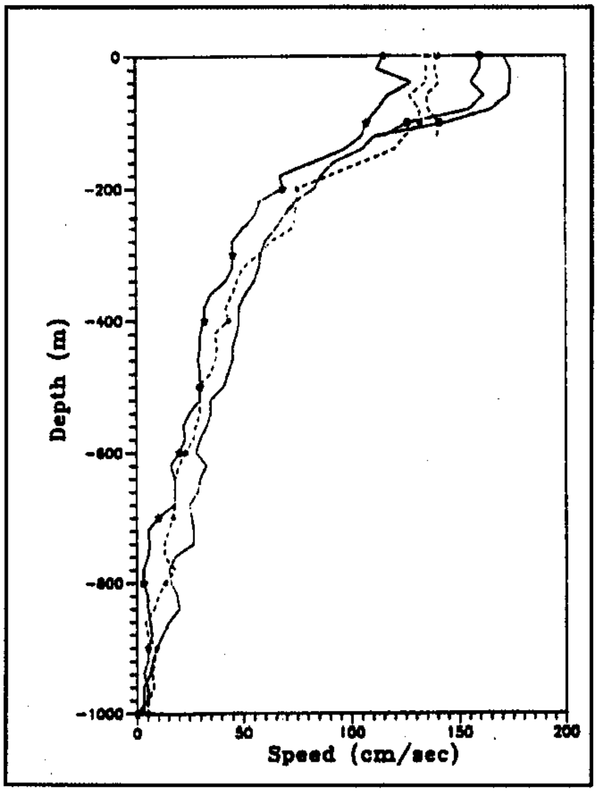

Figure 5 : Measured Water Current Profile at Edge of Loop Current (Forrestall, 1992)

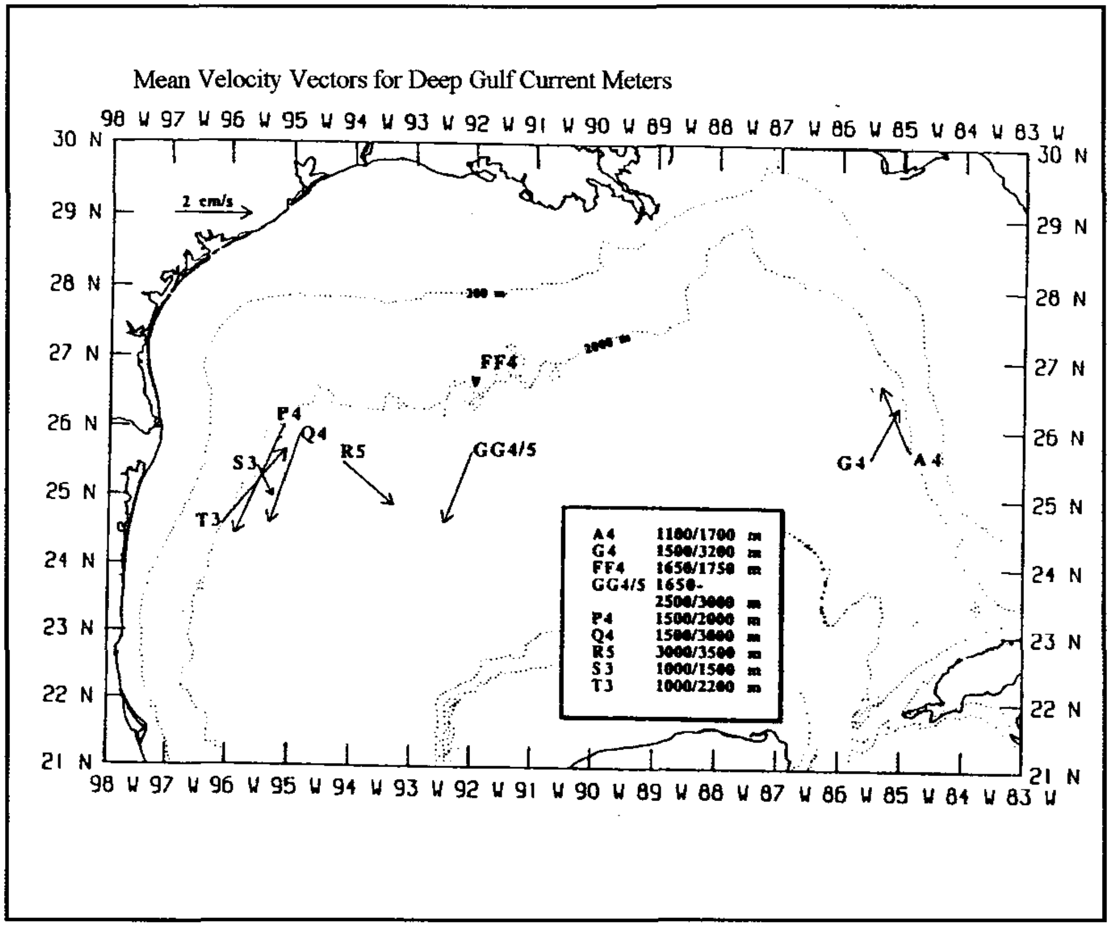

Figure 6 : Measured Deepwater Currents in the Gulf of Mexico (Hamilton, 1990)

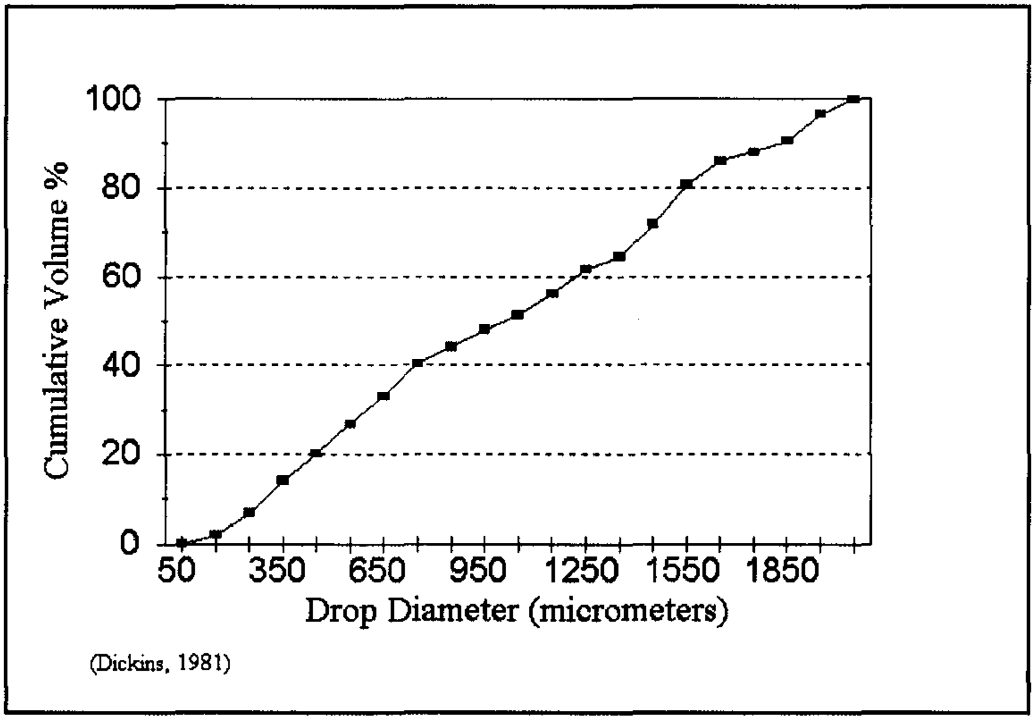

Figure 7 : Subsea Oil & Gas Release Drop Size Distribution

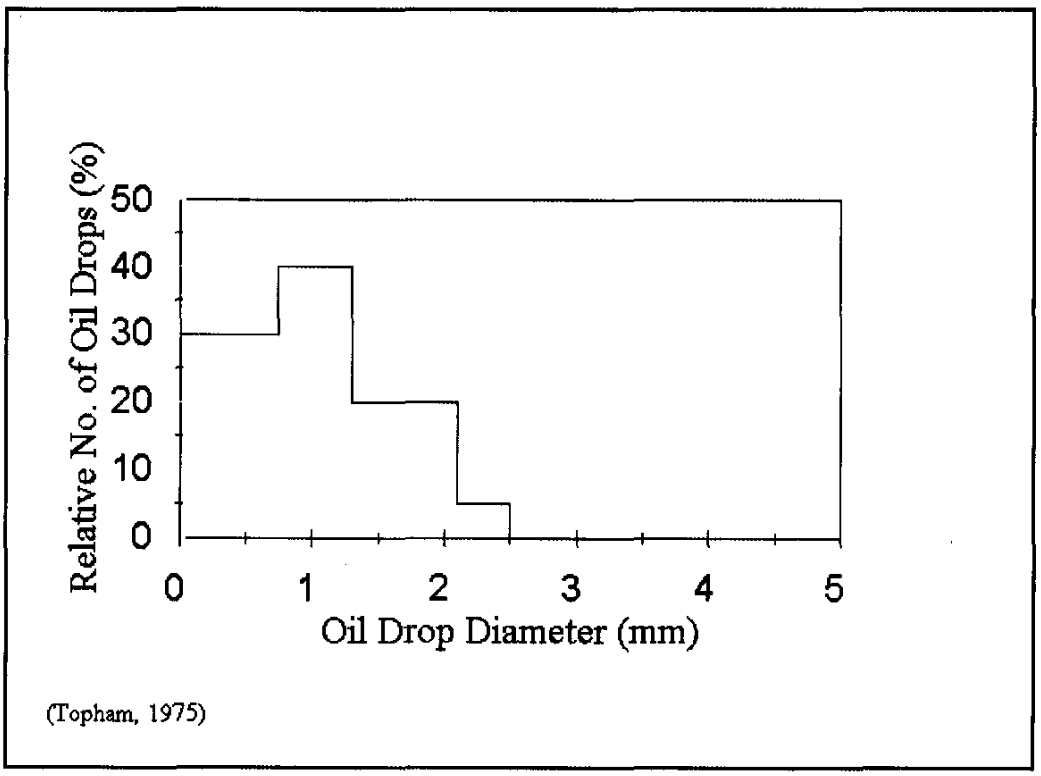

Figure 8 : Subsea Oil & Gas Release Drop Size Distribution

additional research it is not possible to comment on whether these drop size distributions are appropriate for the deepwater blowouts being considered in the study. The data from the larger-scale study (Dickins and Buist) are the best we have and are used in this report for calculating the fate of oil droplets.

4.2 Gas Behavior

Four processes affect how the released gas ultimately will behave:

i) under high pressures and low temperatures, and in the presence of water, the natural gas can convert to a solid hydrate;

ii) the free gas can dissolve into the surrounding water body;

iii) the gas will rise, be subjected to lower pressures and expand due to the lower pressures; and

iv) the gas bubbles can create a pumping action that results in the development of a rising plume of oil, gas and water to the surface at velocities that can override the effects of the prevailing water currents.

A discussion of these processes and their relevance to deep well drilling activities in the Gulf follows.

4.2.1 Hydrate Formation

Gas hydrates are crystalline solids formed under pressure when certain non-polar, or slightly polar, low molecular weight gases are contacted with water. The pressure required for hydrate formation depends on the ambient temperature. Experiments completed in the late 70s and early 80s identified the thermodynamic conditions suitable for hydrate formation (Topham, Bishnoi and Maini, 1979; Topham and Bishnoi, 1980). In these controlled experiments simulated natural gas bubbles were suspended in a pressure chamber using a counter-flowing salt water stream. Temperatures were maintained at 3°C for all tests and pressures were either held constant or reduced over time to simulate the pressure drop that a single bubble would be subjected to during its rise to the surface.

At pressures of 700 to 900 psi (equivalent to a water depth of 480 to 615 m) the hydrate crystals formed a thin layer over the gas bubble. Once the bubble was covered, the rate of hydrate formation decreased except in the decompression tests where the expanding gas "cracked" the hydrate layer and exposed the gas to the surrounding water thus enabling the conversion process to continue.

When the pressure was increased to 1130 psi (775 m depth) the thickness of the hydrate layer increased and the shedding of hydrate crystals from the bubble surface was more prominent. As a result of this, the reduction of the rate of reaction after the bubble was covered with hydrate was not as evident, and the bubble eventually collapsed completely into flakes of hydrates.

When the pressure was increased to 1300 psi (890 m depth) or greater the rate of hydrate formation was extremely fast and any injected bubbles collapsed immediately into large flakes of hydrates. This behavior was confirmed in a simple experiment conducted in the deep waters of the Gulf of Mexico where a small cylinder of gas was opened at depth and the exiting gas immediately formed a cloud of solid hydrate crystals (Brewer et al 1997).

Figure 9 shows the equilibrium diagram for hydrate formation of ethane, methane and natural gas. The work by Bishnoi et al. also revealed that temperature-pressure conditions (as shown in Figure 9) are not sufficient on their own for predicting whether or not the hydrates will form in a blowout. Other factors, such as water turbulence, presence of impurities and temperature history of the water can influence nucleation of hydrate crystals when the pressure and temperature conditions are near the equilibrium point. It is unlikely that these factors will significantly affect the hydrate formation process in field situations since sufficient impurities and considerable turbulence will be present in the water to provide favorable conditions for hydrate formation.

In the decompression tests completed by Bishnoi the hydrate continued to shed until the pressure decreased to about 400 psi (275m depth). Further pressure drop resulted in a decomposition of the hydrate to gas. When the tests were started at 500 psi (345 m depth) 30 to 40 percent of the gas was converted to hydrate prior to reaching 400 psi (275 m depth). When the tests were started at 700 psi (480 m depth) or greater all of the gas was converted to hydrate before reaching 400 psi (i.e. within 205 m or less from the release location). These tests simulated the formation of hydrates on a single

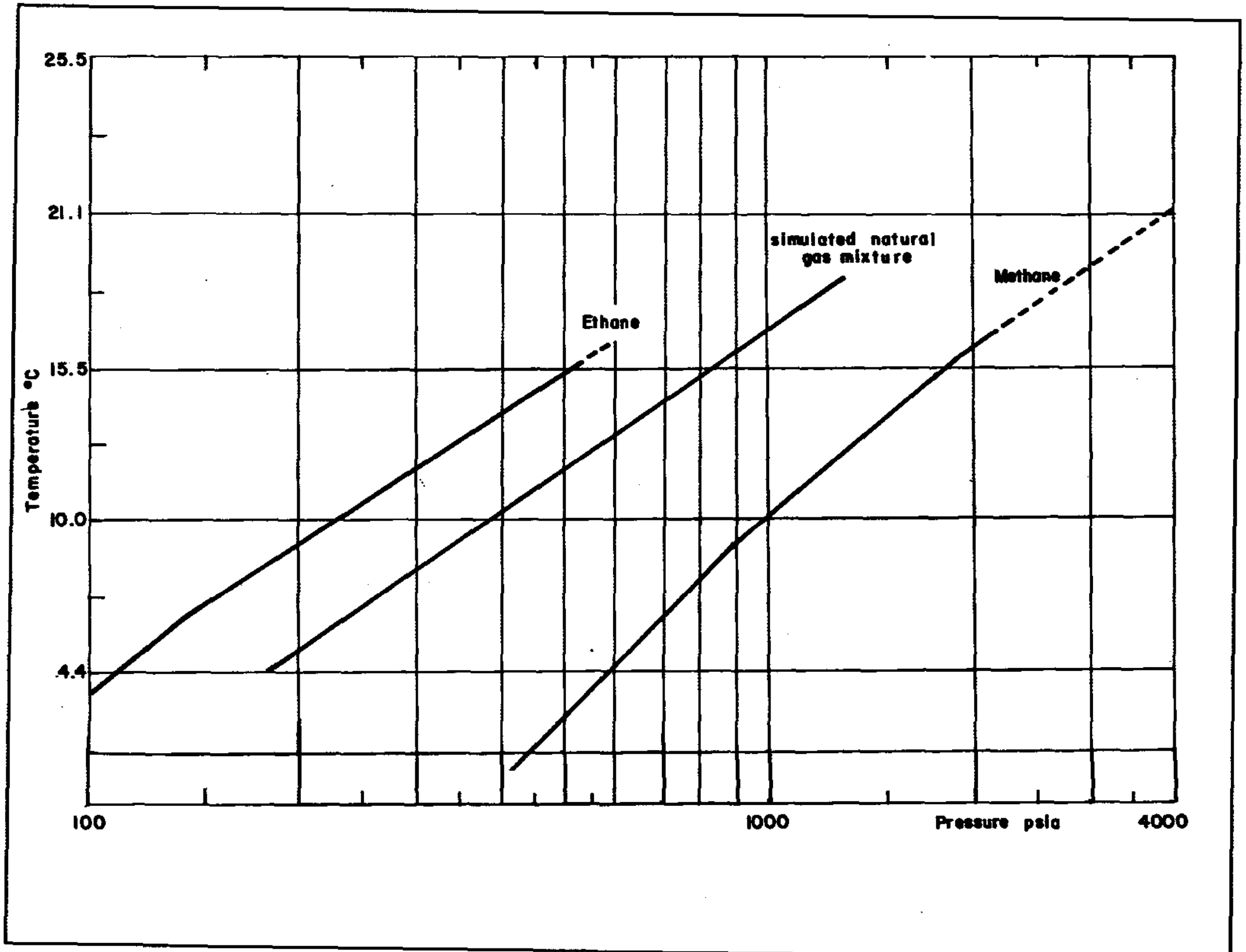

Figure 9 : Equilibrium Diagram for Hydrate Formation (Topham, 1980)

bubble of gas rising through the water column driven by buoyant forces only. The complete conversion of gas to hydrates may not occur for blowouts in water depths having hydrostatic pressures similar to those used in the experimental work with single bubbles. This is because there will be less time available for the conversion to take place due to the faster rise time of the bulk fluid in the bubble plume, as discussed earlier. Topham (1980) attempted to model a bubble plume while accounting for hydrate formation. He lacked sufficient knowledge of the mechanics of the bubble plume to be able to predict the final height of the gas bubbles, prior to complete conversion to hydrate, for various release rates and depths.

Once the gas has been converted to hydrates, the rising oil droplet plume will expand due to diffusive forces in the water. The oil plume will also be deflected by cross currents during the droplets' rise. Because the gas hydrate, having a specific gravity of about 0.98, is significantly more dense than the oil, the differential rise velocities and cross current will serve to separate the hydrate from the oil so that even when the hydrate reconverts to gas, the gas will have little effect on the oil's rise and spread.

4.2.2 Behavior of Rising Gas Bubbles

As mentioned, although the terminal velocity of a gas bubble in stationary water is only about 0.25 m/sec, velocities in the center of blowout plumes can be up to 40 times greater due to the pumping effect of the rising gas in the bulk liquid. For a fully developed plume a considerable quantity of water containing the oil droplets and gas can be pumped to the surface. The presence of this large quantity of water provides an opportunity for a portion of the gas to dissolve into the water. This will reduce the bubble size and, if the residence time of the bubble in the water column is long enough, may result in the complete consumption of the gas bubble. Observations of natural gas seeps off the coast of California have revealed that gas bubbles, of 6mm diameter, released from depths greater than about 100 m, dissolve before reaching the surface (S. Hornafius, Mobil Oil Corporation, 1997 personal communication). This equates to a complete loss of the gas within about a 6-minute period. If an oil and gas release from a subsea blowout were to create a plume with an average bulk velocity of 5 m/sec, the gas in the bubble plume would be consumed by dissolution after 1800 meters of travel (6 min x 60 s/min x 5 m/sec). As was discussed above, all gas would be converted to hydrates for releases at depths greater than 900 meters. No hydrates would form for releases in water shallower than 300 meters. The bubble plume created by a release in 300 m of water can be expected to reach the surface within about one minute (assuming a conservative 5 m/sec bulk fluid velocity in the plume). This would be an insufficient amount of time to lose a large proportion of the gas through dissolution to the water phase. As such, this process is unlikely to greatly alter the characteristics of the surface oil slick for releases from depths less than about 300 meters.

For releases of oil and gas from depths between 900 and 300 meters there will be competition between the conversion of gas to a hydrate film around the gas bubble and the loss of gas via dissolution to the water. Although there is no literature on the subject, one could speculate that the formation of a hydrate layer on the gas bubble would shut down the dissolution process. Loss of gas at these depths would thus be primarily through conversion to hydrates. If a significant percentage of the gas is not converted to hydrates, the gas will still create a pumping action that would suspend the hydrates in the general upward flow. As the hydrates rise above the 300 m water depth they will decompose to gas and again assist in powering the bubble plume.

5. Fate Calculations

The fate of the oil and gas from two extreme cases are examined. These two extremes are for those cases where:

Case 1 - Bubble Plume Forms. Not enough of the gas is either converted to hydrate or dissolves to prevent the formation of a bubble plume. In this case the released gas pumps oil, gas, and water to the surface; and

Case 2 - All Gas is Converted to Hydrate. All of the gas is immediately converted to hydrate and oil rises to the water surface due to its buoyancy only.

Case 1 has been modeled using the SL Ross standard sub-sea blowout model. Case 2 has been modeled using a computer program written specifically for this task.

5.1 Case 1 : Bubble Plume Forms

Individual wells in the deepwater fields of the Gulf of Mexico can produce up to 30,000 barrels of oil per day (bopd). It is possible that these high flow rates might not be reached from a release at the seabed due to the hydrostatic pressure over the well. However, to be conservative, the 30,000 bopd flow and 60 million cubic feet of gas per day have been used in our oil spill behavior model, SLROSM, to estimate the slick widths and thicknesses that might be expected from such blowouts.

No hydrates will form at water depths less than 300 to 400 meters. As the release point moves deeper, hydrates will form at an increasing rate. At a depth of about 900 m it is likely that all of the gas will be converted to hydrates very quickly. Releases from between 300 and 750 meters have been modeled with various gas flows to illustrate the effects of gas loss to hydrate on the final slick characteristics. Table 2 provides a summary of the modeling results. At the 300 and 450 meter depths it is assumed that none of the gas would be converted to hydrates and all of it would be available to power the bubble plume. An alternate run was also completed for the 450 m depth where it was assumed that only 75 percent of the gas was available to drive the plume. At the 600 meter depth 75 percent and 50 percent of the total gas flow was assumed. At the 750 m depth 50 percent and 25 percent gas flows were investigated. The results provide some insight into the properties of surface slicks if some fraction of the gas converts to hydrate in its rise from depths greater than 300 m to the 300 m depth.

It is apparent from Table 2 that as the depth increases so does the estimated slick width for constant gas flows. However, if the gas flow drops off, the slick width narrows and thus counters the widening effect due to increased depth. As a result, the slick widths and thicknesses from these scenarios are not very different. The width of the slicks, at the point down-current from the initial gas "boil zone" where the rising water no longer influences the surface water flow (between 1 to 1.5 slick widths down-current), is between 2.8 to 3.6 km. The slick thickness at this location is predicted to be between 50 and 70 μm.

Table 2 : Estimated slick characteristics from a 30,000 bbl/day subsea blowout (Case 1: no hydrate formation)

Release Depth (m)	Slick Width (km)	Initial Slick Thickness (μm)	Gas to Oil Ratio	% of Total Gas Flow
300	2.9	67	367	100
450	3.4	57	367	100
450	3.1	62	275	75
600	3.6	54	275	75
600	3.1	62	184	50
750	3.6	54	184	50
750	2.8	69	92	25

It should be emphasized that these numbers are for a very large blowout. Thinner and smaller slicks would result from smaller blowouts. These calculations also assume that 25 percent of the total gas flow is adequate to create the water pumping action needed to drive the plume. If the gas flow is not adequate to form the bubble plume, the oil behavior will be similar to that discussed in Case 2.

5.2 Case 2 : All Gas Converted to Hydrate

Blowouts at depths greater than 900 meters will result in a very fast conversion of all of the gas to hydrate. The discharged oil will be shattered into small droplets and will be saturated with gas. As the gas devolves from the oil as it rises hydrates will likely form a rigid shell around the oil droplet. Because the density of the hydrate is very close to that of water, it will not affect the buoyancy of the oil droplet.

To calculate the oil distribution on the water surface from these releases, one needs to know the oil drop size distribution, the drop rise velocities, the water depth, the water current profile and oceanic diffusion processes.

The drop size distribution of Figure 7 has been assumed in the calculations.

The drop rise velocities have been determined using a "terminal velocity" equation for a solid particle as detailed below (Perry and Green, 1984).

$$u_t = \sqrt{4gD_p(\rho_p - \rho) / (3 \rho C)};$$

u_t - rise velocity of drop
g - gravitational constant
D_p - diameter of oil drop
ρ_p - density of oil
ρ - density of water
C - drag coefficient
for $N_{Re} < 0.1$ $C = 24 / N_{Re}$
for $N_{Re} < 1000$ $C = (24 / N_{Re})(1+ 0.14 N_{Re}^{0.7})$
$N_{Re} = D_p u_t \rho_p / \mu$; μ - fluid viscosity

The water current profile of Figure 5 has been used in the calculations. An empirical oceanic diffusion model developed by Okubo (1971) has been used to estimate the horizontal spread of the rising drops.

$$L = 0.00155\, t^{1.17} \;;$$

L - radius of cloud in meters
t - time in seconds since cloud release

The formation of an oil slick from oil droplets rising from a deep subsea blowout is a complex process. The drops have a range of sizes, so they have different rise velocities, and thus reach the surface at different times after discharge. They also reach the surface at different spots because the drops are subjected to cross-currents that cause smaller drops to be swept further down-current than large drops. This droplet separation is further complicated by the fact that the eddies and currents in the water can vary both spatially and temporally. Once a drop reaches the surface it is moved away from its initial surfacing point by time-varying winds and surface currents.

A computer program was written to estimate the oil rise time, slick position relative to the source, slick width and approximate slick thickness as a function of the oil density and release depth. Many simplifying assumptions were made in this model and the results should be viewed as a rough estimate of initial slick conditions. For example, it was assumed that oil drops of similar diameter, released over the duration of the blowout, would follow each other to the surface (i.e., be subjected to identical eddies and water currents). The surface water currents and winds also were assumed to be constant in these calculations. To simplify the calculations, the rise times and initial surfacing locations of a series of discrete drop sizes were modeled. The percentage of total oil flow represented by each drop size class was determined using Figure 7. This information was then used to estimate the slick width, length and thickness for a steady state blowout.

Table 3 shows the results of the analysis. The largest drops surface the most quickly, do not disperse as much laterally, and contain a highest percentage of the total oil released. As a result the slick will be thickest near the source. The modeling predicts that the thickest oil slicks will be about 50 μm thick. This will occur for very light oils (density of 750 kg/m^3) released at a depth of 1000 m. This assumes no oil loss in the water column through dissolution and no surface loss through evaporation or dispersion. More dense oils will result in maximum slick thicknesses of less than 50 μm. As the depth of release increases, the maximum oil thicknesses decrease due to the increased rise time and lateral spreading of the oil.

The slick widths at the point where the largest drops surface vary from about 200 to 1000 meters. This width is estimated using Okubo's relationship which estimates the growth of a dispersed cloud as a function of rise time. The rise times associated with these "first surfacing" large drops vary from about 3 to 15 hours depending on the oil density and release depth.

Table 3 : Estimated surface slick characteristics : 30,000 bbl/day deepwater blowout (Case 2: complete loss of gas through conversion to hydrates)

		Oil Density (kg/m^3)				
	Depth (m)	750	800	850	900	950
Maximum Slick Thickness Near Source (µm)	1000	50	45	30	27	20
	1500	40	35	25	17	8
	2000	20	18	11	8	5
Slick Width Near Source (m)	1000	180	200	240	320	460
	1500	280	340	400	520	780
	2000	400	480	580	740	1100
Rise Time for Largest Drops (hr)	1000	3.2	3.7	4.3	5.3	7.4
	1500	4.9	5.6	6.6	8.2	11.4
	2000	6.6	7.5	8.9	12.8	15.4
Distance from Source to First Surface oil (km)	1000	7.0	8.2	9.5	11.8	16.2
	1500	7.4	8.6	10.0	12.4	16.9
	2000	7.7	8.9	10.0	12.8	17.6
Distance from Source to 10 µm Thick Oil (km)	1000	15	16	17	18	21
	1500	12	13	14	15	n/a
	2000	11	12	13	n/a	n/a
Slick Width at 10 µm Thick Oil (m)	1000	560	570	630	710	710
	1500	690	715	760	770	n/a
	2000	770	800	820	n/a	n/a
Rise Time for Drops Forming 10 µm Thick Oil (hr)	1000	7.1	7.5	8	9	10.5
	1500	9	9.1	9.2	10.2	n/a
	2000	9.5	10.2	10.5	n/a	n/a

n/a - not applicable

The largest drops considered will surface between 7 and 18 kilometers from the release point. This distance is not greatly affected by the release depth because the water velocity profile used assumes a constant and small (.05 m/sec) water velocity below the 1000 m depth. Most of the movement of the oil occurs in the upper kilometer of the water column.

The distance from the source where the slick thickness drops to about 10 μm (micrometers) varies between 10 to 20 kilometers. It is unlikely that slicks with thicknesses less than 10 μm will survive for any length of time or be amenable to any spill countermeasure. This thickness was selected as a cut-off for the extent of the slicks from these blowouts. In a few instances the predicted oil thickness never reaches 10 μm. The widths of the slicks at this cut-off point range from 560 to 820 meters. The rise time for the drops responsible for these thin portions of the slicks range from 7 to 10.5 hours.

It is important to remember that these numbers were generated using a specific drop size distribution and water velocity profile. If the oil drops released were larger than those used for these calculations the slick thicknesses would be greater due to the smaller rise times and smaller opportunity for lateral and longitudinal spreading. The opposite would be true if the drops generated were smaller than those considered here. If the water velocity profile were different the rise locations and overall lengths of the slicks would also differ.

5.3 Comparison of Results

The results of this simple modeling indicate that slicks generated by bubble plume dynamics (Case 1) will likely be wider (in the cross-current direction) and come to the surface much closer to the source. Slicks created by blowouts where the bubble plume is consumed through hydrate formation (Case 2) will result in narrower (cross-current) and longer (down-current) initial slicks. The thicknesses of slicks from both spill types will be similar near the source (on the order of 25 to 70 μm) but a smaller area of this thick oil will be present for Case 2, the situation where hydrates form. Figure 10 illustrates these differences graphically. It should be recognized that the slicks created by the rising oil drops will not likely have the appearance of the long ribbon of oil depicted in this graphic