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Resolving the dilemma of dispersant use for deep oil spill response

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1. Introduction

This spring marked the ninth anniversary of the *Deepwater Horizon* (DWH) oil well blowout in the Gulf of Mexico and the publication, by the National Academies of Sciences, Engineering, and Medicine, of its report on the use of chemical dispersants for oil spills [1]. The DWH incident witnessed the first use of chemical dispersants (Corexit 9550A®) applied directly into the stream of oil, natural gas, and water emanating from the top of the blowout preventer (BOP) located 1500 m below the sea surface (see figure 1). This experimental use of the sub-surface dispersant injection (SSDI) strategy was done ostensibly for two reasons: (1) to reduce the quantity of volatile organic compounds (VOCs) entering the atmosphere around workers above the blowout, and (2) to more efficiently treat the large volumes of oil escaping from the well, compared to traditional surface application with aircraft (which was also done). Since DWH, the oil industry has invested in new technologies for delivering dispersants to BOPs and has stockpiled dispersants with the expectation that SSDI will be used as a primary response strategy for the next 'ultra-deep' (i.e. $\geqslant$1500 m) blowout. Despite extensive research on the topic [1–3], a number of essential questions remain unanswered, including: *How effective was the use of SSDI in reducing the quantity of oil and VOCs eventually reaching the surface?* Answering this question has enormous practical and economic consequences, as the marine oil industry both in the Gulf of Mexico and globally is increasingly reliant on ultra-deep production (see figure 2). However, significant uncertainties in the fundamental mechanisms involving deep sea blowouts and the efficacy of SSDI as a response countermeasure remain. Thus, there exists a fundamental dilemma for oil spill responders: to disperse at depth or not.

1.1. Oil droplet physics

The rise velocity of an oil droplet is an increasing function of its diameter and degree of saturation with natural gas components [1, 4, 5]. For an intermediate-viscosity black oil like Louisiana sweet crude (which has been used as a proxy for DWH studies), oil droplets smaller than approximately 70 μm can be rendered neutrally buoyant due to small-scale ocean turbulence [1]. Extending the sub-surface residence time of rising crude oil droplets allows toxic VOCs (including BTEX compounds and other components) to dissolve into the water column prior to surfacing [6, 7], thus theoretically reducing VOC exposure to responders and air-breathing wildlife. Previous modeling studies have calculated reductions in VOC exposure of up 28% with the addition of SSDI [6]. Several iterations of comparative risk assessments (CRAs) have also concluded that SSDI is an effective and preferred response option for deep blowouts given consideration of impacts to wildlife and their habitats [8]. However, these modeling studies calculate oil droplet size distributions in the absence of SSDI that include *de minimis* quantities of droplets below this 70 μm threshold. Results of some droplet size experiments and models upon which the existing CRAs are based (e.g. results of V-DROP-J, ASA and SINTEF droplet size models; [1, 9, 10]) conflict with yet other experiments and models, especially those including 'live' (gas-saturated) oil at ambient deep sea pressures (~15 MPa) that show a substantial fraction of small droplets [11, 12] without the addition SSDI.

1.2. Research to date

The interfacial tension between crude oil and water declines two-fold or greater with dispersant/oil volume ratios of 0.01–0.04 [1]. All empirical evidence shows that droplet sizes are reduced in the presence of dispersants,

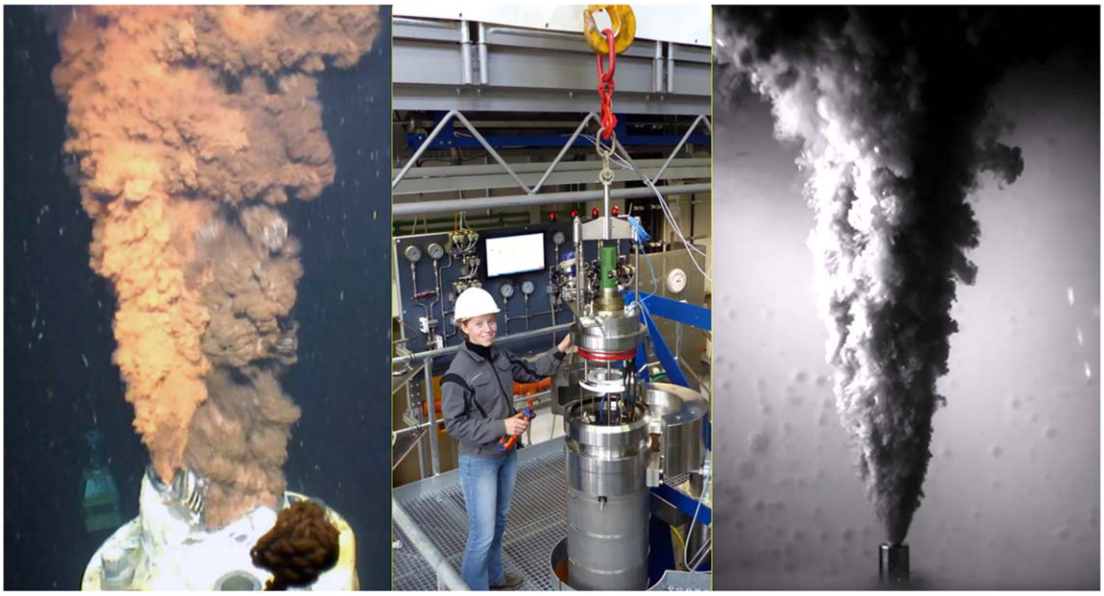

Figure 1. Left, escaping oil, gas and water from the top of the severed blowout preventer of *Deepwater Horizon*. Center, high-pressure oil spill simulation module, Hamburg University of Technology (TUHH). Right, simulated high-pressure oil blowout of methane-saturated oil imaged in the TUHH facility. The pipe diameter of DWH was ∼0.5 m diameter (left), the TUHH experiments used a 1.5 mm orifice (right).

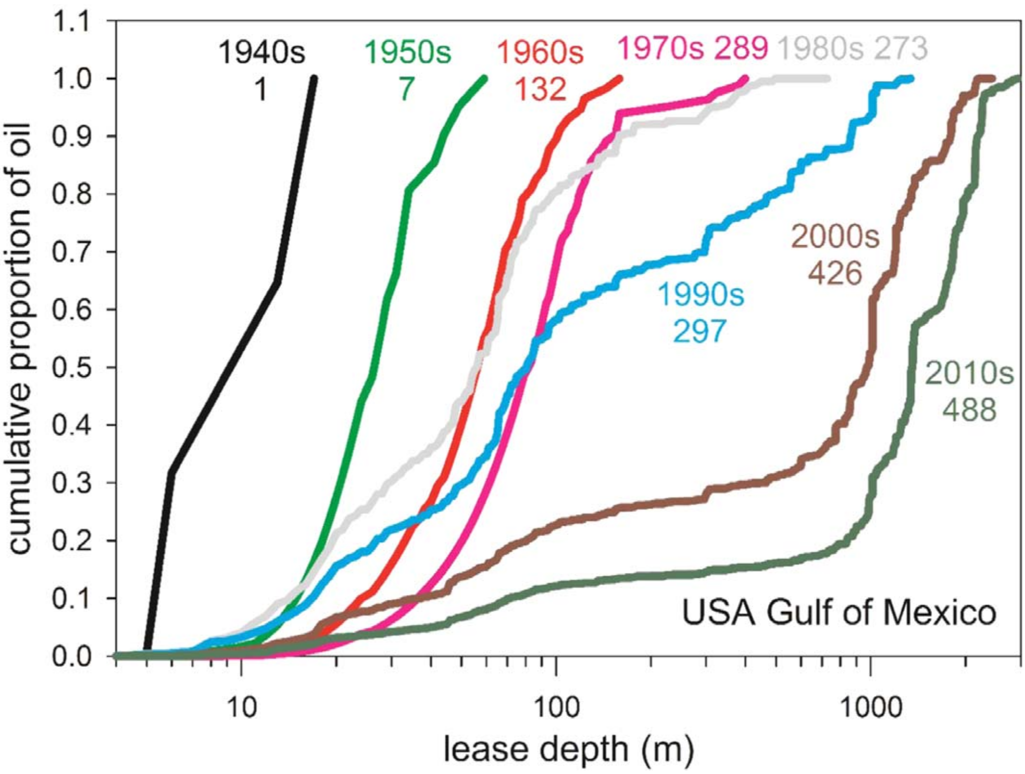

Figure 2. Cumulative distributions of water depth of oil production in the USA Gulf of Mexico, 1940s–2010s. Number next to the decade is the average yearly production in millions of barrels per year (mBpY) (graphic re-drawn and content added from 3). Total USA oil production for the Gulf of Mexico in 2018 was 641 mB. [3] (2019) © Springer Nature Switzerland AG 2020. With permission of Springer.

both at sea-level pressures and in deeper waters [1–3]. The critical question, however, is not *if* small droplets can be created by SSDI during ultra-deep spills, but the extent to which small droplets would occur in the *absence* of SSDI because of the natural turbulence of sub-surface blowouts and pressure drops associated with gaps within the BOP causing rapid degassing of oil oversaturated with gas (like an effervescent champagne bottle upon opening). Put another way, what are the relative contributions of SSDI and natural processes to the formation of deep sub-surface oil plumes as observed during DWH [1–3]?

Evidence for the formation of small droplets in the presence of dispersants comes in the form of laboratory experiments, field observations conducted before, during and after DWH, and modeling studies. A number of studies have conducted or summarized experimental approaches to estimate oil droplet sizes from scaled-down laboratory experiments, in test tanks, and, in one case, a field-scale experiment [1, 12, 13]. Laboratory experiments to assess oil droplet diameters have been undertaken in a small number of facilities: the SINTEF facilities in Norway, the OHMSETT tank in New Jersey, the Southwest Research Institute high-pressure vessel in Texas, the high-pressure test facility at the Hamburg University of Technology in Germany [4, 5, 12] and in stirred sapphire cells at the University of Western Australia [11] and elsewhere. Extrapolating droplet behavior from these laboratory apparatus to ultra-deep field-scale conditions is complicated by a number of factors. The jet-based experiments are limited in scale to nozzle diameters far smaller than the ~0.5 m diameter pipe at the top of the DWH BOP (see figure 1). As nozzle diameter affects maximum droplet size, scaling of the experimental results requires the use of engineering approximations of turbulence (e.g. *Reynolds*- or *Weber*-based scaling), or more detailed knowledge of fundamental turbulence quantities, including the turbulent kinetic energy and turbulence dissipation rate [9, 12]. Importantly, for the jet injection experiments, nozzle diameters ranged from 1.5 mm (SINTEF and Hamburg) to 25–50 mm (OHMSETT) and 120 mm in DeepSpill [1, 12, 13]. Because of their small size, results of the jet experiments require substantial scaling-up and extrapolation to emulate the DWH conditions [12]. Likewise, a plurality of experiments assessed droplet diameters at ambient (i.e. sea level) pressure rather than the 15 MPa of pressure relevant to DWH conditions (and higher for deeper simulated blowouts). Additionally, only the Hamburg facility is capable of simulating the pressure drop observed at the DWH BOP [3, 12]. Finally, a number of the experimental protocols have used ‘dead’ versus ‘live’ (e.g. methane saturated) crude oil for droplet size experiments. Obviously, real-world blowouts create a chaotic multi-phase (oil, gas, water) flow that is also influenced by the exit pipe diameter, edge and roughness contributions, and orifice effects (e.g. pipe bends, partially closed shear rams, etc) that have been neglected by most researchers. Experiments to date with ‘live’ oil have emphasized the criticality of dissolved gas to both the thermophysical properties of the oil *and* potential for rapid de-gassing across an orifice, where gas bubbles emerge from the oil phase, inducing secondary turbulence fields ([4, 5, 10, 12], see figure 1).

A variety of models have been used to predict droplet diameter and fate with and without the use of dispersants (e.g. the VDROP-J, SINTEF, ASA and oil-CMS [1, 9, 10, 12, 14]). Contingent on the sub-set of experimental data chosen for incorporation in the models, the fraction of oil accumulating in deep plumes as a result of the application varies significantly. Thus, understanding how well experiments replicate realistic chemical and physical characteristics of the blowout, as well as oil and gas behavior under extreme pressure, is critical for validating model performance.

2. Strategies for resolution

There are three viable options for resolving the impasse regarding the efficacy of SSDI [1, 3, 15], including the construction of bigger, more elaborate laboratory-based facilities, additional field-scale experimentation, and systematic observations collected during future marine blowouts, briefly:

(1) *Development and use of larger-scale high-pressure facilities*: Laboratory-based experiments as a modality for learning have the distinct advantage of controlling experimental factors one at a time or in a factorially-designed matrix. Laboratory experiments can be used to test a range of oil types and viscosities and how dispersants may differentially affect their behavior. However, as noted above, the small scales of extant high-pressure experimental facilities preclude the use of larger diameter nozzles and longer duration flows of oil, gas and dispersants. One important consideration with the existing high-pressure facilities is their physical size (see figure 1). Only a few moments of oil release can be observed during a single trial before the pressure vessels become polluted and unobservable, requiring extensive cleaning between trials. While the OHMSETT facility is comprised of a 9800 m^3 outdoor test tank, the system cannot be pressurized. Construction and operation of a larger, more sophisticated high-pressure facility, perhaps by a consortium of oil companies, foundations, and government agencies (as is the case with the OHMSETT facility) would allow researchers to test a fuller range of spill scenarios and innovative response strategies. Most importantly, the design of such pilot-scale facilities must pre-emptively consider the up-scaling relationship of fundamental turbulence and fluid mechanics quantities; that is, ‘shrinking’ the system in physical size requires correlative changes in both the blowout rate and thermophysical properties of fluids studied in the laboratory in order to accurately represent the *turbulence* generated at field scale.

(2) *Field-scale experiments*: Much was learned from the DeepSpill experimental release of diesel fuel and methane gas at 800 m depth off Norway [16], especially regarding the fate of gas and oil from a simulated deep spill. A similar experiment in the

ultra-deep presents more complicated technical issues because of the extreme pressures involved and the challenges of observing of oil and gas behavior at the point of release and thereafter, notwithstanding the challenges of permitting, regulatory oversight and perceptual issues associated with a controlled oil spill into the environment. Nevertheless, modest-size releases under field conditions can be an important complement to laboratory-based studies because they incorporate the myriad of factors operating simultaneously in the environment bearing upon the interpretation of results, including sub-surface and surface currents, winds, temperature and pressure gradients, biodegradation, and other factors.

(3) *Observing a 'Spill of Opportunity'*: During the DWH spill scientists attempted to gather critical data related to the behavior of oil exiting the broken riser and BOP. However, because of the priority for controlling the blowout and the congested space around the wellhead, many observations that would be important to *post hoc* interpretation were not obtained. As well, critical instrumentation, for example to image very small oil and gas droplets, was not yet available. Had the proper imaging equipment existed and a more systematic, experimental approach been taken to quantifying oil behavior with and without the addition of SSDI, data critical for model development and interpretation, would have been collected. In the event of the *next* ultra-deep blowout, we recommend that in USA waters, the Federal On-Scene Coordinator (a high-ranking member of the US Coast Guard), the Responsible Parties (oil and oil services companies) and scientific advisors implement such procedures as a 'spill of opportunity' to collect these critical data. To do so, the necessary equipment, trained personnel, and nimble scientific protocols need to be developed, pre-planned, pre-positioned, and available to be deployed rapidly into the field. This will necessitate investments on the part of all parties, a recognition of the importance of scientific data collection in the chaotic milieu that is oil spill response, and as well a willingness on the part of the scientific community to respond rapidly to such emergencies. While a logical compliment to the options outlined above, this strategy involves a highly infrequent and unpredictable time frame for implementation.

3. Conclusions

Resolving the disparities in experimental, modeling and empirically derived oil particle behavior is perhaps the most critical issue facing ultra-deep oil spill response. It is in the long-term interests of the oil companies, national governments and other potential funders to support a more vigorous scientific effort to do so, particularly as more than half of USA Gulf of Mexico oil production now comes from ultra-deep waters ([3], see figure 2) and ultra-deep plays are being explored globally. Of the three strategies we propose to close this critical information gap, the construction of a large-scale high pressure facility capable of using gas-saturated oil at simulated operating depths of the ultra-deep industry appears the most technically and operationally feasible.

Acknowledgments

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Data availability statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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