Marine Oil Fate: Knowledge Gaps, Basic Research, and Development Needs; A Perspective Based on the Deepwater Horizon Spill

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Abstract

The various complex forms of transport as well as many other fate processes ongoing in the marine water column require research for the understanding and prediction of impacts of deepwater releases on the marine ecosystem. Such research is useful for assessing the context and limits of future deepwater oil and gas development in the Gulf of Mexico. The Deepwater Horizon incident in the Gulf represents the first oil spill occurring at significant depth, \( \sim 5,000 \) ft \((1,500 \) m\). It is also the first situation where dispersants were directly added to the hydrocarbon effluent from the wellhead in efforts to disperse the droplets over a large volume of the water column. In this regard, this perspective is an original work in that it provides an in-depth analysis of gaps and needs, which will guide future work in the field. Preliminary reports have led to a variety of images that highlight new physiochemical phenomena whose comprehensive understanding will be needed in assessing the oil and associated hydrocarbon chemical fate and environmental impact. Camera images of the oil and gas entering the water at depth and subsurface remote-operated vehicles have revealed droplet clouds and hydrocarbon plumes suspended thousands of feet below the surface moving horizontally with the water currents. Although preliminary, these and other observations are sufficient to piece together new hypothetical deepwater chemodynamic processes and phenomena that have yet to be fully understood. This position article focuses on unique and new research issues raised and relevant to this spill specifically. The ultimate fate of the oil constituents is a very broad subject. Our objective was concerned with the deepwater spill-initiating event. We focused on selected fate processes associated with the oil and dispersant chemodynamics from the blowout point, on the seabed, in the water column upward, and finally, into the marine surface mixed layer. An observation-conceived, process-based, mass balance-crafted engineering science predictive tool is proposed. It is needed for forecasting, projecting in anticipation of and managing the next spill, and answering the question “where does it all go?”

Key words: oil droplet clouds, blowout, hydrocarbon plumes, oil transport and fate, dispersants in oil, oil mass balance

Introduction

The Macondo/Deepwater Horizon oil spill and Gulf coast: The U.S. Gulf coast is home to a large portion of the oil and natural gas sources for the United States, where \( \sim 24\% \) of the natural gas and 18% of petroleum oil are processed or produced. Louisiana’s outer continental shelf is the most extensively developed region in the United States, and over the last two decades, drilling activities have increased. This area is also home to some of the most sensitive ecosystems in the world. The coastal wetlands and the Gulf contribute \( \sim 28\% \) of the total volume of U.S. fisheries and is also a rich habitat for several rare species. The wetland ecosystems buffer the landmass from hurricanes and tropical storms. The Mississippi river drains one-third of the United States and delivers the largest amount of sediment to the continental shelf. The confluence of such a rich ecosystem and oil and natural gas reserves makes it imperative that we exercise caution in the utilization of resources from the region.

The Gulf is prone to natural seeps and there have always been minor leaks and spills in shallow water. The IXTOC blowout (at a shallow depth of 52 m) occurred off the coast of Mexico in 1979. However, the most significant event occurred on April 20, 2010, when the Deepwater Horizon drilling rig managed by British Petroleum (BP) exploded and caught fire while drilling about 50 miles off the coast of Louisiana. The blowout produced a gas/oil mixture and was located \( \sim 1,500 \) m below the sea surface, where the specific conditions...
are high pressure (~160 atm) and low temperature (4°C). The oil reservoir was 13,000 ft (4,000 m) below sea bottom. The Flow Rate Technical Group (Lubchenco et al., 2010) convened to study the amount and the flow rate of the oil released has estimated that about 4.7–5.5 million barrels (1 bbl = 160 L) were released and the flow rates range from 53,000 to 62,000 barrels per day. Oil dispersants were injected into the gushing plume at a volume ratio of ~1% (~0.8–0.9 L per 100 L oil) to disperse the oil/gas mixture with the goal of minimizing the overall environmental impact.

The Big Question

Clearly, deep-ocean oil and gas (O&G) exploration, production, and transportation are risky operations. With continuing O&G activity occurring in deepwater, there will be future failures with massive spills and we are now ignorant about any overall impact on the Gulf health in general and the specific impacts to other vital coastal industries, that is, ports, fisheries, tourism, and coastal living. The big question: Is it wise to do deepwater O&G extraction in the Gulf, and if so, under what conditions? The following three unknowns beg the question: (1) The science/engineering community knows too little about the massive deep-sea O&G release processes, (2) where does all the material released in the deep go?, and (3) its impact on the Gulf biota (Camilli et al., 2010). As a consequence, there are no mathematical model tools for projecting oil release aspects tuned to deepwater forecasting blowout oil/chemical fate in the marine environment. These would be used for hypothetical spill scenario analysis, studying long-term exploration and development strategies from a spills perspective, and projecting where and how much oil has gone, so as to manage remediation and cleanup when they do occur, both with and without dispersants. In our opinion, these three knowledge gaps are of primary concern and have come to our attention because of the BP spill. Providing answers filling these knowledge gaps by highlighting the issue is one key purpose of this essay.

Overall Chemical Fate of Spills

An overview of impacts and oil chemical fate as it applies to the deepwater origin is presented in Table 1. Here, it is convenient to divide the question of fate into three consecutive time events. First is the oil release and initiating event; it is the main focus of this essay. Next, on the intermediate time-scale (hours to weeks and months), the fate question gets more complex and involves its impact on the ecosystem. These include oxygen depletion, oil contact with biota, acute fish toxicity, vegetation oiling, dispersion and advection by wind and water onto beaches, wetlands, bays, harbors, estuaries, etc. The third and final oil fate aspect in the table is the long-term (months, years, decades) oil fate question. Oil will accumulate in environmental locales where mobility, biological uptake, and degradation processes are very slow. In these locales, the impacts of the oil chemicals (hydrocarbons and dispersants) released can endure for decades or longer. They include those fractions in so-called sheltered places such as sea bottom sediments, quiet pycnocline layers, estuarine sediments, wetlands soils, rocks/sandy covered beaches deposits, etc. In addition, what are the long-term biological effects on individual species and the impact on system diversity?

In large part, the impact events follow and depend heavily on the state of oil and chemical concentrations produced in the water column during the initiating event, which is the focus of this essay. We hope that the perspective we present on the subject will be useful to both physical and life scientists working on the environmental aspects of the spill.

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<th>Table 1. Where Does Spilled Oil Go? — Some Chemical Fate and Environment Impact Issues</th>
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Initiating Event

The oil plume illustration in Fig. 1 highlights the initiating event and rising plume. The locations of the oil reservoir, seafloor, water column, and the atmosphere are displayed. Superimposed are the temperature and salinity profiles, which cause pycnocline development. Commencing at the O&G blowout jet the in-column processes depicted include clathrate ("methane ice") formation/fallback, oil droplet fall-back, sediment burial, species dissolution and diffusion, suspended droplets, emulsion formation both above and below the pycnocline, dispersant application, breaking-bubble aerosol, etc. We will present and briefly discuss aspects of the oil and chemodynamic processes associated with the initiating event that involve new research challenges that will need to be addressed, in our opinion. The technical problems, with and without dispersants that govern the generation of potentially multiphase droplets, are the interfacial, thermodynamics, and interphase mass-transport phenomena, their stability and dispersion through the water column, and their interactions with sediment and other multimedia processes associated with the gas/liquid release or spill. Collecting and analyzing oil and hydrocarbon data from the field is a very
necessary part of the information acquisition process as is performing bench- and laboratory-scale experiments. All this is required for developing a creditable mass balance model of the oil spill initiation event that can aid in projection where it all goes.

Here, we will emphasize the four issues in the initiating event of Table 1 with respect to oil released to the environment. The perspective will focus on the unique research issues relevant to the Deepwater Horizon spill related to the interfacial, thermodynamic, and transport phenomena that govern the various aspects mentioned earlier. The objective of this essay was to define the significant processes with regard to the short-term oil fate, summarize the available knowledge, and highlight research and development needs.

**Blowout and Oil Phases Formed**

In the case of a deep-ocean release of fluid consisting of oil liquid and its associated gas, this is a short-term event. The oil solid (wax or crystal?), oil liquid, and gas phases emerging is a multicomponent mixture of individual hydrocarbon chemicals. These oil constituents have a range of chemical and physical, thermodynamic, and transport properties plus reactions processes, which operate on a very short time-scale (seconds to hours). These establish the answers to short-term fate or the first question as to “where does it go?” The answers needed are posed in a mass balance context so as to identify and quantify the individual fractions produced. For example, commencing with a 1 ton (1,000 kg) fluid of gas and liquid blowout, what fraction enters into the sea water as soluble material (i.e., in solution) as it moves from the sea floor and works its way up the water column? Many of the hydrocarbons are soluble and thus a significant mass of material is transferred to the sea water. This is an illustration of the types of individual processes the mass balance will need to have to be a realistic oil chemical release model.

**Mass Fractions and Oil Chemical Constituents**

Next, what mass fraction of the hydrocarbon emerges as a gas phase at the sea surface to escape into the atmosphere? This is a separate process and unlike volatile chemical evaporation from the floating surface slick that may form during a shallow subsurface blowout. The answer will depend upon the oil chemical composition, the size of the bubble or other physical form, the travel time to the surface, etc. Some mass produced at the sea bottom blowout point fall-back to the ocean floor, which begs the question: what is this mass fraction and its composition? While working its way to the surface, some mass fraction remains suspended in the water column because of small drop size and near-neutral buoyancy; its mass fraction and composition needs to be known. Oil liquid and (semi?) solid material, which finally emerges onto the surface, becomes the well-known surface “slick”; what is this mass fraction and composition? On the sea surface, volatilization to the atmosphere occurs, and the percentage of volatilization depends on properties (vapor pressure) of the species mass fraction in the oil phase, the physical form of the surface layer (i.e., mousse, liquid, or tarball), temperature, wind velocity, wave intensity, etc.

**Mass Balance**

The level of uncertainty quantifying the mass of O&G entering the water column is disturbing from an engineering science perspective. It has been placed at between 4.6 and 5.4 million barrels and speaks loudly to knowledge gaps in understanding and quantifying basic issues about oil fate and impacts in deepwaters. The Lavoisier law of mass conservation provides the first principle approach for assessing oil and chemical fate. Its use provides the exact accounting needed for the answer to the question “where does all the oil go?” It is a key fate question both with and without dispersants and must be approached at several levels of inquiry. These include field
observations such as time-series measurements of phase fraction and chemical mass emerging from the rising plume. Ideally, the mass sum measured should balance the blowout mass. Individual mass rates from the many physiochemical processes should equal the mass sum as well. A theoretical tool in the form of a mathematical model based on field data and individual processes capable of making forecasts of future oil fate behavior patterns will also be the product of the mass balance.

**Predictive Tool and Its Uses**

The answer to the question “where does it all go?” certainly has pure science aspects. However, it also has important implications that must drive the engineering science and provide practical solutions related to the cleanup and impact responses to future spill/blowout events. With regard to the need of a predictive tool (i.e., model), in its final form such a tool should consist of part theoretical mathematical structure and part empirical data and observational information. Its development is too complex to exclude either. The tool projections/forecasts for both sea bottom blowouts and sea-surface spills will be the oil mass fractions and their chemical constituents.

Some specific uses include the following, although there are likely many more applications: (1) Anticipated focus of oil remediation resources: although sea surfaces are common oil accumulation end points, significant mass fractions fall to the bottom or remain suspended in the water column. Knowing the relative quantities of each fraction, chemical constituent makeup, and the sensitivity of the potential impacted ecosystem should enter the planning process for allocating remediation resources. (2) Risk assessment: the volatile fraction released from a surface spill of a light crude oil may contain levels of certain constituents that contribute to the local air contamination hazard and impact air quality in general. In the water column, the soluble fraction will enter selected biota such as finfish and shellfish, resulting in their contamination. In both cases, knowing the fractions and constituents makeup will help project the short-term chemical exposure levels in air and water, respectively. (3) Projecting ecological damage: similarly, knowing water column chemical and on-bottom loading levels due to deposition of the settleable fraction will aid in the assessment of potential ecological impact as well as quantifying fisheries and resource damages, for example. (4) Hypothesis building: field work assessing where the oil goes, sampling, and quantifying concentration levels are expensive. Early-on model prediction provides a level of forecast guidance as to where to look for oil and its chemical signature.

These include the significant mass fractions and particular suites of contaminant mixtures and their concentration levels in the water column, benthic boundary layer, bottom sediment layers, and the sea surface mixed layer. The field observations and acquisitions of the field data can be used for model refinements such as calibration and/or verification.

Based on these example applications, it seems clear that such a tool can provide much needed quantitative and qualitative information about oil behavior in the marine environment. Besides the emphasis described earlier, the suggested tool could be used in a wider geographic (environmental and ecological) context for applications to specific single events. For example, as offshore O&G activities increase in the Gulf of Mexico and elsewhere, several spill-related events associated with exploration, production, or transportation may occur simultaneously. In such cases, for assessing the sum total oil and chemical loadings, several probable and worst-case scenarios will need to be evaluated. The availability of a theoretically sound, process-based tool tuned with field data so as to lend confidence to the quantitative predictions will be of immense value to the oil companies, governmental agencies, as well as other nongovernmental organizations.

**Special Issues Unique to Deepwater**

*Oil dispersion, dispersants, and minimizing environmental impacts*

One method used to prevent oil from reaching the coastline is the use of dispersants. These are surfactants formulated to break up the oil into small droplets so they may disperse easily over a wide area. Commonly used dispersants contain a mixture of two nonionic surfactants, sorbitan monooleate (Span 80) and ethoxylated sorbitan monooleate (Twee 80), together with an anionic surfactant diocyl sodium sulfosuccinate (AOT). It is commercialized as the COREXIT class of surfactants with the relative distribution of the three components not clearly defined for proprietary reasons.

Requirements for dispersant efficacy are given as follows (National Research Council [U.S.], 2005): (1) the dispersant must be applied at sufficient dosage to form droplets. (2) It must be applied early before the lighter components of the oil evaporate. (3) It must lower the oil–water interfacial tension sufficiently so to produce small oil droplets that remain suspended for biodegradation of the soluble chemical fractions released. Alternatively, if the droplets can be made to deposit onto the ocean floor, biodegradation of chemical fractions may occur here as well. While the concept of oil sinking appears counterintuitive because the lower density of the lighter fractions of crude oil mandates buoyancy, fractions >C50 have densities greater than unity at ambient conditions and constitute about 12%–13% by weight of the oil.

Fate of oil droplets in the deep-sea water column: The need to both understand and control emulsion behavior in dispersant systems is extremely important. The Deepwater Horizon incident only emphasizes the fact that little is known about dispersant behavior at high pressures and low temperatures. As mentioned previously, it has been observed that treatment of the Macondo oil appears to have resulted in the formation of undersea oil plumes at depths of up to 2,500 ft. These plumes are about 10 miles long, 3 miles wide, and up to 400 ft in depth (Camilli et al., 2010; Giant Plumes of Oil Forming Under the Gulf, 2010). “Given their size, the plumes cannot possibly be made of pure oil, but more likely consist of fine droplets of oil suspended in a far greater quantity of water, Dr. Joye said.” (4) The formation of these so-called plumes is still not clear, although it is suspected that these are caused through dispersant addition at depths close to the well head. These aspects of dispersant addition have not been reported in the literature, which has solely addressed the spraying of dispersant on surface spills (National Research Council [U.S.], 2005).

Pressure–temperature–salinity data on the Gulf of Mexico are available (Thacker, 2007) and can be duplicated in the laboratory so as to understand the role of dispersants and duplicate the phases produced when used in this system. As the hydrocarbon mixture of liquid and gas emerges, it quickly equilibrates to the pressure and temperature of the bottom.
water, which is about 17.1 MPa (2,500 psi) and 278.15 K (5 C), respectively. At these conditions, hydrocarbons beyond C14 (tetradecane) may crystallize out into a waxy solid phase. In addition, the solubility of methane in liquid hydrocarbons is significant, indicating that the liquids in an oil droplet are readily gas expanded; a rough calculation for methane solubility in dodecane at these conditions indicates a weight percent of 9 or a mole fraction of 0.51 in the liquid phase. As the droplets rise to encounter lower pressures and higher temperatures, the gas solubility decreases, leading to perhaps gas bubble formation in the droplet.

The formation of gas hydrates is another important consideration. Figure 2 illustrates the gas hydrate phase boundary as a function of depth and it is clear that at the pressures of 17.1 atm, hydrates will easily form at the temperatures of the water column.

It is not quite clear where the location of the hydrates is in this system. Will the hydrates break free of the oil droplets and become suspended in the water column and rise therefore to the surface because of their lower densities? Or will hydrate crystals be entrained in the droplet? As surfactants adsorb onto hydrate surfaces, it is also likely that hydrate crystals accumulate on the droplet interface. In other words, a surfactant-stabilized droplet may contain up to four phases (hydrate, free gas, a gas-expanded liquid, and solid hydrocarbon).

There is therefore a significant knowledge gap in the understanding of droplet microstructure. There are several aspects here involving the compositional variations of dispersants and their effects on droplet microstructure and stability. Similarly, the effect of oil compositional variations on droplet microstructure poses a knowledge gap that research must address. The role of dissolved gas in the droplet and hydrate formation are other aspects that will govern droplet microstructure and droplet transport. The inclusion of hydrate thermodynamics to such systems is essential as deep-sea releases will involve the formation of hydrates. Further, as the droplets travel through the water column experiencing lowered pressures and increasing temperatures, the hydrates will dissociate with concomitant formation of gas bubbles, which can be entrained in the droplet.

Careful analysis of the transport of these deep-sea dispersant-formed plumes is needed, including effects of temperature and density gradients and the variability of transport coefficients and buoyancies of the droplets as they age and the plumes age. What fraction of the oil can we expect it to stay at depth and for how long? What is the nature of the droplet materials after 10-100-1,000 days? For subsurface applications, it should be possible to design dispersants denser than sea water. This raises the issues of green surfactants in a different context: these materials might be sufficiently ordinary by being inoffensive on the seafloor without further degradation. Molecular-scale support for the aforementioned goals might be obtained from aggressive direct molecular-scale simulation of the friction, adhesion, and coalescence of coated oil droplets with sedimentary materials, for example, silica and clays. Does coated oil droplets roll along a silica/clay surface or do they stick? And what dissipation can we expect from those processes?

Oil fate in benthic sediments, wetland soils, and beach sand

Fate of oil droplets upon contact with subsea sediments. A unique aspect of the Horizon spill is that a significant amount of the hydrocarbon mass does not emerge on the sea surface but remains in the water column. As droplets approach the continental shelf, they may interact with subsea sediments. It will be important therefore to understand whether the droplets adhere through surfactant-mediated adsorption to the sediments or continue to “roll” on the sediments and gradually reach shallow water and eventually beach areas or marshland. We note that such subsea oil does not weather rapidly; however, as they reach regions of higher temperature and shallow water, the release of light
hydrocarbons and coalescence of droplets can result in the formation of “tar balls,” which is the most conspicuous manifestation of crude oil washing up on the beaches.

Once the oil reaches the bed sediment either at depth, in the marshlands, or on the beaches, its transport is one of multiphase systems traveling through or lodging in porous media. Such transport may involve oil drops of various sizes, oil banks, solidified oil particles, etc. Further, the transported oil will influence—even cause—transport or deposition/aggregation of bacteria and other (bio) particulates. The ways in which the oil in its various forms will interact with a given host porous medium will affect its fate and eventual degradation. Such realizations can produce strategies for remediation of sediments, soils, and beaches.

Natural bioremediation and weathering of porous substrates that host the contaminant oil are expected to happen in cases where the ecosystem is not overwhelmed and has sufficient strength for the task, although such processes can be very slow. After the spill has stopped and the short-term operations (e.g., skimming burning, scooping up) have served their own purposes, to restore the beaches and marshlands to their prespill condition, decades of judicious intervention may be necessary. Remediation can be greatly enhanced in many ways: (1) by biostimulation (creating more favorable conditions for existing bacteria to metabolize the oil); (2) bioaugmentation (introducing new bacteria into a contaminated site); and (3) physicochemical remediation (using dispersants to mobilize and remove the oil from a site). Seen differently, such interventions will fulfill their purpose by influencing and even drastically altering the transport and fate of oil within the porous-medium structure of sediments, soils, and sands. The consistency of the crude at any given site can be vastly different than its composition at the blowout location, and the concentration of dispersant will also vary. By themselves these are parameters that will determine the oil’s attachment onto the porous-medium substrate or its relative mobility. They will also influence the motility, or conversely, the aggregation and substrate deposition, of those bacteria that are capable of performing the important task of biodegradation.

The schematic in Fig. 3 shows a porous medium, with its solid constituents (grains) depicted in black and the oil in orange. Flagellated remediating bacteria are shown in green, blue, and red. Bacteria are known to swim in the confined space of capillaries and their transport is influenced by chemotaxis and electric fields. It will be of critical importance to know and influence the ways in which such bacteria can be facilitated so as to access the contaminant (red bacteria) as opposed to aggregating, depositing on the porous solid’s substrate, and creating a blockage against the movement of other bacteria (blue). In terms of physicochemical remediation, a multitude of interfacial phenomena are active and a great role will be played by the oil’s emulsification and wetting/nonwetting of the porous substrate. In the schematic, oil banks are seen with concave and convex menisci, representing wetting and nonwetting situations, respectively, whereas the emulsified oil is shown in the form of tiny drops.

At different sites, the overall results may differ greatly from one another, depending on the interaction of the various phases present, with a major role played by surface-active agents, which can be constituents of the oil or dispersants, or naturally occurring molecules, for example, humic acids.

Closure and Implications

Moving forward with drilling to extract O&G from deepwater-residing geologic formations should be done with a much better understanding of the fate of the hydrocarbon in the marine environment. Closure on the mass balance quantifying where all the fractions go when they emerge from deepwater spills is paramount. Too many in-water column and benthic chemodynamic processes are completely unknown or poorly understood at this time for attempting any realistic answer to the question. To arrive at this conclusion, we presented an overview outlining the general nature of the initiating and short-term processes involving oil and dispersants. In doing so we enumerated the knowledge gaps.

The currently available tools needed for predicting oil fate are based primarily on sea surface spills. These need to be modified to handle subsurface releases and deepwater spills both with and without dispersants. Extensive research is needed for their development. First, a clear identification and understanding of the significant processes based on field observations and measurements by marine geoscientists are needed. Next, these water column and bed-sediment processes must be studied and precisely quantified by scientists and engineers by performing experiments in laboratory microcosms and small-scale field sites. Lastly, these data, theoretical mechanisms, and empirical formulas describing processes must be rendered into mathematical models by scientists, engineers, and mathematicians using mass balance protocols. The forecasts of projected quantities made by these tools will include the mass fractions and the associated chemical compositions in the marine environment and the degree of uncertainties in the numerical quantities. At this final achieved stage, the engineering science community will be much better equipped for the design and management of such spills.

In an engineering sense, these models are design tools for making risk assessments and management. Accidents will happen; however, the availability of such tools allows for some level of event simulation in a scenario analysis fashion. Having the simulation results in quantitative form allows levels of comparative risk analysis to be performed. The scenarios could include alternatives taken for drilling, field development, and product transportation, for example. In the
case of an actual release or spill, these engineering design tools can project the many aspects needed concerning oil fate. In this case, its use involves projecting where it might all go so as to be prepared to address issues of biological impacts and remediation cleanup activities. There are likely many more uses.

Author Disclosure Statement

No competing financial interests exist.

References


