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Lab tests on the biodegradation of chemically dispersed oil should consider the rapid dilution that occurs at sea ☆

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ABSTRACT

Most crude oils spread on open water to an average thickness as low as 0.1 mm. The application of dispersants enhances the transport of oil as small droplets into the water column, and when combined with the turbulence of 1 m waves will quickly entrain oil into the top 1 m of the water column, where it rapidly dilutes to concentrations less than 100 ppm. In less than 24 h, the dispersed oil is expected to mix into the top 10 m of the water column and be diluted to concentrations well below 10 ppm, with dilution continuing as time proceeds. Over the multiple weeks that biodegradation takes place, dispersed oil concentrations are expected to be below 1 ppm. Measurements from spills and wave basin studies support these calculations. Published laboratory studies focused on the quantification of contaminant biodegradation rates have used concentrations orders of magnitude greater than this, as it was necessary to ensure the concentrations of hydrocarbons and other chemicals were higher than the detection limits of chemical analysis. However, current analytical methods can quantify individual alkanes and PAHs (and their alkyl homologues) at ppb and ppm levels. To simulate marine biodegradation of dispersed oil at dilute concentrations commonly encountered in the field, laboratory studies should be conducted at similarly low hydrocarbon concentrations.

1. Introduction

The primary goal of any oil spill response operation is to minimize harm to people and the environment. Complete containment and removal of oil from the environment is an expectation that is improbable or impossible for large offshore spills due to physical limitations of mechanical recovery systems. In fact, mechanical recovery operations in the offshore only collect a small fraction of oil even under ideal circumstances (ITOPF, 2010). The extensive mechanical recovery operations during the *Deepwater Horizon* response were estimated to have recovered only 3% of the oil (NOAA, 2010).

Alternative response tools, such as oil spill dispersants, were developed because of the known limitations of mechanical recovery for large offshore spills. Dispersants, applied at the surface or subsea, allow rapid atomization of large volumes of oil, and thereby facilitate the removal of oil from the environment through biodegradation. Dispersants break a surface slick into micron-sized droplets that are transported into the water column and rapidly diluted. The small oil droplets are now a readily accessible food source for oil degrading bacteria. All marine environments contain petroleum-degrading bacteria because of the abundance of natural oil seeps (Prince et al., 2010).

The rapid dilution that occurs in the open oceans allows bacteria to aerobically biodegrade dispersed oil without exhausting natural levels of biologically available nutrients or oxygen. Laboratory studies have shown that oil degrading microbes colonize dispersed oil droplets within a few days (MacNaughton et al., 2003), and the composition of some dispersants even enhances biodegradation by serving as an initial food source for bacterial growth (Lee et al., 1985; Varadaraj et al., 1995). Fig. 1 illustrates the biodegradation process after applying surface and subsea dispersants.

Measurements made in the Gulf of Mexico indicate that biodegradation is rapid in marine environments (Hazen et al., 2010; Valentine et al., 2012), but there is a significant amount of seemingly

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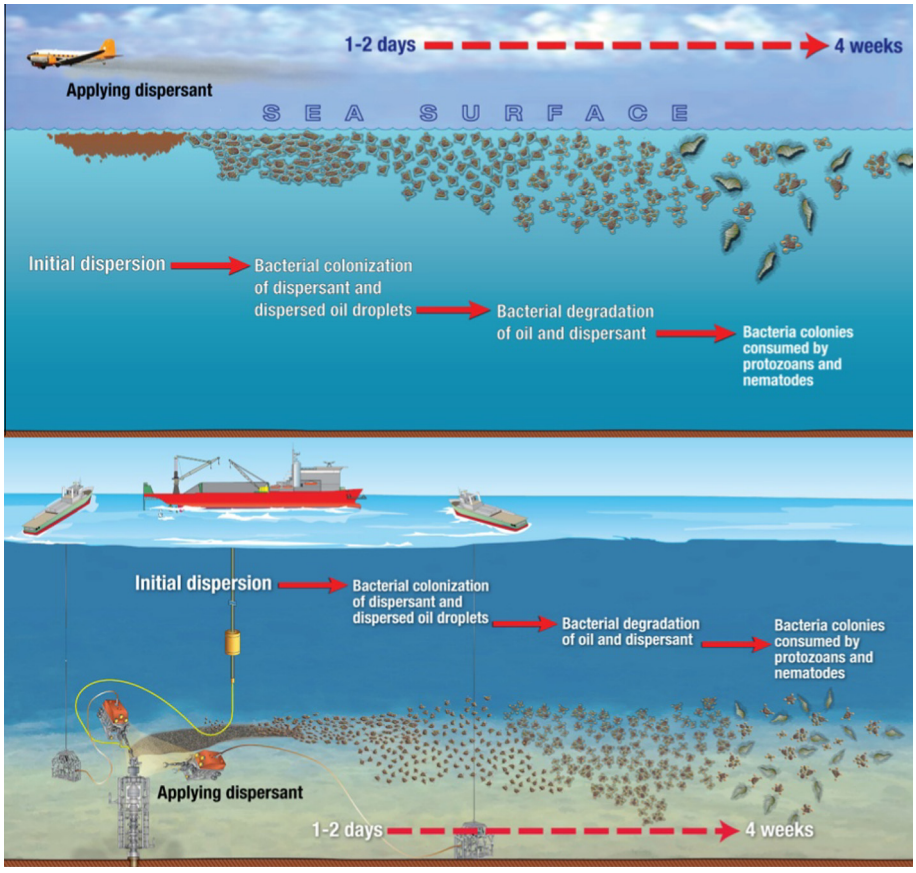

Fig. 1. Diagram illustrating the biodegradation process that begins when dispersants are applied to surface slicks (top) and to a deepwater release (bottom).

contradictory evidence on the biodegradation of dispersed oil in the laboratory. We propose that many of the contradictions are likely the result of study designs that are unrepresentative of the field conditions encountered in the Gulf of Mexico and most oil spills at sea, or limitations in lab-based test methods. This paper describes the important characteristics of plume dilution and dispersion stability that should be accounted for during microcosm studies of dispersed oil fate and effects. We provide evidence from field and wave basin studies to show the speed of dispersed oil dilution and the stability of effective dispersion.

2. Background

Conducting representative biodegradation studies on dispersed oil in a closed microcosm has at least two important challenges that need to be considered. The first challenge is to determine what are the low dispersed oil concentrations representative of field conditions that a researcher wants to investigate, and how to conduct tests at these concentrations. Low-viscosity oil is expected to have an average thickness of 0.1 mm on the sea surface (based on Lehr et al., 1984). Applying dispersants to a slick in 1 m waves causes mixing of dispersed oil into the top 1–1.5 m of the water column (Delvigne and Sweeney, 1988). This results in immediate dilution by a factor of 10,000 producing an average oil concentration of 100 ppm (worst case) or less.

Trudel et al. (2009) confirmed the near immediate dilution in wave tank dispersion tests, finding maximum dispersed oil concentrations between 5 and 147 ppm. Dispersion effectiveness for these tests ranged from 85% to 100%. In another wave tank study under continuous flow conditions, Li et al. (2009) found that the concentration of weathered Alaskan North Slope crude oil dispersed with Corexit 9500 declined from 12 ppm to 2 ppm within 60 min (at a depth of 0.75 m 10 m downstream from the dispersant application). Dispersed oil plumes continue to dilute with time, and are estimated to become very dilute in less than a day (French-McCay and Payne, 2001; French-McCay et al., 2007; Cormack and Nichols, 1977; McAuliffe et al., 1980). Dispersed oil plumes are expected to have average oil concentrations well below 10 ppm before biodegradation becomes significant because microbes require more than one day to colonize dispersed oil droplets (MacNaughton et al., 2003). Further, average concentrations are expected to be well below 1 ppm over the weeks to months that it takes for biodegradation to complete.

Unfortunately published biodegradation studies have been conducted at unrealistically high concentrations of dispersed oil in closed microcosms. Prior research either did not account for the rapid dilution that occurs at sea or employed methods that were not sensitive to low concentrations. Dispersed oil concentrations used in biodegradation studies range from: 1400–4500 ppm (Lindstrom and Braddock, 2002), 266 ppm (Swannell and Daniel, 1999), 250 ppm (Davies et al., 2001), 227 ppm (Yoshida et al., 2006), 100–200 ppm (Zahed et al., 2010), and 830 and 83 ppm (Venosa and Holder, 2007). Studying dispersed oil biodegradation at concentrations orders of magnitude above expected at-sea concentrations in closed systems can limit biodegradation rates and total degradation due to the depletion of nutrients. To counteract this effect, some experiments have been done using high initial concentrations of nutrients in the batch system, but this likely leads to an unrepresentative modification of the microbial community. Prince et al. (2013) found that dispersed crude oil at 2.5 ppm was rapidly and extensively biodegraded without the need for added nutrients

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