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Deep Oil Spills

Facts, Fate, and Effects

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Foreword and Dedication

Eric Brown, a British aircraft engineer, described structural engineering as "*the art of molding materials we do not really understand into shapes we cannot really analyze, so as to withstand forces we cannot really assess, in such a way that the public does not really suspect*" (quote from Broad 2010). There is much to learn from engineering failures regarding the fragility of such structures and systems (Love et al. 2011), no more so than those of oil rig blowouts such as *Deepwater Horizon* (DWH) and Ixtoc 1, the two largest accidental blowouts in world history.

While the forensics of engineering and systems failures in the *Deepwater Horizon* case are well documented (National Commission on the BP *Deepwater Horizon* Oil Spill and Offshore Drilling 2011; Boebert and Blossom 2016), perhaps less well understood were the failures of regulators, legislative oversight, and science to anticipate, plan for, and understand the risks involved in such a catastrophic failure. Quantifiable risk is the product of both the probability of events happening and the consequences of such an event should it happen. In the case of deepwater blowouts, the event has an exceedingly low probability of occurrence but a very large potential consequence. A system subject to a critical single point of failure combined with the inability to contain the ensuing blowout for 87 days points to systematic breakdown in regulatory as well as industrial oversight systems for risk reduction. Doubtlessly, the oil and gas industries have learned from these spectacular engineering failures and put in place what they believe to be appropriate risk reduction measures. Similarly, additional government regulation, inspection, and oversight have been forthcoming.

The DWH event also clearly pointed out the dearth of scientific information necessary to make informed decisions once the blowout occurred, including deciding on appropriate response measures and calculating the impacts of that event in the milieu that is the Gulf of Mexico. Previous research was insufficient to confidently evaluate the risks and trade-offs of, for example, using chemical dispersants injected into the stream of oil and gas emanating from the blown-out well. Likewise, the lack of systematic contaminant baselines for nearly all biota and habitats in the Gulf of Mexico made assessing the damage from that disaster more difficult than it needed to be if such baselines had been available. The lack of specific information points to a larger failure of science and science administration to adequately assess the risks involved in deepwater oil and gas production and to organize a research program of sufficient rigor and scope to have answers – or at least a plausibly narrow set of outcomes – that would guide such a response. The science necessary for informed decision-making regarding oil spills is well documented in the “wish lists” of government agencies (ICCOPR 2015), but the industry, various federal and state administrations, and government agencies were unable to muster the political will and resources to close these gaps.

Much changed in the funding and direction of oil spill-related research following DWH. Through a $500 million grant from BP (British Petroleum, for whom the Macondo well was being drilled), the Gulf of Mexico Research Initiative was established. This ambitious 10-year program has produced an enormous body of research spanning the physical, geological, chemical, engineering, biological, and human health sciences. Additionally, significant funding spent by the Natural Resources Damage Assessment (NRDA), the Gulf Restoration Council, and the National Academy of Sciences Gulf Research Program (GRP) is also contributing to the wealth of new science informing oil spill risk reduction, preparedness, and assessment. The scope of the research programs supported by these funds has been both broad and deep, with many of the fundamental uncertainties of what, how, and why of oil spill science being addressed. As with any science portfolio, the GoMRI-funded research spanned the theoretical to applied science continuum and that of high risk-high reward to incremental.

This volume synthesizes a considerable portion of GoMRI-sponsored research and that commissioned by government, industry, and other entities. Many of the chapter authors are members of the Center for Integrated Modeling and Analysis of Gulf Ecosystems (C-IMAGE) and a number of other GoMRI-funded science centers (ADDOMEx, ECOGIG, RECOVER). Additional authorship includes researchers working for the federal government, in academia, and in private industry. The goal of this book is to synthesize what has been learned from these research investments and to identify additional or as yet unanswered research questions going forward. Given the considerable wealth of new information generated during the 9 plus years after DWH, it is contingent on researchers and regulators to put this information into practical application. The challenge will be for the industry and regulators to assimilate and use this information to devise more risk-averse oil and gas exploration and exploitation strategies and to implement more agile, targeted, and effective response strategies in the event of future accidents. One of the particular barriers for more complete integration of new science into the current industrial regulatory frameworks supporting oil and gas production will be that much of the new, relevant research has been generated by academics not traditionally affiliated with industry or government. The aversion to research “not invented here” by those outside the historical institutional relationships supporting the industry is thus a concern. However, while academic scientists may not understand the history or details of industrial applications, science conducted by independent researchers has the positive attribute of being unencumbered by dogma. New, more expansive, and more productive working relationships among the tripartite science community (industry-government-academia) need to be nurtured.

This volume is dedicated to our mentors, C-IMAGE colleagues, and friends Drs. John W. ("Wes") Tunnell, Jr., John E. Reynolds, and Benjamin ("Ben") Flower.

John W. ("Wes") Tunnell, Jr. Wes had many roles during his illustrious career in marine research, focusing on Gulf of Mexico studies. Working from his home institution at Texas A&M-Corpus Christi, Wes conducted wide-ranging and important studies of the natural history of the Gulf. As a young researcher, Wes was literally on the spot of the Ixtoc 1 oil well blowout in 1979–1980 along the Campeche coast of Mexico. His studies located oil deposition centers along the Campeche, Veracruz, and Tabasco coasts, northward to south Texas. He and his students and collaborators revisited these locations over the next 30 years. In 2016, the C-IMAGE-II consortium undertook the "Tunnell Trek" visiting these deposition locations to apply new methods for understanding oil weathering over a nearly 40-year interval.

Wes was a central figure in conceiving the "OneGulf" concept to encourage multinational research among scientists from Cuba, Mexico, and the United States. Without his enthusiasm, patience, and sense of purpose, the international collaborations sponsored by GoMRI – many documented in this volume – would not have occurred. We are forever grateful to our friend and colleague for his humor, generosity, dedication, and sage advice.

John E. Reynolds Dr. John Elliott Reynolds, III, was an icon in the world of marine mammal science and conservation. The volume and value of his science, and his rare ability to understand, inspire, and lead those around him, will ensure his lasting legacy. At the very young age of 36, John was appointed by President George H. W. Bush as Chair of the US Marine Mammal Commission and was retained under Presidents Clinton, G. W. Bush, and Obama. He had a keen interest in helping to recover the health and integrity of the Gulf of Mexico ecosystem after the *Deepwater Horizon* spill, using sound conservation decisions that came both from the head and the heart. John was the epitome of a "gentleman scholar" with his humor and gentle nature integrated with his incredible knowledge and experience. The conservation world, and indeed the world in general, is a lesser place without him.

Benjamin P. Flower We also dedicate this volume to our friend, mentor, and colleague Benjamin ("Ben") P. Flower. Ben's paleoceanographic research focused on the role of ocean circulation in past global climate change on decadal through orbital timescales. He was a pioneer in recognizing the value of pairing foraminifera to determine the past oxygen isotopic composition of seawater. Despite his propensity for seasickness, Ben participated in eight oceanographic research cruises, including expeditions in the Gulf of Mexico following the DWH oil spill. He was a key player in early work to assess the impact of the *Deepwater Horizon* oil spill on the sediments and deepwater communities of the West Florida Shelf and Slope. He coined the terms "flocculent blizzard" and "dirty bathtub ring" referring to two mechanisms for oil residue sedimentation. He also initiated a high-resolution sediment sampling approach, which proved to be essential for detecting the *Deepwater Horizon* in the sediments of the northern Gulf of Mexico. Although his scientific accomplishments were substantial, Ben was also a loving and involved father and an accomplished athlete. He played tennis competitively at Brown, was an avid soccer and ultimate Frisbee player, and was a member of the National Champion Santa Barbara Condors ultimate team. In ultimate, players are responsible for playing fairly, refereeing themselves, and upholding the "spirit of the game." Ben was a special person: kind, caring, hardworking, honest, and dedicated to his family, friends, and colleagues. In Ben's personal and professional life, he truly embodied the "spirit of the game."

Wes, John, and Ben were ardent scientists with a passion for the natural world. Their contributions to GoMRI and C-IMAGE and to science and society were significant and long lasting. They will be missed.

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Part I
Introduction

Curtis Whitwam
Fever
Watercolor on Aquaboard
20” × 16”

Chapter 1
Introduction to the Volume

Steven A. Murawski, Cameron H. Ainsworth, Sherryl Gilbert, David J. Hollander, Claire B. Paris, Michael Schlüter, and Dana L. Wetzel

Abstract Over half of the US supply of marine-derived crude oil now comes from wells deeper than 1500 meters (one statute mile) water depth – classified by industry and government regulators as "ultra-deep" production. A number of factors make ultra-deep exploration and production much more challenging than shallow-water plays, including strong ocean currents, extremely high pressures and low temperatures at the sea bottom, varied sub-bottom rock and sediment strata, and high oil and gas reservoir pressures/temperatures. All of these factors, combined with the extremely high production costs of ultra-deep wells, create enormous challenges to explore, develop, and produce from ultra-deep oil and gas extraction facilities safely and with minimal environmental damage. In the wake of the *Deepwater Horizon* and other well blowouts, a considerable body of scientific research on the fate of spilled oil and the resulting environmental effects of deep blowouts has emerged. This and a companion volume, published by Springer, *Scenarios and Responses to Future Deep Oil Spills: Fighting the Next War*, are intended to contribute to the ongoing and important task of synthesizing what we know now and identifying critical "known-unknowns" for future investigation. How can society minimize the risks and make informed choices about trade-offs in the advent of another ultra-deep blowout? Also, what research questions, experiments, and approaches remain to be undertaken which will aid in reducing risk of similar incidents and their

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ensuing impacts should ultra-deep blowouts reoccur? It is to these questions that this volume intended to contribute.

Keywords Ultra-deep oil and gas · Ixtoc 1 · *Deepwater Horizon* · Oil spill response

1.1 Background

The *Deepwater Horizon* (DWH) oil spill in 2010 (Lubchenco et al. 2012) challenged the essence of what industry, government, scientists, and the public perceived at the time about marine oil spills, and revealed the tremendous technological challenges – and risks – being undertaken to maintain hydrocarbon supplies globally. Currently, offshore oil from the Gulf of Mexico accounts for >90% of US marine production and about 20% of total US oil production (terrestrial and marine). Over half of the US supply of marine-derived crude oil now comes from wells >1500 meters (one statute mile) water depth – classified by industry and government regulators as “ultra-deep” production. The technologies to exploit ultra-deep and highly productive formations within them have developed rapidly since 2000 (Murawski et al. 2020b) when no ultra-deep wells existed anywhere in the world. Deep water drilling no longer involves derricks standing on the sea bottom, but rather ships tethered to anchoring systems with extended drilling and production pipe strings from the sea surface to blowout preventers (BOPs) resting on the seafloor. A number of factors make ultra-deep exploration and production much more challenging than shallow-water plays, including strong ocean currents, extremely high pressures and low temperatures at the sea bottom, varied sub-bottom rock and sediment strata, and high oil and gas reservoir pressures/temperatures. All of these factors, combined with the extremely high production costs of ultra-deep wells, create enormous challenges to explore, develop, and produce from ultra-deep oil and gas extraction facilities safely and with minimal environmental damage.

1.2 Introduction to the Volume

In the United States, offshore oil and gas exploration, development, and production are primarily regulated by the federal government, under conditions specified by the Outer Continental Shelf Lands Act (OCSLA), originally signed into law in 1953. Additional regulations and applicable statutes related to marine oil and gas production include the Clean Water Act (1972), the Marine Mammal Protection Act (1972), and the Endangered Species Act of 1973, among others. The latter two statutes are primarily applicable to the exploration phase (regulating the use of seismic testing for sub-bottom profiling) and, with respect to oil spills, damages that may be incurred to species and their habitats subject to law’s jurisdictions. The response to marine oil spills is managed by the US Coast Guard acting with other related federal and applicable state "trustee" agencies, and the responsible parties, using authorities granted to them under the Oil Pollution Act of 1990 (OPA-90). None of these regulatory regimes were crafted, nor did their congressional or administration framers anticipate, the rapid development of ultra-deep exploration and production, and the unique issues associated with them. In the wake of the 1989 *Exxon Valdez* tanker spill in Prince William Sound, Alaska (Peterson et al. 2003), new regulations were forthcoming the following year – OPA-90. In contrast, in the 9-plus years following DWH, no new federal legislation specifically addressing the unique issues associated with ultra-deep drilling oversight, production, and spill response has been forthcoming. Administratively, the then Minerals Management Service (MMS) of the Department of the Interior was subsequently split into two agencies following DWH – the Bureau of Ocean Energy Management (BOEM) and the Bureau of Safety and Environmental Enforcement (BSEE). The stated goal of the reorganization was to separate "… conflicting missions of promoting resource development, enforcing safety regulations, and maximizing revenues from offshore operations."[1] Under these new agencies, a brief moratorium on additional new drilling permits for the Gulf of Mexico was enacted (and has since been lifted) and additional requirements for BOP design and inspection promulgated (Krupnick and Echarte 2018). The essential question that remains, however, is: Has enough been done both by the industry on its own volition, and through regulatory processes, to lower the risk of another catastrophic ultra-deep well failure, and if such a spill occurs again, have the lessons learned from previous spills been incorporated into spill response to minimize impacts on humans and the environment both from the spill itself and the mitigation measures employed?

Globally, the landscape for fossil-derived energy sources is changing rapidly. Notwithstanding the effects of burning fossil fuels on the global climate system, maintaining and expanding the use of hydrocarbon-based fuels for transportation, home heating, and industrial purposes has resulted in novel applications of science and technologies to produce from "tight" formations by the use of hydraulic fracturing of shale rock ("fracking") to free natural gas. Injection of fluids and gasses has allowed once abandoned oil and gas sources to yet again yield economically recoverable quantities. The quest for hydrocarbons to supply the ever-growing human population of the earth (>7.5 billion) has increased the urgency to explore new frontier areas where oil and gas might exist. Thus, marine oil and gas operations now extend to water depths >3000 m (2 miles) and will likely to continue into yet deeper waters. Recent industry projections are that exploration and ultimately production from deep frontier operations will occur off six continents (Murawski et al. 2020b), with the most likely finds in the "golden triangle" between West Africa, Brazil, and the Gulf of Mexico. Other areas will also be explored, including the Arctic, which presents yet other unique challenges.

The number of marine oil and gas-related tanker accidents has declined steadily for several decades following several catastrophic and highly publicized groundings and collisions (Ramseur 2010). The decline in tanker accidents resulted from more stringent vessel construction standards, development of more precise global positioning, navigation and tracking aids, and a concomitant rise in the use of pipelines and offshore unloading facilities minimizing tanker traffic close to shores. Resultantly, the risks of

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[1] https://www.boem.gov/Reorganization.

serious tanker accidents have declined substantially both in terms of the number of accidents and the number of barrels of spilled oil. With the advent of ultra-deep exploration and production, however, the risks of another serious blowout remain essentially incalculable because of the myriad of factors that influence the integrity of deep subsurface technologies, operations, ocean and formation conditions, and the degree of training of operators to deal with unique and rapidly changing situations. The industry, and society in general, can ill-afford another ultra-deep blowout of the magnitude of DWH (Lubchenco et al. 2012). That single accident resulted in approximately $60 billion in cleanup costs, fines and penalties, and compensation payments (Bomey 2016). The DWH accident likewise shook people's faith in the ability of engineering solutions to solve environmental problems quickly with minimal damage to people and wildlife. That the equipment to cap and contain such a catastrophic blowout had never been developed or tested prior to the accident is a monumental failure to anticipate and prepare for a truly "worst case" scenario (National Commission on the BP *Deepwater Horizon* Oil Spill and Offshore Drilling 2011; Boebert and Blossom 2016). Subsequent to the DWH accident, billions of dollars have been invested in technology and scientific research to better understand the conditions and environmental consequences of DWH and, by inference, ultra-deep regions of the world that are likely targets for frontier oil and gas development (Global Industry Response Group 2011).

In addition to the DWH spill, there are a number of deepwater blowouts and other spills that can provide relevant lessons learned bearing upon strategic planning for spill prevention and response strategies. The Ixtoc 1 spill off Campeche, Mexico, occurred in 1979–1980 and ran unchecked for 9 months before being shut down (Soto et al. 2014). While only at 54 m water depth, it was, prior to DWH, the largest unintentional marine oil spill in history (about 2/3 the volume of DWH). It is relevant to these discussions because of the extended spatial footprint of the spill, the use of massive quantities of Corexit® dispersant, and because large quantities of Ixtoc 1 oil came to rest in ultra-deep waters (Chap. 13). In 2000 a unique set of controlled release experiments – called DeepSpill – occurred off the Norwegian coast in 844 m of water (Johansen et al. 2003). DeepSpill is elucidating because of the intensive monitoring of fuel oil and natural gas from this series of releases, the results of which were subsequently used to calibrate models of spill behavior. In 2009 the Montara spill in the Timor Sea was uncontrolled for 10 weeks before a relief well successfully controlled oil releases. Similarly, in November of 2011, Chevron had a deep well control failure off Brazil resulting in releases through the underlying rock formations. This volume makes use of research following accidents and investigative reviews in their aftermath. Thus, there are a series of field-scale experiments and monitoring studies, laboratory-based experiments, and monitoring of accidental releases of oil and gas, from which significant research has been generated and summarized in this volume.

We consider the physics, chemistry, and ecological characteristics surrounding deep frontier oil and gas operations, with special emphasis on information obtained from the multiple spill sources of information listed above. From all of these spills, the appropriateness of mitigation techniques and lessons learned from them bear on the seminal question of whether the inherent risks are balanced by the rewards of ultra-deep oil and gas production. After the DWH well was capped, we initiated a scoping effort to characterize factors bearing on deep spill dynamics and how they would impact various sub-ecosystems potentially impacted by a deep spill (Fig. 1.1). The resulting schematic (Fig. 1.1) considers three important domains affecting the outcomes from any set of deep spill circumstances: (1) the oil spill scenario – that is, the specifics of the surrounding oceanographic setting, type, and characteristics of oil and gas being released, the geometry of the subsurface casualty (e.g., BOP failure, casing rupture, formation failure), etc. These factors and responses to them all set the stage determining (2) the fate of oil and gas released into the environment. Much has been learned about oil and gas fate from deep spills from experiments, field observations, and models. The DeepSpill experiment (Johansen et al. 2003), for example, demonstrated that natural gas would dissolve nearly completely prior to surfacing – a result demonstrated in field measurements and models of DWH. This is in contrast to the Ixtoc 1 experience (shallow water) where gas was transported and ignited at the sea surface (Soto et al. 2014).

When the schematic (Fig. 1.1) was constructed in 2011, we had only a rudimentary understanding of the potential impacts of a number of the mechanisms influencing the fate of oil and gas from an ultra-deep blowout. In particular, the relative contribution of the use of subsurface dispersant injection (SSDI) vs. the formation of small oil droplets from the sudden, rapid degassing of gas-saturated, highly pressurized oil has proved to be one of the most fundamental and significant issues from a response planning perspective. It is also an issue of continuing vigorous scientific debate and investigation. This volume considers the issue of SSDI and the state of the science surrounding it, in detail. Similarly, the finding that significant quantities

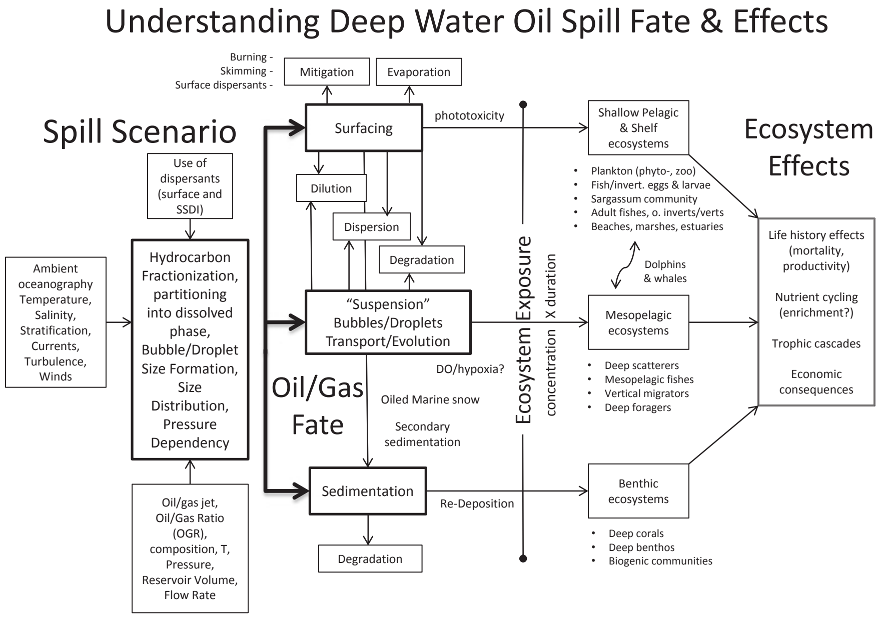

Fig. 1.1 Schematic of the potential mechanisms affecting the circumstances, fate, and effects of a hypothetical deep-water oil and gas spill. (Graphic courtesy of the Center for Integrated Analyses of Gulf Ecosystems – C-IMAGE)

of weathered oil would be transported to the deep sea bottom via a complex set of mechanisms is an important and, prior to DWH, a poorly understood phenomenon.

Ecosystem-level effects (3) from an ultra-deep spill integrate the full range of benthic, water column, sea surface, and coastal ecosystems (Fig. 1.1). This is due to the complex transport mechanisms affecting the fate of oil and gas. Because oil in various states of weathering (fresh crude, dissolved, weathered oil components, emulsified oil, etc.) will be transported both vertically and horizontally in a large ultra-deep spill, the potential environmental and human impacts are much more diverse and complex than in typical surface oil spills. Because response measures can influence the fate and thus the exposure vectors of spilled oil, spill response managers are thus faced with the challenge of balancing trade-offs among ecosystem components, recognizing that there are no benign options in oil spill mitigation and cleanup. For example, the use of SSDI in large quantities is likely to toxify deep benthic and mesopelagic realms where highly diverse, but relatively unproductive communities exist (Fisher et al. 2016; Romero et al. 2018). However, allowing oil to surface in large droplet sizes may increase the oil volume affecting surface-dwelling and coastal animals and plants (French-McCay et al. 2018). The ultimate choice of response measures for a particular spill must be made with transparency and forethought and not simply left to ad hoc, situational decision-making, particularly since the nature and implications of such choices are becoming more clear with additional research.

The concept of this two-volume series (e.g., this book, *Deep Oil Spills, Facts, Fate and Effects*, and the companion volume – *Scenarios and Responses to Future Deep Oil Spills: Fighting the Next War*) is to synthesize some of the salient research examining key issues that have emerged since the DWH casualty and from other deep oil spills and experiments. Much of the scientific research summarized in these volumes was sponsored by the Gulf of Mexico Research Initiative (GoMRI), funded by a grant of $500 million from BP. Additionally, under the DWH Response and Natural Resource Damage Assessment (NRDA) programs following DWH, a large number of studies examined the impacts on wildlife and lost human uses of the environments affected by the spill. Much of that research has now been widely disseminated in reports and scientific publications (e.g., *Deepwater Horizon* Natural Resource Damage Assessment Trustees 2016). The GoMRI Research Board, chaired by Eminent Biologist Dr. Rita Colwell, overseen by Chief Scientist Dr. Charles “Chuck” Wilson, and comprised of experts in many scientific domains, has consistently encouraged synthesis of research findings as a way to improve the rigor and relevance of the research applied to real-world issues. These books are meant to contribute to the ongoing and important task of synthesizing what we know now and for identifying critical “known-unknowns” for future investigation. How can society minimize the risks and make informed choices about trade-offs, such as the use of subsurface injection of dispersants at the wellhead in the advent of another ultra-deep blowout? Finally, what research questions, experiments, and approaches remain to be undertaken which will aid in reducing risk if similar incidents and their ensuing impacts should ultra-deep blowouts reoccur? It is to these questions that this volume intended to contribute.

This book is organized into eight thematic sections, generally following the fate and effect scheme outlined in Fig. 1.1. Each section is introduced with a brief chapter outlining the significance of issues addressed by the chapters within that section. Part 8 provides an overall summary of major science and management-related themes emerging from the book as well as a reprise of significant "lessons learned."

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Part II

Physics and Chemistry of Deep Oil Well Blowouts

Tessa Wilson
Perfect Plumes
India ink, Gold ink, Motor oil on Canvas
18” × 26”

Chapter 2
The Importance of Understanding Fundamental Physics and Chemistry of Deep Oil Blowouts

William Lehr and Scott A. Socolofsky

Abstract The science of deep oil spills is complex, spanning several engineering and scientific specialties, different environmental conditions, and a large range of dimensional scales. It is also an applied and pragmatic field where research is expected to produce a better assessment and improved response of any spill incident. This summary chapter reviews at an introductory level the important physical and chemical factors relevant to deep oil blowouts, beginning with the nature of the crude oil itself. While knowledge of the necessary properties of such a mixture of hydrocarbons is often limited, this chapter describes the information typically known to spill responders, expressed in units common to the industry. Material characteristics of the leaking reservoir are defined along with some special features of the subsurface release and plume that are not present in surface spills. Finally, the early far-field behavior of the submerged oil is described.

Keywords Bulk oil properties · API · Oil viscosity · Oil reservoir · Porosity · Gas hydrates · Oil plumes · Oil jets

2.1 Introduction

A common expression, "challenging as rocket science," is occasionally used to describe a complex topic. Analysis of oil releases at great water depth is not rocket science. It is in fact much more imposing than rocket science, spanning numerous fields of science and technology and great extremes of environmental conditions. Consider, for example, the extreme ranges of temperature and pressure to which the spilled oil is subjected. For the *Deepwater Horizon* (DWH) oil spill, pressure ranged

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from 1 bar at the water surface to 817 bars in the reservoir; water temperature varied from a few degrees °C at the wellhead to117 °C in the reservoir (Blunt 2013).

The range of spatial and temporal scales affecting the behavior of oil spills is also large. Transport of surface oil may involve oceanographic features that span thousands of kilometers while "weathering" processes such as oil-water dissolution operate at the molecular scale. Evaporative loss rate for oil that reaches the water surface is greatly reduced after the first day, while biodegradation of beached oil or oil dispersed in the water column may take months or even years.

The spilled oil itself presents an insurmountable problem for complete description from first principles. Rather than being a single substance, crude oil is a mixture of thousands of hydrocarbons with traces of non-hydrocarbon molecules that are known to the spill responder in only the most cursory manner. Moreover, the deep water spill release is a multiphase process of gas and liquid hydrocarbons along with entrained water that changes rapidly over short spatial and temporal ranges.

Fortunately for those researchers that have chosen oil spill science as their field of study, it is also a pragmatic subject. Unlike rocket science, high precision is often not required. Answers need only be as accurate as necessary to make educated cleanup or damage assessment decisions. Approximations are allowed, in fact required, and a great amount of spill literature involves discussion of the better approximation for a particular spill phenomenon.

Several chapters in this book examine specific recent improvements in our understanding of spill mechanisms. Much of this new research is a result of the Gulf of Mexico Research Initiative (GoMRI) launched as a consequence of the DWH spill. A herculean task for those responsible for funding such investigations is estimating for any individual study its importance and applicability to the pragmatic goals of the entire field of oil spill science. Assessing a particular tree's value requires knowing its connection to the entire forest. Therefore, this introductory review chapter will discuss at least part of the forest, as it relates to our understanding of the fundamental physics and chemistry of deep oil well blowouts. A word of warning to the reader: the chapter must neglect some important topics and cover others at a level that may seem too basic to the specialist. However, the specialist needs to recognize that outside of their specialty, they are themselves a novice.

2.2 The Oil

Deep oil spills involve crude oil, as opposed to petroleum products generated by the world's refineries and transported in the marine environment by pipeline or, more commonly, surface shipping. Deep oil spills may involve a single reservoir or a network of reservoirs connected to a common platform. In either case, the oil that is extracted will change its characteristics over time, sometimes resulting in slightly different behaviors if spilled.

Industry characterizes crude oils by properties that are important for commercial purposes, but these properties do not provide a complete description for environmental impact. For example, while the information available for DWH was more extensive than a typical spill incident, certain weathering characteristics remained unknown. Crude oil has a typical elemental composition of 83–87% carbon, 10–14% hydrogen, 0.1–2% nitrogen, 0.05–6% sulfur, 0.05–1.5% oxygen, and less than 1% other trace elements (Speight 2007). Industry traditionally separates oil by structure into one of four somewhat arbitrary categories, labeled SARA after the first letter in the category name: saturates, aromatics, resins, and asphaltenes.

The first two groups, saturates and aromatics, represent the largest mass fraction of most crude oils. The saturate group is nonpolar oil molecules without double bonds that include linear, branched, and cyclic saturated hydrocarbons. The group name refers to the fact that the carbon atoms are "saturated" with the maximum number of hydrogen atoms. Smaller saturate molecules (less than seven carbons) are relatively volatile and are mostly lost to evaporation in surface oil spills. However, they have extremely low solubility in seawater, even when compared to other hydrocarbons of similar molecular weight. For example, while hexane and benzene (smallest aromatic) have similar molar masses and limited solubility, benzene is nevertheless the much more soluble by more than an order of magnitude. This distinction between the two hydrocarbon categories has consequences for deep oil spills where dissolution replaces evaporation as an important weathering process and toxicity is a concern.

The aromatic group hydrocarbons have at least one benzene ring and often play the lead role with regard to toxic impacts from the oil while being generally less biodegradable than saturates of the same carbon number. Fingas and Fieldhouse (2012), based on laboratory results, claim that the ratio of aromatics to saturates plays a role in the formation of stable water-in-oil emulsions. However, the quantity and ratio of the two remaining groups, resins and asphaltenes, are even more important for emulsion stability. Resins are large hydrocarbon molecules with one to three sulfur, oxygen, or nitrogen atoms per molecule. Resins can dissolve in oil, an important factor in the initiation of emulsification where they prevent escape of water droplets until the larger asphaltene molecules can migrate to the oil-water interface. Asphaltenes are not uniquely defined in the literature although a common definition might be very large hydrocarbon molecules that have one to three sulfur, oxygen, or nitrogen atoms per molecule but do not dissolve in oil. The ambiguity in asphaltene classification between laboratories complicates the task of devising computer models of spill weathering, particularly emulsification onset. Added to this complication is the inherent limitation of the SARA classification scheme itself, as it does not record important oil characteristics such as the detailed structure and degree of polarization in the larger hydrocarbons, particularly the asphaltenes. This is an active area of research (Groenzin and Mullins 2007) with good prospects for improved oil characterization databases in the future.

Certain bulk oil properties are not dependent on the individual hydrocarbons in the oil but still have a major impact on the fate and behavior of the spill. One obvious example is density. Industry reports density in API degrees:

$$\mathrm{API} = \left\{ \frac{141.5}{\mathrm{sg}} \right\} - 131.5 \tag{2.1}$$

where sg = specific gravity at stock tank conditions (1 bar, 16 C). The number constants are selected so that pure water has an API of 10. Oils with API less than 10 would be non-buoyant in freshwater but might be slightly buoyant in seawater. While spilled oil density usually increases with weathering, it is rare that the resulting density change will cause a buoyant oil to sink. Instead, other processes may interact to cause submergence. During DWH, aggregation with marine snow (Passow and Ziervogel 2016) may have played a major role in causing oil to settle on the bottom.

Industry refers to oil that does not contain dissolved gases as "dead oil." Such oils show relatively little change to density as pressure increases. However, deep well-released oils such as that from DWH are "live oils" and contain significant amounts of dissolved gases, mainly methane, ethane, propane, and butane. Some dissolved gases will escape during the pressure drop from reservoir to water surface. The oil formation volume factor calculates the change in oil volume from reservoir conditions to the resulting volume of liquid and gas if it were directly brought to stock tank conditions. For DWH, the oil formation volume factor was about two and a third (Hsieh 2010). This does not represent the actual observed change between reservoir volume and surface spill volume since dissolved gas release, other weathering processes, and incorporation of surrounding seawater are not included.

Like most fluids, the density of the oil increases as the temperature decreases. The increase parameter is a nonlinear function of temperature and density (ASTM 2007) but can be approximated as linear over conditions outside the reservoir.

Another important bulk property is viscosity. Unfortunately, the term relates to two different properties with different dimensional units. Kinematic viscosity has dimensions of area/time with its SI unit being the stoke. Dynamic viscosity, sometimes called absolute viscosity, is kinematic density multiplied by the oil density. Its SI unit is the poise. The oil industry traditionally used neither but instead would use the time for an oil sample to flow through a certain type of measuring viscometer (e.g., Saybolt universal second). Fortunately, this is less common today, and most large oil property libraries store viscosity in one hundredth of poise or centipoise.

Oil viscosity is highly sensitive to temperature change. Past practice in older surface spill models was to utilize the Eyring's equation (1935) to calculate (kinematic) viscosity

$$v_0 = v_{\mathrm{ref}} \exp\left[k_v \left(\frac{1}{T_0} - \frac{1}{T_{\mathrm{ref}}} \right) \right] \tag{2.2}$$

at the environmental temperature T_0 (K) by extrapolating from some measured laboratory viscosity v_{ref} and temperature T_{ref}. Choice of k_v varied depending on the model, but a typical value, expressed in Kelvin, would be 5000 K (Bobra and Callaghan 1990). Industry itself needed more accurate estimates over greater environmental extremes, so more complex methods have been developed (e.g., Orbey and Sandler 1993; Abu-Eishah 1999; Hemmati-Sarapardeh et al. 2013) but are not necessarily imported into current spill modeling.

While mass loss through evaporation (for surface oil) or dissolution will also increase viscosity, the most significant cause of viscosity increase for susceptible oils is water-in-oil emulsification where the emulsified oil viscosity can increase by more than an order of magnitude. The Moody equation (MacKay et al. 1982) remains the most common method used to calculate an estimated increased emulsion viscosity value:

$$v_{\text{emul}} = v_0 \exp\left[\frac{k_1 f_w}{1 - k_2 f_w}\right] \tag{2.3}$$

where k_1, k_2 are empirically determined constants and f_w is the water fraction of the emulsion, which can be as much as 90%. Some newer models have replaced the Moody equation by the approach of Pal and Rhodes (1989).

A final bulk property introduced in this chapter is important in part because of the use of chemical surfactants as a cleanup device. Oil-water interfacial tension, the tension that holds the surface of each liquid phase together, has been measured by industry for a century (Johnson 1924). However, the actual range of measured interfacial tension values for most crudes is small, typically between 20 and 40 dynes/cm. Application of chemical surfactants at the interface drastically reduces interfacial tension by one or more orders of magnitude. If the oil is simultaneously subjected to turbulent energy, numerous small oil droplets will be produced that can then disperse over a wider aqueous domain and increase certain weathering processes such as dissolution and biodegradation. Chemical surfactants, both on the surface and subsurface at the oil release point, were widely used in DWH.

2.3 The Reservoir

To be economically viable, oil from deep well reservoirs should be under high pressure. As previously mentioned, the DWH reservoir fluid was at 817 bars. At this pressure with a corresponding high temperature, the liquid-gas mixture is a critical fluid, meaning that the gas and liquid are indistinguishable from each other. In spite of a common public misconception, the fluid does not exist as a uniform subterranean pool but is instead interspersed in pore spaces of rock structures such as those in sandstone (e.g., DWH) or dolomite.

Two key characteristics that define a reservoir potential are the porosity of the reservoir rock (fraction of open space) and permeability, a measure of the reservoir fluid capability to pass through the rock pores: the connectivity of the rock pores. Porosity can be surprisingly high for a productive reservoir. DWH was reported to have better than 20% average porosity (Bommer 2010), and porosities of 30% are not uncommon (Ehrenberg et al. 2009). Porosity varies both spatially and temporally. Different rock layers may demonstrate different porosities, and not all rock pores may be filled with fluid. As the reservoir fluid is extracted, the rock is compressed down, reducing the size of the pore spaces. The relative change in volume (V) per unit change in pressure (p) is called compressibility, c:

$$c = -\frac{1}{V} \cdot \frac{\partial V}{\partial p} \tag{2.4}$$