Montogue

Quiz EV103

OIL SPILLS

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PROBLEMS

Conversation Starter

Which of the following was the greatest accidental oil spill/blowout in history, in terms of volume of oil?

A) 1967 Torrey Canyon spill
B) 1979 Ixtoc I blowout
C) 1989 Exxon Valdez spill
D) 2010 Deepwater Horizon blowout

Problem 2

Evaporation is the most important weathering process after a spill. With respect to gasoline and diesel fuel, two common petroleum products, it can be said that the rate of evaporation is:

A) Logarithmic with respect to time for both products.
B) Logarithmic with respect to time for gasoline and proportional to the square root of time for diesel.
C) Proportional to the square root of time for gasoline and logarithmic with respect to time for diesel.
D) Proportional to the square root of time for both products.

Problem 3

The following statements concern various aspects of oil spill science and technology. True or false?

1.( ) Use of dispersants was the main technique in the UK's attempt to minimize damage from oil released in the 1967 Torrey Canyon spill, especially when it came to coastal waters and ecosystems. Responders resorted even to eminently ineffectual techniques such as burying drums of dispersant, pouring dispersants directly onto beach sands en masse, or dropping whole dispersant barrels over cliffs. Nonetheless, response was effective: in 1968, a year after the incident, the Marine Biological Association of the United Kingdom surveyed coastal areas affected by the spill and found that loss of wildlife attributable to pooled oil had ceased completely.

2.( ) In the wake of the 1979 Ixtoc I blowout in the Bay of Campeche, the Mexican government attempted a variety of surface-lowered and diver-deployed containment structures to stem the flow of oil, to no avail. The next viable technique was the use of dispersants deployed by aerial tankers. As the oil approached the Texas coast, however, the US chose not to deploy dispersants of its own, deeming their value limited as the oil was highly weathered by the time it reached American shores.

3.( ) One of the mechanisms of transport and fate of oil in the environment is *advection* as a result of wind, current, and wave forcing. Modeling this phenomenon requires some method to generate wind fields, and at least three approaches are available: random walk processes, Markov chain processes, and meteorological methods. Meteorological methods are the most sophisticated of the three, but also tend to be the most computationally intensive.

4.( ) In addition to wind, modeling of surface currents is likewise important in many oil spill dispersion models. It can be said that gauged rivers and tidal-driven estuaries enjoy a greater level of uncertainty in current prediction than, say, the waters in the inner continental shelf.

5.( ) *Definition 1:* The volume fraction of oil that is broken up into droplets that are sufficiently small to be stably suspended can be calculated from oil properties, wind speed, and initial oil layer thickness. This variable, named *dispersibility factor*, represents the combined result of the different dispersion processes and provides a good indicator of dispersion success.

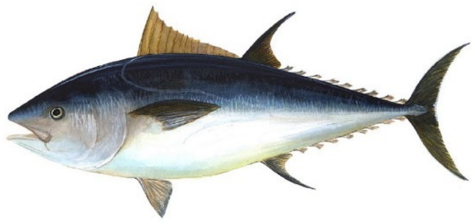
Definition 2: When discussing oil slick behavior, the most relevant aspects are thickness profile, slick length, and lifetime of the oil slick. These parameters can be summarized by a spill's *surface expression*, defined as the "time-integrated length of the slick part with a thickness > 25 μm."

Statement: A highly dispersible slick will disappear quickly and have a correspondingly high surface expression value.

6.( ) The issue of dispersant toxicity rekindled after the Deep Water Horizon blowout, in which some types of surfactants were used as part of the remediation process. In response to public pressure, the CDC moved to prohibit sales of two commercial dispersants, Corexit® 9500A and Corexit® 9527A.

7.( ) When it comes to oil spills, perhaps more important than dispersant toxicity per se is the toxicity of dispersed oil. In this regard, variable loading experiments comparing chemically enhanced water-accommodated fractions (CEWAF) to water-accommodated fractions (WAF) have shown that the higher concentration of microdroplets in the CEWAF increases the toxicity even when the oil loading is relatively mild – say, 50 mg oil/L.

8.( ) Populations of widely valued Atlantic bluefin tuna (*Thunnus thynnus*) use the Gulf of Mexico as spawning ground. Although the effects of the Deepwater Horizon blowout on the pelagic species of the Gulf of Mexico remain unclear, research by NOAA has shown that there is significant overlap between bluefin tuna spawning habitats and oiled surface waters of the GOM.



9.( ) Although it may be too early to assess the mutagenicity effects of the Deepwater Horizon blowout on the Gulf of Mexico ecosystem, initial results have been reassuring. Studies have found that phytoplankton populations in the coast of Florida and the northeastern Gulf of Mexico sampled in the initial months of the blowout exhibited little to no DNA damaging response at various depth levels, including those with the greatest concentrations of oil. Also encouraging is the fact that, as the DWH blowout oil naturally biodegrades, there should be a greater accumulation of polynuclear aromatic hydrocarbons (PAHs), which are known to be milder mutagenic compounds than most oil products.

10.( ) Part of BP's cleanup effort in the wake of the Deepwater Horizon blowout was the deployment of controlled *in situ* fires. The fires had combusted more than 10 million US gallons of oil before the EPA, on the basis of findings by its Office of Air Quality Planning and Standards, moved to ban the practice because the fires were releasing substantial amounts of dioxins into the air.

11.( ) Research performed after the Deepwater Horizon blowout underscored the fact that there are fundamental differences between sea-surface oil spills and deep-water oil spills. During sea-surface oil spills, highly water-soluble components such as BTEX aromatics and naphthalene quickly volatilize and are lost to the atmosphere within hours to days, thereby limiting the extent of aqueous dissolution into the water column. In the case of the Deepwater Horizon blowout, however, gas and oil experienced a significant residence time in the water column with no opportunity for the release of volatile species to the atmosphere. As a result, water-soluble petroleum compounds dissolved into the water column to a much greater extent than is typically observed for surface spills.

12.( ) Deepwater blowouts pose a unique challenge for reliable predictions of oil transport and fate, since live oil spewing under very high hydrostatic pressure has characteristics remarkably different from oil spilling in shallow water. It is thus important to describe in detail the complex thermodynamic processes occurring in the near-field, meters above the wellhead, and the hydrodynamic processes in the far-field, up to kilometers away. Most codes developed to this day have been developed for one or the other region, but not both. One recent example is the Texas A&M Oilspill Calculator (TAMOC), which was originally devised to model the far-field region of a deepsea spill.

13.( ) One approach to evaluate the seafloor impact of the Deepwater Horizon blowout was the use of chemical proxies. Some studies traced hopane, a relatively recalcitrant petroleum biomarker. These approaches are based on the assumptions that hopane does not degrade – a reasonable conjecture for a heavy hydrocarbon in the deep seafloor – and that all hopane present in the Gulf came from the DWH blowout – also a valid hypothesis, as the Gulf has no active hydrocarbon seeps to contribute hopane in the sediments and water column.

14.( ) In the wake of the Deepwater Horizon incident, the US government launched, as part of its Restore the Gulf initiative, the so-called 'Oil Budget Calculator,' whereby the short-term fate of the oil released in the blowout could be estimated and the methodology underlying its calculation could be disclosed. Emphasis should be placed on 'short-term,' as the Oil Budget Calculator was not created to draw conclusions about long-term environmental impact.

15.( ) Different models were developed to predict the initial droplet size distribution of an accidental subsea oil discharge. These models can be divided into two principal groups, namely (1) models that use characteristic flow parameters for up- or down-scaling of a median diameter and (2) models that calculate a complete droplet size distribution through mechanistic modeling of the flow. Scaling models are more computationally expensive than mechanistic models.

16.( ) Interest in bioremediation of contaminated beaches increased substantially since, during the response to the Exxon Valdez spill, it was verified that nutrient enrichment (application of fertilizer) accelerated the biodegradation of oil on beach surfaces. Laboratory studies on microcosms of oil-biodegrading bacteria have shown that the efficiency of these microorganisms is directly related to the dose of oil to which they are subjected; that is, the weight of the oil degraded is proportional to the weight of the oil dose.

17.( ) Studies on biodegradation of hydrocarbons by microorganisms that thrive at high pressures such as those found in the deep sea, or "piezophiles," began in the 1970s and rekindled after the Deepwater Horizon blowout. These studies indicate that increasing pressure generally lowers the rate of microbial hydrocarbon degradation. What's more, lowering the temperature amplifies any effects of pressure on the microbial metabolism and subsequently lowers the rates of hydrocarbon degradation, indicating that low temperature and high pressure act synergistically to slow the rate of hydrocarbon degradation.

18.( ) One of the earliest attempts to model oil evaporation equations for oil evaporation at sea is Blokker's 1964 paper, 'Spreading and evaporation of petroleum products on water.' Two important features of Blokker's work are the fact that his formulation used theoretical principles (i.e., the Clausius-Clapeyron equation) and modeled oil as a multi-component fluid.

19.( ) A number of findings support the claim that oil evaporation, unlike water evaporation, is not boundary-layer regulated. Supporting this claim is the fact that increasing area does not change the oil evaporation rate. What's more, the volume or mass of oil evaporating correlates with the evaporation rate, reinforcing the hypothesis of lack of boundary-layer regulation because, with water, volume (rather than area) and rate do not correlate.

20.( ) At least three models of oil-in-water emulsification have been devised: the old exponential model, which represents water uptake in emulsification as a first-order process; the ADIOS model, which is NOAA's original tool for modeling oil spills: and Merv Fingas's new model, introduced in his volume *Oil Spill Science and Technology*. Fingas conducted a systematic comparison of how accurately each model computes water content and viscosity as the emulsification process evolves and found that ADIOS afforded the greatest number of accurate predictions.

21.( ) If the length of an oil boom were doubled and the velocity of the sea current flowing perpendicular to it were increased 1.5-fold, the normal force imparted on the boom by the current would increase by more than 320%.

22.( ) The use of fire-resistant booms as a method of containment of oil slicks before *in situ* fire deployment was first attempted during the Exxon Valdez spill. These devices were also employed as part of the response to the Deepwater Horizon incident. In view of growing interest on FRBs, the ASTM instituted a standard on the subject, *F2152 – Standard Guide for In-Situ Burning of Spilled Oil: Fire-Resistant Boom*. One drawback of the standard, noted by industry and academia alike, is that it assessed the durability of FRBs on the basis of only one burning period, when in fact most devices are subjected to multiple such periods in succession over the course of a *in situ* burning procedure. What's more, some FRBs, especially older ones, were devised to be used in more than a single oil spill incident before being discarded.

23.( ) *In situ* burning has been regularly used as an oil spill countermeasure since the 1967 Torrey Canyon incident. Recent research on the practice has been mostly positive, indicating, for instance, that *in situ* burning does not release any more oil components or combustion byproducts into the water column than are present if the oil is left unburned on the water surface. Water samples from under-burning oil have been analyzed, and only low levels of hydrocarbons were found, at concentrations that would not result in fish mortality, even in a confined body of water.

24.( ) In an *in situ* burning operation, an oil spill remediation team burned a 3-mm thick slick over an area of 2000 m^2. After burning, an estimated 5000 liters of residual oil remained on the site. Accordingly, the burn efficiency, as defined in ASTM F1788-08, is greater than 92%.

25.( ) Regulation of oil pollution in Antarctica has been a pressing issue in international environmental policy in the past 30 years. The waters of Antarctica have been designated as a special area under the IMO's MARPOL 73/78 convention, and most discharges of oils from ships are banned. Regulation has moved one step further in recent years with the prohibition of carriage of heavy grade oils, be it as cargo or fuel, including bitumen, tar, and their emulsions.

26.( ) In addition to the skimmer types considered in Problem 4, there are also *submersion skimmers*. These devices use a belt or inclined plane to force the water beneath a plane. The belt or plane forces the oil downward toward a collection well where it is removed from the belt by a scraper or gravity. The oil then flows upward into the collection well, and is removed by a pump. Submersion skimmers cover larger areas at a greater pace than their counterparts, but tend to have lower tolerance to debris and cannot be used in shallow waters (say, shallower than 120 m).

▶ Problem 4

Associate the skimmer type in the left column with the corresponding definition in the right column.

Skimmer type	Definition
P. Oleophilic surface skimmers	**I.** Uses conveyors to lift oil from the water surface into a recovery area
Q. Weir skimmers	**II.** Uses a surface to which the oil can adhere to remove the oil from the water surface
R. Suction skimmers	**III.** Uses a vacuum to remove oil from the water surface
S. Elevating skimmers	**IV.** Uses gravity to drain the oil from the surface of the water into a submerged water tank

A) P.III, Q.IV, R.I, S.II
B) P.IV, Q.III, R.II, S.I
C) P.II, Q.IV, R.III, S.I
D) P.II, Q.I, R.III, S.IV

▶ Problem 5

Read the ITOPF paper *Clean-up of Oil from Shorelines* and answer: which of the following is generally considered to be the easiest type of shoreline to clean?
A) Sea defenses.
B) Coasts with cobbles, pebbles, and shingle.
C) Coasts with rocks and boulders.
D) Sand beaches.

▶ Problem 6

An ellipsoidal buoyant oil droplet of 2-mm equivalent diameter is released upon rupture of a pipeline located 200 m below the surface. At this depth, the density and viscosity of water are about 1.01 g/cm^3 and 1.55 cP, respectively. The oil density is 0.92 g/cm^3, and the water/oil interfacial tension can be taken as 30 dyn/cm. Using the equations provided in the Appendix, calculate the buoyant velocity of this oil droplet as it exits the pipeline.
A) u_T = 1 cm/s
B) u_T = 4 cm/s
C) u_T = 7 cm/s
D) u_T = 10 cm/s

APPENDIX – BUOYANT VELOCITY OF NONSPHERICAL DROPLETS/PARTICLES

Clift *et al.*'s 1978 textbook *Bubbles, Drops, and Particles* provides equations for the calculation of the buoyant velocity of different particle shapes.

Previous research has shown that the shape of fluid particles, such as gas bubbles and liquid drops, in most systems can be closely approximated as a sphere in the small size range (typically $d_e \leq 1$ mm), an ellipsoid in the intermediate size range (typically 1 mm $< d_e \leq 15$ mm), and a spherical-cap in the large size range (typically $d_e > 18$ mm), in which d_e = equivalent particle diameter. For spherical fluid particles, the viscosity of ambient fluid is the most important factor determining the terminal velocity. Moreover, the spherical fluid particles in a contaminated system behave like spherical solid particles. For ellipsoidal fluid particles, the interfacial tension and the system purity play important roles. For spherical-cap fluid particles, their terminal velocities are independent of the viscosity of the ambient fluid, interfacial tension, and system purity. Based on theoretical arguments and a substantial amount of experimental data, Clift *et al.* provided correlation formulations for contaminated fluid particles and solid particles in three size ranges, as follows:

1. *The regime of spherical shape (small size range):*

$$u_T = \frac{\mathrm{Re}\,\mu}{\rho d_e}$$

where u_T is the terminal/buoyant velocity, *Re* is the Reynolds number, μ is the viscosity of the ambient fluid, ρ is the density of the ambient fluid, and d_e is the equivalent diameter (which, for spherical particles, is simply the diameter of the spheres themselves). As the reader should notice, this equation is simply the definition of Reynolds number solved for u_T.

2. *The regime of ellipsoidal shape (intermediate size range)*:

$$u_T = \frac{\mu}{\rho d_e}\mathrm{Mo}^{-0.149}\left(J - 0.857\right)$$

where

$$J = 0.94H^{0.757} \;\; ; \;\; \left(2 < H \leq 59.3\right)$$

$$J = 3.42H^{0.441} \;\; ; \;\; (H > 59.3)$$

and

$$H = \frac{4}{3}\mathrm{Eo}\mathrm{Mo}^{-0.149}\left(\frac{\mu}{\mu_w}\right)^{-0.14}$$

where μ_w is the viscosity of water at the same temperature of μ. Parameter *Mo* is the Morton number,

$$\mathrm{Mo} = \frac{g\mu^4\Delta\rho}{\rho^2\sigma^3}$$

where g = 9.81 m/s^2, $\Delta\rho$ is the density gradient, and σ is the interfacial tension. Parameter *Eo* is the Eötvös number (also known as the Bond number),

$$\mathrm{Eo} = \frac{g\Delta\rho d_e^2}{\sigma}$$

For an elliptical size regime to apply, one must have $Mo < 10^{-3}$ and $Eo < 40$.

3. The regime of spherical cap (large size range):

$$u_T = 0.711\sqrt{\frac{gd_e\Delta\rho}{\rho}}$$

The criterion for this regime to hold is $Eo > 40$.

SOLUTIONS

P.CS ➡ *Solution*

The Deepwater Horizon blowout was the greatest accidental oil spill in history, with an estimated 189 – 231 million of US gallons released to the surrounding water. Until 2010, the greatest such event was Mexico's Ixtoc I incident, a blowout that led to the loss of over 140 million of US gallons of oil. The Torrey Canyon spill had a relatively modest oil toll, estimated to be no larger than 37 million US gallons, but had undeniable historical importance, in that it was the one of the first opportunities to test remediation techniques such as *in situ* oil burning and, together with the 1969 Santa Barbara spill in California, helped drive environmental awareness towards oil pollution. The same can be said of the Exxon Valdez incident, which remained the greatest spill in US waters for many years and led to the passage of the 1990 Oil Pollution Act. In spite of the low amount of oil spilled (10.8 million US gal), the Exxon Valdez event is notable for its environmental impact.

♦ The correct answer is **D**.

P.2 ➡ *Solution*

The evaporation of most oils follows a logarithmic curve with respect to time, but select oils, including diesel, have an evaporation rate proportional to the square root of time. One investigator (see reference below) found that the evaporation kinetics of artificial oil is related to the number of components of the oil: products consisting of more than 7 components are well-described by a logarithmic rate, while those made up of 3 to 7 components can be modeled in proportion to the square root of time.

Reference: Fingas (1997).

♦ The correct answer is **B**.

P.3 ➡ *Solution*

1. False. On the contrary, the Marine Biological Society of the UK found that dispersants magnified toxicity by making spilled oil more bioavailable than untreated oil, rendering the management decision to use dispersant "largely ineffective, uneconomic, and wasteful of effort." The statement also errs by saying that loss of marine life as a consequence of the incident has ceased; in a 2010 story on the subject, *The Guardian* observed that "forty-three years on, the crude from the Torrey Canyon is still killing wildlife on a daily basis." It is worth noting that there is a bit of a terminology issue in the discussion of the Torrey Canyon spill, as the 'dispersants' used in the response to this incident were essentially first-generation degreasers, created and applied with little or no concern for toxicological impacts upon natural systems.

2. True. Indeed, federal managers of the US government decided against using dispersants as this resource seemed unwarranted in view of the highly weathered state of the oil that approached the American coast. The 2-month time lag between the onset of the blowout and surface oiling of the Texas coast proved to be a valuable period in terms of preparedness. For instance, federal responders realized the importance of coastline mapping relative to oil sensitivity, and the resulting mapping/classification project produced the first Environmental Sensitivity Index (ESI) for coastal oiling. In the longer term, the period in question helped cement the notion that littoral communities are the most vulnerable ecological communities and that future spill mitigation planning should de-emphasize concern for pelagic-benthic communities.

3. True. Indeed, meteorological methods are generally more accurate than random walk and Markov chain models, but tend to require more computational resources.

4. False. This statement is debatable. In contrast to what is said in the statement, the fact that many rivers are gauged and controlled by locks and dam systems actually makes their current regimes more, not less, predictable than those of the high seas. In addition, for spills that occur in tidal-driven estuaries or an ungauged river system, the uncertainty in direction is relatively low, but the strength of the current may not be accurately known; hence, the overall uncertainty is low to medium. Then there is the inner continental shelf, which extends from the shoreline to where the depth increases to about 120 m. In this area, most of the oil releases result in shoreline impacts, and the uncertainty, unfortunately, is medium to high. Currents in this region are marked by a complex interplay of long-shore winds, freshwater runoff, and tides, making their hydrodynamics usually more complex to work out than those of gauged rivers and tidal-driven estuaries. The following table, from Fingas (see reference below), summarizes categories of uncertainty in prediction of currents for various bodies of water.

Surface current	Uncertainty
River - Gauged	Low
River - Ungauged	Low – Medium
Lake	Low – Medium
Tidally dominated estuary	Medium
Inner continental shelf	Medium - High
Deep ocean	High
Under ice cover	High

Reference: Fingas (2011).

5. False. In actuality, a highly dispersible slick should disappear quickly and have a *low* surface expression. In case of low dispersibility, a slick is present on the surface for a long period of time and increases in size before disappearing, resulting in a high value for surface expression. The dispersibility factor was introduced in a recent paper by Zeinstra-Helfrich (see reference 1 below) and his colleagues as part of research on the dynamics of oil slicks. A later paper (see reference 2 below) reviewed his findings over the course of the 2010s and provided an interesting discussion on the effects of individual key parameters on dispersion dynamics; the authors suggest, for instance, that oil type hardly affects the overall dispersibility and the oil slick behavior outputs of the model.

References: 1. Zeinstra-Helfrich, Koops and Murk (2017) and 2. Zeinstra-Helfrich and Murk, in Mariawski *et al.* (2020).

6. False. Regarding the safety of the dispersants in question, in 2010 the CDC released the statement that the "ingredients [of Corexit® 9500A and Corexit® 9527A] are not considered to cause chemical sensitization; the dispersants contain proven, biodegradable and low toxicity surfactants." Nonetheless, the safety of exposure to such dispersants, even when not mixed with oil, has been questioned. For instance, one group of researchers (see reference below) reported that exposure to Corexit® 9500A caused acute effects on cardiovascular function; rats that inhaled dispersant fumes exhibited dose-dependent increases in heart rate and blood pressure.

Reference: Krajnak, Kan, Waugh *et al.* (2011).

7. False. In the variable loading approach, a water-accommodated fraction (WAF, aqueous phase separated from the oil after mixing) is prepared for each concentration of oil to be tested; for example, 100 mg oil/L. When a dispersant is included, a chemically enhanced water-accommodated fraction (CEWAF) is produced at the same oil concentration. Both WAFs and CEWAFs contain microdroplets, but CEWAFs contain a higher concentration of microdroplets for the same initial loading of oil. WAF and CEWAF have the same dissolved oil concentration because at equilibrium the dissolved concentration depends on the oil-to-water ratio, not the amount of oil present in microdroplets. An analysis using available variable loading toxicity tests comparing CEWAFs to WAFs shows that the higher concentration of microdroplets in the CEWAF does not increase toxicity until the oil loading is above approximately 100 mg oil/L. Hence, variable loading experiments indicate that at or below approximately 100 mg/L, dispersed oil is no more toxic than untreated oil. Above approximately 100 mg oil/L the increase in toxicity with dispersants is due to increased generation of oIl microdroplets.

Reference: National Academies of Sciences, Engineering, and Medicine (2020).

8. True. Indeed, a 2016 paper (see reference below) has demonstrated that there is significant overlap between bluefin tuna spawning habitat (eggs, larvae, and adults) and oiled surface waters in the Gulf of Mexico. The authors caution that the effects, especially chronic ones, of having spawning grounds that overlap with those of the oiled waters are unclear, but increased larval mortality due to oil exposure is likely to reduce the resilience of this population to continued high fishing pressure.

Reference: Hazen, Carlisle, Wilson *et al.* (2016).

9. False. In actuality, the two voyages to the coast of Florida and the northwestern GOM culminated in a 2013 paper (see reference below) whereby the authors reported a DNA damaging response in phytoplankton communities sampled from stations close to the blowout. Thus, organisms in contact with these waters might experience DNA damage that could lead to mutation and heritable alterations to the community pangenome. The statement also errs by saying that PAHs are “mild” mutagenic compounds; in fact, they are some of the most aggressive oil products known to man. As well as being capable of causing DNA damage, PAHs such as tricyclic fluorene have been shown to be cardiotoxic to herring embryos.

Reference: Paul, Hollander, Coble *et al.* (2013).

10. False. The EPA never attempted to prohibit oil burning, stating, in November 2010, that concentrations of cancer-causing dioxins in 27 smoke plumes stemming from controlled Gulf fires were similar to those of wildfires.

11. True. This is an excerpt from a 2012 paper (see reference below) by an interdisciplinary team of researchers. The authors conclude that “the deep sea entrainment of water-soluble hydrocarbons has far-reaching implications for deep water oil spills. Our results demonstrate that most of the C_1-C_3 hydrocarbons and a significant fraction of water-soluble aromatic compounds were retained in the deep water column, whereas relatively insoluble petroleum components were predominantly transported to the sea surface or deposited on the seafloor, although the relative proportions are not known.”

Reference: Reddy, Arey, Seewald *et al.* (2012).

12. False. TAMOC was originally intended to model the near-field region of a deepsea spill. This is a free modeling suite that offers a robust physical, chemical, and thermodynamic treatment for hydrocarbon fluids and allows for simulations of a single bubble or droplet or an integral plume of blowout fluids. The model has been validated to available data in the literature, demonstrating accuracy on par with similar models based on the integral approach.

There are also models for investigation of the far-field region of deepsea spills; one example is Oil-Connectivity Modeling System (Oil-CMS). A recent paper (see reference below) has reported the development of a dynamic, coupled approach that combines TAMOC and oil-CMS in an integrated model, which has been validated with experimental data.

Reference: Vaz, Paris, Dissanayake *et al.*, in Murawski *et al.* (2020).

13. False. Both assumptions associated with the use of hopane as a biomarker are debatable, and may ultimately lead to erroneous estimates of the oil that reached the seafloor. For starters, in contrast to the hypothesis that all hopane stems from the DWH spill is the presence of many hydrocarbon seeps that contribute hopane to the water column and sediments, and using a single hopane compound to trace oil does not distinguish between spill and seep sources. If background hopane never degrades, 100% of the hopane ever released from the seeps would be present in the Gulf. However, there are grounds to believe that hopane *does* degrade in the Gulf environment, potentially complicating interpretations.

At any rate, as Murray *et al.* (see reference below) conclude in their paper, the material containing the hopane on the seafloor is certainly not chemically similar to fresh oil – it is the highly degraded residue of that oil, and studies show that degradation began before deposition. Assuming that the hopane in the sediments represents fresh oil substantially overestimates the amount of oil that reached the seafloor.

Reference: Murray, Boehm and Prince, in Murawski *et al.* (2020).

14. True. At the time, NOAA Administrator Jane Lubchenco said that "the Oil Budget was not created to draw conclusions about the long-term environmental impact. The estimates were designed to guide operational response decisions and provide clarity on how much oil could be captured or mitigated and how much oil was not recoverable." She added that a full understanding of the damages and impacts of the spill on the Gulf of Mexico ecosystem required "continued monitoring and research by federal and academic scientists."

15. False. Scaling models based on dimensionless numbers are relatively simple and computationally inexpensive. One such model, known as the "unified droplet size model," scales the volume median diameter, $d_{v,50}$ with a combination of Weber and Ohnesorge numbers in the explicit equation

$$\frac{d_{v,50}}{D} = r\left(1+10\mathrm{Oh}\right)^{p}\ \mathrm{We}^{q}$$

where D is a characteristic length scale, and $r = 14.05$, $p = 0.460$, $q = -0.518$ are empirically-derived coefficients for a liquid-liquid jet. The model was proposed as a way to determine both the $d_{v,50}$ of a jet and of wave entrainment at the surface. Coefficients p and q were determined on the basis of 28 wave entrainment datasets, whereas r was calculated from the $d_{v,50}$ of the Norwegian DeepSpill experiment. The model was tested against both laboratory data and field measurements by a Holocam during the DWH blowout.

Reference: Malone, Aman, Pesch *et al.*, in Murawski *et al.* (2020).

16. False. One may surmise that the weight of oil degraded would be proportional to the weight of the oil dose, since increasing quantities of oil contain increasing amounts of relatively degradable oil components. However, microcosms cultivated by Lepo *et al.* (see reference below) did not exhibit this behavior. The fact that the absolute weight loss increased no more than 2- or 2.5-fold even though the oiling rate increased 5- to 10-fold (for beach and open-water systems, respectively) suggests that limiting factors operate at the higher oil doses. For example, perhaps the biomass of applied degrading bacteria can process only a limited amount of hydrocarbons, and any excess remains undegraded. Or, given the restricted surface area of the slick on which biodegrading microbes might act, diffusion-limited availability of degradable components becomes critical: as the slick thickness increases, an increasing percentage of biodegradable components is sequestered from microbiota.

Reference: Lepo, Cripe, Kavanaugh *et al.* (2003).

17. True. The pioneering studies on piezophile degradation of hydrocarbons were published by Schwarz and his colleagues in the 1970s. Conducting an enrichment culture experiment at 4°C for elevated and atmospheric pressures, they found lower cell density and significantly lower degradation rates (tenfold decrease) at high pressure, even though the observed total amount of degraded hydrocarbon was similar between the two tested pressures. Lowering the temperature amplified any effects of pressure on the microbial metabolism and subsequently lowered the rates of hydrocarbon degradation, indicating that low temperature and high pressure act synergistically to slow the rates of hydrocarbon degradation.

Few studies of hydrocarbon degradation by piezophiles at pressures relevant to the deep sea were carried out from the 1970s until the Deepwater Horizon blowout. Since that time, accumulating evidence points to a threshold in pressure effects, whereby hydrocarbon degradation is only moderately affected at 10 – 15 MPa, and more dramatic effects are observed at extremely high pressures reaching 50 MPa. A 2016 study (quoted in the reference below) reported that hydrocarbon degradation rates diminished by approximately one-third at 15 MPa in comparison to atmospheric pressure in incubations of seawater collected from a depth of 8 m off the coast of Newfoundland, Canada. The study in question is notable in that weathered crude oil (3 ppm) and dispersant (dispersant/oil ratio of 1:15) were amended to close *in situ* concentrations expected during response efforts. The majority of *n*-alkanes were degraded within the first 7 days of the incubation, while the aromatic fraction was only partially degraded by day 35 at 15 MPa (> 100 day half-life for aromatic fraction).

Reference: Kostka, Joye, Overholt *et al.*, in Murawski *et al.* (2020).

18. False. In Blokker's approach, the ASTM distillation data distillation data and the average boiling points of successive fractions were used as a starting point to predict an overall vapor pressure. The average vapor pressure of these fractions was then calculated with the Clausius-Clapeyron equation; this signifies that Blokker's research was, at least in part, steeped on theoretical principles. The statement errs, however, by saying that Blokker modeled oil as a multi-component liquid; it actually modeled the material as a one-component liquid.

19. True. In addition to the two aspects mentioned in the statement, that oil evaporation is not boundary-layer regulated can be attributed to two other observations. First, a study of the evaporation rate of several oils with increasing wind speed shows that the evaporation rate does not change past the 0-level wind; water, known to be boundary-layer regulated, does show the predicted increase with increase with wind speed. Second, exploration of pure hydrocarbons with and without wind (turbulence) shows that compounds larger than nonane and decane are not boundary-layer regulated; oil products are generally constituted of compounds larger than these two and there is every reason to believe that such products also do not exhibit boundary-layer regulated evaporative behavior.

Reference: Fingas (2011).

20. False. In Fingas's test, the "old" exponential model predicted the correct water content only 7% of the time in the set of oils considered and the order of magnitude of the magnitude of viscosity was over two order-of-magnitudes from the actual viscosity on the day of formation. Such a result would seem to indicate that exponential water uptake models are not useful and are, in fact, misleading. As it regards to the ADIOS model, Fingas found that water content was predicted within 25% in about 49% of cases, while viscosity averages about 1.6 orders-of-magnitude in error from the actual value. A third model put to the test was the author's own approach, which was found to predict the correct water content in 100% of cases and yielded viscosities within 0.2 orders-of-magnitude of actual values. As a result, Fingas's test established his new approach as the most accurate one.

Reference: Fingas (2011).

21. True. In general, the force imparted by a sea current on an oil boom perpendicular to it is given by $F = kLHV^2$, where L is the length of the boom, H is the height of the skirt, V is the velocity of the current, and k is a constant. By doubling L and multiplying V by 1.5, the force F' due to the current would become

$$F' = k \times (2L) \times H \times (1.5V)^2 = 4.5kLHV^2$$

$$\therefore F' = 4.5F$$

That is, the normal force would be raised by 350%.

22. False. Per the ASTM-F2152 test, the standard is a minimum 5-h test involving three 1-h burning periods with two 1-h cool-down periods between the burning periods. Booms are tested in a test tank with crude oil or diesel fuel. Oil is pumped into the center of the boom at a predetermined rate and is burned. The oil is continuously fed into the boom for a 1-h burn and then is shut off, allowing the burn to die out. The boom then cools for 1 h and is tested for two additional 1-h burn/1-h cooling sessions. At the start of the third burn, oil is pumped into the boom to test for gross leakage. In short, the ASTM standard does attempt to evaluate the durability of FRBs when subjected to successive burning. It should be mentioned, nonetheless, that while older FRBs were often designed to be used in more than one *in situ* burning incident, newer devices are designed to survive several burns at one site but are then disposed of or refurbished.

23. True. Indeed, water samples from under-burning oil have been analyzed, and no organic compounds were detected. Only low levels of hydrocarbons were found, at concentrations that would not result in fish mortality, even in a confined body of water. No polycyclic aromatic hydrocarbons (PAHs) have been detected in water samples from underburning oil. Toxicity tests of the water column were also conducted, and no toxicity was noted.

24. False. The initial volume of oil to be burned was $v_{0,i}$ = 0.03 × 2000 = 60 m^3. The residual oil remaining on the site is $v_{o,f}$ = 5 m^3. Per ASTM F1788-08, the burn efficiency is given by

$$E = \frac{v_{o,i} - v_{o,f}}{v_{o,i}} = \frac{60-5}{60} = \boxed{91.7\%}$$

25. True. A IMO ban on the carriage of heavy fuel oils was approved in 2009 and entered into force in August 2011. There is now a similar push to prohibit HFOs in the Arctic: in February 2020, at the 7th session of the IMO's Pollution Prevention and Response Subcommittee, delegates agreed on a draft text of a ban on the carriage and use of HFOs in the region. Environmentalists hope that the initiative will lead to the adoption of a full-fledged rule before the end of the 2020s.

26. True. This is an excerpt from Fingas (see reference below). Submersion skimmers are an excellent choice for large spills of light oils with low viscosity, and when the slick is relatively thin. On the other hand, this equipment is sensible to debris and cannot be used in shallow waters.

Reference: Fingas (2012).

P.4 ➡ *Solution*

Oleophilic surface skimmers, sometimes called *sorbent surface skimmers*, use a surface to which oil can adhere to remove the oil from the water surface. The oleophilic surface can be in the form of a disc, drum, belt, brush, or rope, which is moved through the oil on top of the water.

Weir skimmers are a major group of skimmers that use gravity to drain the oil from the surface of the water into a submerged holding tank. A typical weir skimmer consists of a weir or dam, a holding tank, and a connection to an external or internal pump to remove the oil.

Suction or *vacuum skimmers* use a vacuum to remove oil from the water surface. Often the" skimmer" is only a small floating head connected to an external source of vacuum. Suction skimmers are generally more economical than their counterparts.

Elevating skimmers use conveyors to lift oil from the conveyor surface into a recovery area. A paddle belt or wheel or a conveyor belt with ridges is adjusted to the top of the water layer and oil is moved up the recovery device on a plate or another moving belt. The oil is usually removed from the conveyor by gravity.

Reference: Fingas (2012).

♦ The correct answer is **C**.

P.5 ➡ *Solution*

According to the ITOPF paper, sand beaches usually have good access and, because the depth of oil penetration into the beach for many oils is limited, are generally considered to be the easiest shoreline type to clean. However, oil can become buried by successive tides and low viscosity oils will penetrate into coarse-grained sands. Flushing, surf washing, or harrowing techniques may be appropriate to address buried oil.

♦ The correct answer is **D**.

P.6 ➡ *Solution*

To begin, we compute the Morton number,

$$\text{Mo} = \frac{g\mu^4\Delta\rho}{\rho^2\sigma^3} = \frac{981\times 0.0155^4\times(1.01-0.92)}{1.01\times 30^3} = 1.68\times 10^{-10}$$

and the Eötvös number,

$$\text{Eo} = \frac{g\Delta\rho d_e^2}{\sigma} = \frac{981\times(1.01-0.92)\times 0.2^2}{30} = 0.105$$

Notice that $Mo < 10^{-3}$ and $Eo < 40$, as we should have for the elliptical regime to apply. Then, we determine parameter H,

$$H = \frac{4}{3}\text{EoMo}^{-0.149}\left(\frac{\mu}{\mu_w}\right)^{-0.14}$$

$$\therefore H = \frac{4}{3}\times 0.105\times\left(1.68\times 10^{-10}\right)^{-0.149}\times\left(\frac{0.0155}{0.0155}\right)^{-0.14} = 4.0$$

Since $H \in (2, 59.3)$, the correlation to use for parameter J is

$$J = 0.94H^{0.757} = 0.94\times 4.0^{0.757} = 2.68$$

Finally, the corresponding terminal velocity is

$$u_T = \frac{\mu}{\rho d_e}\text{Mo}^{-0.149}\left(J-0.857\right)$$

$$\therefore u_T = \frac{0.0155}{1.01\times 0.2}\times\left(1.68\times 10^{-10}\right)^{-0.149}\times(2.68-0.857) = \boxed{4.06\,\text{cm/s}}$$

Per Stokes' law, the terminal velocity would have been

$$u_T = \frac{gd^2\Delta\rho}{18\mu} = \frac{981\times 0.2^2\times(1.01-0.92)}{18\times 0.0155} = 11.3\text{ cm/s}$$

Stokes' law overestimates the terminal velocity of the particle by nearly 180%. That Stokes' law provides exceedingly large terminal velocities for particles of nonspherical shape is shown in the paper by Zheng and Yapa (see reference below).

Reference: Zheng and Yapa (2000).

♦ The correct answer is **B**.

ANSWER SUMMARY

Problem CS	D
Problem 2	B
Problem 3	T/F
Problem 4	C
Problem 5	D
Problem 6	B

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