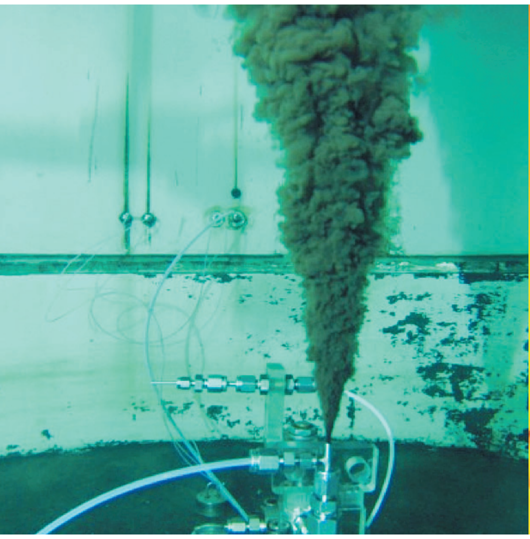
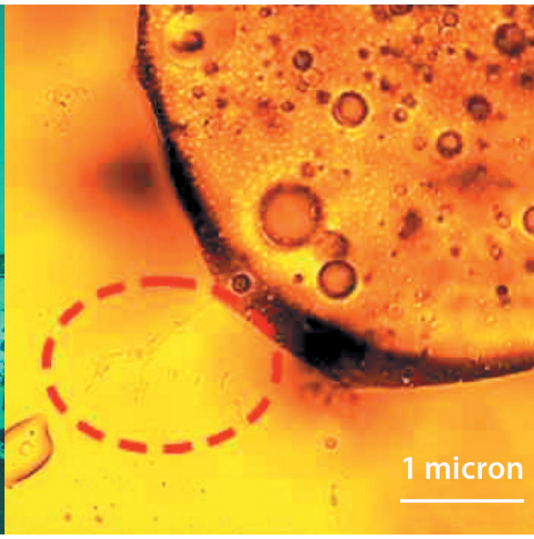
IPIECA

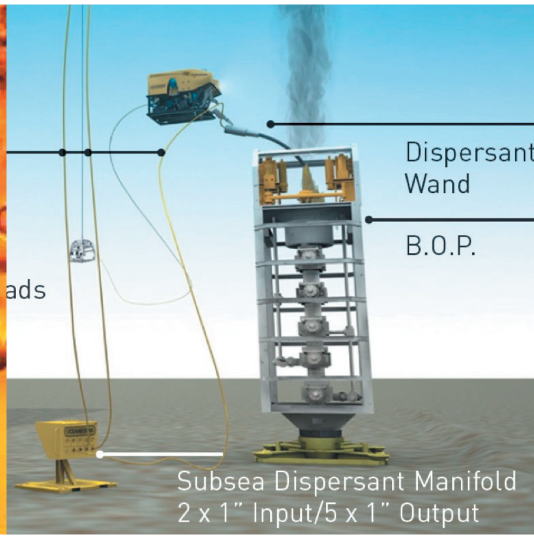
International Association of Oil & Gas Producers

Dispersants: subsea application

Good practice guidelines for incident management and emergency response personnel







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Preface

This publication is part of the IPIECA-IOGP Good Practice Guide Series which summarizes current views on good practice for a range of oil spill preparedness and response topics. The series aims to help align industry practices and activities, inform stakeholders, and serve as a communication tool to promote awareness and education.

The series updates and replaces the well-established IPIECA 'Oil Spill Report Series' published between 1990 and 2008. It covers topics that are broadly applicable both to exploration and production, as well as shipping and transportation activities.

The revisions are being undertaken by the IOGP-IPIECA Oil Spill Response Joint Industry Project (JIP). The JIP was established in 2011 to implement learning opportunities in respect of oil spill preparedness and response following the April 2010 well control incident in the Gulf of Mexico.

The original IPIECA Report Series will be progressively withdrawn upon publication of the various titles in this new Good Practice Guide Series during 2014–2015.

Note on good practice

'Good practice' in the context of the JIP is a statement of internationally-recognized guidelines, practices and procedures that will enable the oil and gas industry to deliver acceptable health, safety and environmental performance.

Good practice for a particular subject will change over time in the light of advances in technology, practical experience and scientific understanding, as well as changes in the political and social environment.

Contents

Executive summary

The reason for using dispersants, either on floating oil or by subsea application, is the same: to minimize the overall ecological and socio-economic damage, by preventing the released oil from drifting into nearshore or coastal habitats and onto the shore. Dispersant use on floating oil breaks the surface slick into many small oil droplets that are dispersed, rapidly diluted and subsequently biodegraded in the upper layer of the water column. Subsea dispersant use aims to prevent the oil released subsea from reaching the sea surface by dispersing the oil into the water close to the release. This provides a major health and safety benefit by greatly reducing the exposure of personnel responding near the release site to volatile organic compounds (VOCs). Adding dispersant to the released oil and gas subsea causes a greater proportion of the released oil to break into small oil droplets that will be dispersed, diluted and biodegraded in the water column, unlike the larger oil droplets that will float up to the sea surface. The surfactants in the dispersant greatly reduce the oil/water interfacial tension that exists between oil and water and this permits the turbulence associated with a subsea oil and gas release to convert a greater proportion of the released oil into small oil droplets.

The experience gained during the response to the release from the Macondo well associated with the Deepwater Horizon accident off the Gulf of Mexico in 2010 has shown that subsea dispersant injection (SSDI) can be an effective response technique for subsea oil and gas blowouts. More oil would have come ashore if subsea dispersant use had not been undertaken. The challenges of conducting a response to oil released 5,100 feet (1,550 m) below the sea surface with a technique that had never been used before were great. Considerable ingenuity and expertise were required to develop SSDI into a viable response during the largest oil spill response ever conducted.

As a subsea response to a subsea oil release, SSDI has many advantages over the strategy of responding to the released oil only when it reaches the sea surface. For example, SSDI:
- treats oil released at the point of release;
- requires less dispersant compared to surface oil treatment;
- reduces the exposure of responders to the health and safety hazards of VOCs and oil; and
- can be conducted continuously, day and night and in practically any weather conditions, unlike response techniques on the sea surface.

Dispersing released oil into the water column has capabilities and limitations plus potential benefits and risks that, like the consideration of any response technique, need to be addressed by conducting net environmental benefit analysis (NEBA). The addition of dispersant will cause more of the released oil to be produced as smaller oil droplets that will be dispersed within the water column. SSDI has the following benefits:
- Dispersing the released oil into the water column prevents, or reduces the amount of, oil reaching the sea surface where it could drift inshore, potentially causing serious damage to oil-sensitive coastal habitats, wildlife and socio-economic resources.
- Dispersing the oil into the water as small oil droplets permits rapid colonization by petroleum-degrading microorganisms that naturally occur in ocean environments. These microorganisms will substantially biodegrade the majority of the oil within days and weeks. The dispersant will also be biodegraded.

SSDI use also has some potential risks. Increasing the amount and concentrations of dispersed oil in the water may temporarily increase the risk to marine organisms resulting from the exposure to dispersed oil. However, high levels of dispersed oil in the water column will occur in a high-velocity, high-flow rate oil and gas blowout, even if subsea dispersants are not used. The trade-offs involved in using SSDI need to be understood by all concerned and, ideally, should be addressed during contingency planning.

The logistics of conducting SSDI require considerable specialist equipment, trained personnel and support. Multiple ROVs will be required with dedicated offshore supply vessels and a logistical supply chain for dispersant stocks.

Subsea dispersant use requires subsea monitoring to assess whether it is being effective and where the subsea plumes of oil would be transported by the prevailing deep water currents. To address concerns about the possibility of toxic effects on marine organisms caused by the dispersed oil, it may be necessary to conduct additional water monitoring and water-sampling surveys with subsequent chemical analysis to ensure that oil concentrations and oil extent do not exceed the NEBA assumptions for the event. This was done during the Macondo accident. Although research is still under way, available data indicate that concerns about substantial toxicity to marine organisms, oxygen depletion in the water due to biodegradation and the persistence of dispersant in the water column were demonstrated to be unfounded, and subsea dispersant use proved to be a very effective spill response tool.

The role of dispersant use in oil spill response

Surface dispersant application is one of several possible at-sea response techniques. Dispersant application can be a useful way of minimizing safety risks at a release site and reducing an incident's overall damage by removing oil from the sea surface by transferring it into the water column, preventing it from reaching sensitive coastal habitats and shorelines. Dispersion of oil enhances the natural biodegradation processes that break down oil. Dispersant use does not cause the oil to sink to the seabed.

Like all techniques in the response toolkit, dispersant use has some limitations, but also has capabilities that make it particularly useful in responding to larger oil spills at sea. This IPIECA-IOGP Good Practice Guide (GPG) is concerned with the use of dispersant to address subsea oil releases; a companion GPG entitled *Dispersants: surface application* (IPIECA-IOGP, 2015) describes the use of dispersant in responding to floating oil.

During the release of oil and gas from the Macondo well associated with the Macondo accident in 2010, subsea dispersant injection (SSDI) was used for the first time to treat the oil with dispersant directly at the source of a large-scale blowout event. This was a novel way to apply dispersants and is described in this GPG.

The reason for using SSDI at a subsea oil release is the same as for any dispersant use: to prevent, or minimize the amount of, the oil from subsequently drifting into shallow coastal waters or onto the shore, where it could cause serious damage to habitats and species present and disrupt socio-economic activities. Any successful dispersant use involves transferring more oil into the water column than would otherwise be the case, i.e.:

- dispersant use on floating oil disperses oil from the sea surface into the upper layer of the water column where it can be more quickly diluted and biodegraded; and
- SSDI increases the proportion of oil that is dispersed, diluted and biodegraded in the water column, compared to that which reaches the sea surface and could drift ashore.

Subsea dispersant use is a response to a subsea oil release. It is therefore convenient to first consider how oil released subsea can behave.

Behaviour of oil released subsea

Oil can be released subsea in a number of ways, including:

- subsea blowouts, for example the Macondo accident in 2010 and the Ixtoc 1 incident in 1979 (Farringdon, 1980);
- seabed fissure, for example the Frade Field seep in Brazil's Campos Basin in 2012 (Chevron, 2012) and other widespread natural seeps throughout the world's oceans;
- subsea flowline (the pipes connecting subsea wells to the offshore installation) leaks or ruptures;
- subsea oil export pipeline leaks or ruptures; and
- releases from fuel or cargo tanks of sunken vessels.

The behaviour of the oil released will be determined by the:

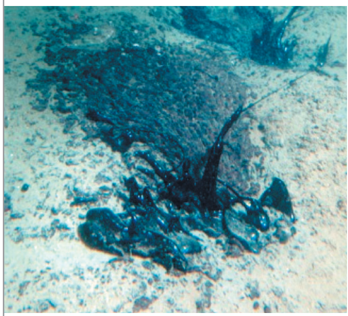
- characteristics of the release, i.e. the oil and gas pressures and flow rates, gas-to-oil ratio (GOR), and the size and geometry of the release.
- water conditions into which the oil is released, i.e the water depth (therefore hydrostatic pressure), temperature, currents and oceanographic conditions at the release site; and
- the properties of the released oil; in most cases, the oil released at a subsea blowout will be at high temperature, but will be rapidly chilled when it comes into contact with the cold seawater in deep water. The density, viscosity and pour point of the oil—and how these oil properties change with time—will influence the behaviour of the released oil.

The principle characteristic of oil released subsea that affects its subsequent behaviour is the size, or size distribution, of the oil droplets that are produced:

- High-pressure, high-velocity oil releases, particularly with a gas phase present, will produce small oil droplets and gas bubbles in the water. The subsequent behaviour of the oil and gas will depend on the water depth.
- Low-pressure, slow releases without gas present will allow the oil to enter the water as large globules.

The speed that an oil droplet will rise through static seawater (salinity of 32 ‰ i.e. density of 1.024 g/ml) is dependent on the oil density and droplet size.

Below: natural low-pressure seep off the Californian coast



Source: USGS

Table 1 *Oil droplet diameter and rise times through static seawater*

Oil droplet diameter (oil density = 0.85)	Time to rise 1 metre	Time to rise 1,500 metres
4 mm (4,000 µm)	3 to 5 sec	1 to 2 hours
3 mm (3,000 µm)	5 to 10 sec	2 to 4 hours
2 mm (2,000 µm)	About 15 sec	About 6 hours
1 mm (1,000 µm)	About 20 sec	About 8 hours
0.4 mm (400 µm)	85 sec	35 hours
0.2 mm (200 µm)	5 min	5 days
0.1 mm (100 µm)	19 min	Biodegraded before rising this distance
0.05 mm (50 µm)	1.3 hours	Biodegraded before rising this distance
0.02 mm (20 µm)	8 hours	Biodegraded before rising this distance
0.01mm (10 µm)	31 hours	Biodegraded before rising this distance

Note: oil droplets larger than 0.4 mm in diameter deform from a spherical shape during a rapid ascent through water, and time estimates become less accurate.

Almost all crude oils are less dense than seawater so will tend to float, but large oil droplets float towards the sea surface much more rapidly than smaller oil droplets (Table 1). Smaller oil droplets from an oil release in deep water will be biodegraded before they could reach the sea surface, as indicated. Biodegradation will also result in all droplets slowing their rise velocity as they reduce in size through this process; this factor is not included in these estimated times.

Subsea blowout

Theoretical studies of what could happen to oil released at subsea blowouts in deep water have been made, but only one large-scale field experiment had been conducted to either confirm or modify the theoretical considerations. This was the DeepSpill experiment conducted in the Norwegian Sea in 2000 in 844 m (2,770 feet) of water roughly 125 km off the coast of central Norway (Johansen *et al.*, 2001 and Johansen *et al.*, 2003). Four controlled discharges of oil and gas were made, amounting to a total of 120 m^3 (755 bbl) of oil and 10,000 standard m^3 of natural gas. This experiment only studied untreated oil and no dispersant was used. Extensive observations were made of wind, currents, water density, surface and subsurface oil concentrations, and chemical and biological samples in the water column. The oil started reaching the surface about an hour after the release began and within a few hundred metres of the release site. Oil continued to surface for several hours after the release stopped. No gas hydrates were formed. No gas bubbles reached the sea surface, indicating that the gas had dissolved into the water. The echo sounders onboard the research vessels were able to track the oil/gas plume as it rose through the water column.

The conclusions of the DeepSpill field experiment, two other follow-up laboratory studies and three model comparisons were summarized in a 2005 report entitled *Review of Deep Oil Spill Modeling Activity Supported by the DeepSpill JIP and Offshore Operators Committee* (Adams and Socolofsky, 2005). This report indicated that:

- High-velocity jets of oil and methane gas released subsea in deep water will be broken up by the intense turbulence of the release conditions into small oil droplets and gas bubbles. This is often referred to as 'mechanically' dispersed oil to distinguish it from oil dispersed by dispersant use.
- The plume of small oil droplets, gas bubbles and entrained water will initially rise rapidly in the form of a buoyant plume, with the gas providing the dominant source of lift and buoyancy. Close to the point of release, this plume will behave like a single-phase plume.
- As the plume of oil droplets and gas bubbles rise through the deep water (more than 500 m in depth), the methane gas will dissolve into the sea (due to its solubility at high pressure); this reduces the buoyancy of the plume, thereby slowing its ascent through the water.
- Stratification in the water column and currents will then separate the oil droplets and gas bubbles (if not already dissolved) from the plume of entrained water.
- The larger oil droplets will then continue to rise slowly to the sea surface under their own buoyancy which is a function of size, while the smaller oil droplets will be carried horizontally and remain suspended in the water column as they dilute and biodegrade.

These processes are represented schematically in Figure 1.

Not all of the oil that is released from the subsea blowout in deep water will reach the sea surface. The turbulence caused by the high-velocity, high-flow rate jet of oil and gas release will convert a

Figure 1 *Schematic representation of a subsea release (not to scale)*

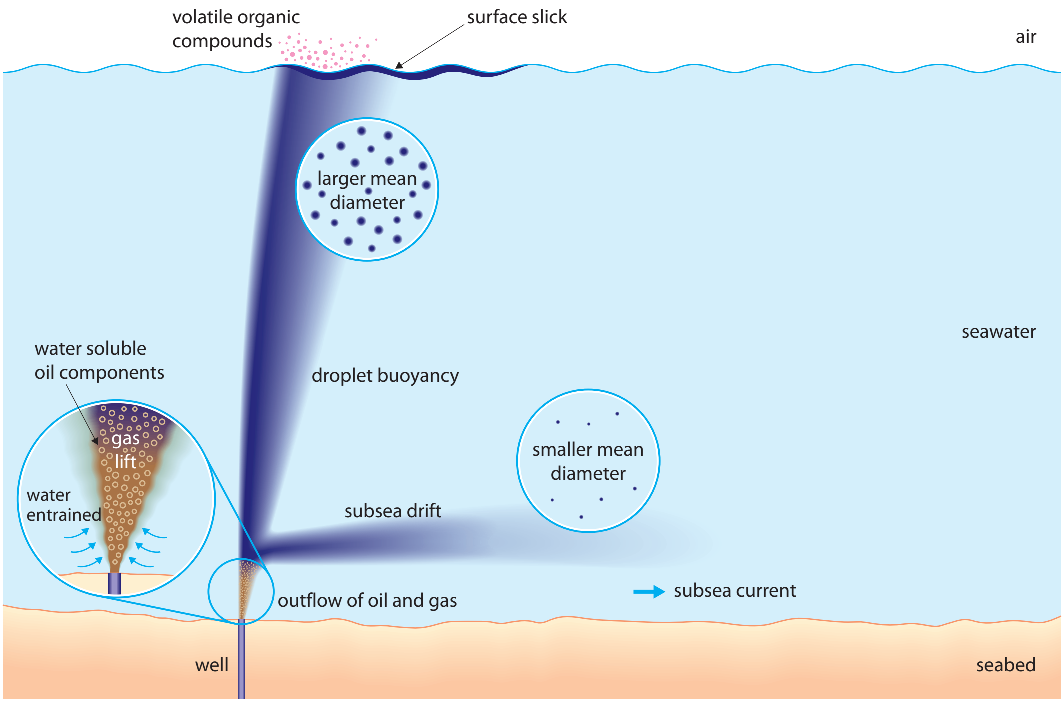
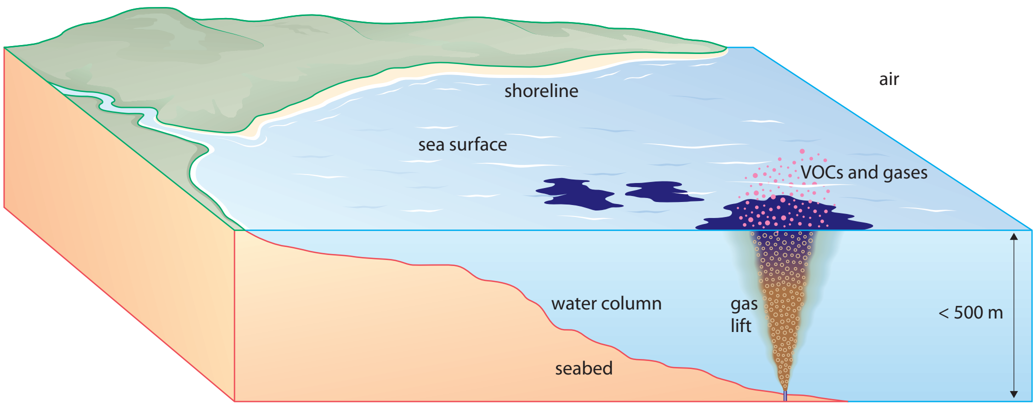


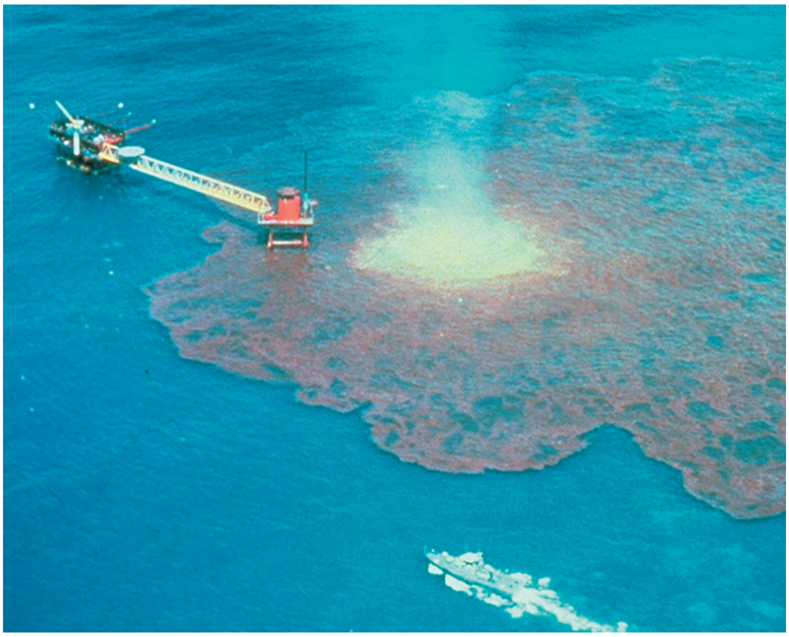
Figure 1 is representative of the processes that occurred at the DeepSpill experiments and at the Macondo accident in 2010 (not to scale). The plume of larger oil droplets that rise to the sea surface and the plume of smaller dispersed oil droplets that are stratified horizontally and remain in the water column are visualized in colour in the diagram purely as an aid to the explanation. Dispersed oil plumes in the water column are not visible; sensitive instrumentation is required to detect them as the dispersed oil is diluted into the water column.

proportion of the oil into droplets that are small enough to be dispersed into the water column by the prevailing currents in the stratified water column. The proportion of oil that is dispersed by the turbulence of the release will depend on the precise circumstances of the release.

At oil and gas releases from subsea blowouts in water of less than 500 metres depth (see Figure 2), the gas is not likely to totally dissolve into the water. At oil and gas blowouts in more shallow water, the buoyant plume of gas bubbles is likely to rapidly arrive at the sea surface where the gas

Figure 2 *Schematic representation of a shallow water oil and gas blowout with the majority of the released gas reaching the surface (not to scale)*




Source: NOAA

The Ixtoc I blowout in Mexico, 1979, in water less than 100 m deep

will escape into the air (with the possibility of a fire/explosion hazard), and the oil will initially spread out radially over the sea surface. The surfaced oil will then be subjected to typical weathering processes including wind-driven and surface current-driven movement, evaporation, fragmentation and possible emulsification.

Other subsea releases

The circumstances of each subsea oil release need to be considered when assessing the probable outcome. Several computer models are available to forecast the likely oil behaviour.

- A pinhole leak in a subsea flowline carrying oil and gas will result in a fine jet of small oil droplets entering the water, but the volume of the released oil will be low. A rupture of such a flowline will result in an initially rapid discharge of oil and gas, but this will cease as the flowline is isolated and the line depressurizes.
- The rupture of a subsea oil export pipeline after the gas has been removed by processing offshore will cause an initially rapid displacement of the oil into the water, followed by a much slower release of oil as the ruptured pipeline fills with water. The oil is more likely to rise as large globules.
- Releases from sunken vessels would depend on the circumstances but are likely to be slow and result in large globules of fuel or cargo oil.

The use of SSDI for the above release scenarios is unlikely to be either feasible or appropriate.

Potential consequences of oil released subsea

As described in the previous section, oil released from a subsea blowout is likely to enter the water column in the form of oil droplets of a variety of sizes. Relatively large oil droplets will rise relatively rapidly through the water column, but smaller oil droplets will rise much more slowly and some will not reach the water surface, being dispersed, rapidly diluted and subsequently biodegraded in the water column.

Potential for effects in the water column

There is a potential risk to marine organisms in the water column that are exposed to dispersed oil droplets and any compounds that may be dissolved and released from the oil droplets. Whether these exposures cause harm to the organisms depends on multiple factors, including the chemical composition of the oil, the concentration of droplets and dissolved compounds to which the organism may be exposed, the duration of exposure and the sensitivity of the species. Adult fish can detect oil compounds in the water and have the ability to move away from areas with higher oil concentrations in the vicinity of a release, while plankton drift with the currents and cannot avoid exposure to the compounds from the oil.

Adult fish (far left) can detect oil compounds in the water and are likely to move away to avoid the contaminated area; while plankton (near left) drift with the currents and are unable to avoid exposure to the oil.

Potential for effects on the sea surface

Released oil rising to the sea surface will spread out and form oil slicks in the vicinity of the release. Some portions of the more volatile components of the oil (benzene, toluene, ethylbenzene and xylenes (BTEX), often collectively referred to as volatile organic compounds or VOCs), can dissolve in the water column; the amount of dissolution will depend on the depth at which the oil was released, as well as on other factors (such as the use of SSDI). VOCs that reach the sea surface will evaporate from the oil and into the air. Whether this may present health and safety concerns for responders should be considered in a spill response plan.

Floating oil will drift under the influence of the prevailing wind and currents. Oil drifting on the sea surface may pose a risk to wildlife such as seabirds that land on, or dive through, the oil, and turtles and marine mammals that break through the surface oil to breathe. Whether these exposures result in harm will depend on multiple factors, including the chemical composition and concentration of the oil, the duration and method of exposure and the sensitivity of the species. Potential effects may include irritation, hypothermia, and sublethal or lethal toxic effects.

The most oil-sensitive ecological resources are most often those in coastal waters or on shorelines. These nearshore areas are also the breeding grounds for many species of fish and invertebrates, as well as nesting areas for birds. Oil drifting towards the shore could come into contact with these ecological resources and also disrupt important coastal socio-economic activities.

Oil spilled at sea has the potential for negative effects on a variety of ecological and socio-economic resources, depending on the environmental compartment. These are summarized in Figure 3 (below) and Table 2 (page 13). Further information is provided in the IPIECA-IOGP Good Practice Guides on marine ecology (IPIECA-IOGP, 2015a) and shorelines (IPIECA-IOGP, 2015b).

Figure 3 *Schematic representation of the environmental compartments in relation to a subsea release in deeper waters*

Note: dispersed oil plumes in the water column are not visible; sensitive instrumentation is required to detect them as the dispersed oil is diluted into the water column. The potential emulsification of floating oil is indicated by the change to a brown/orange colour.

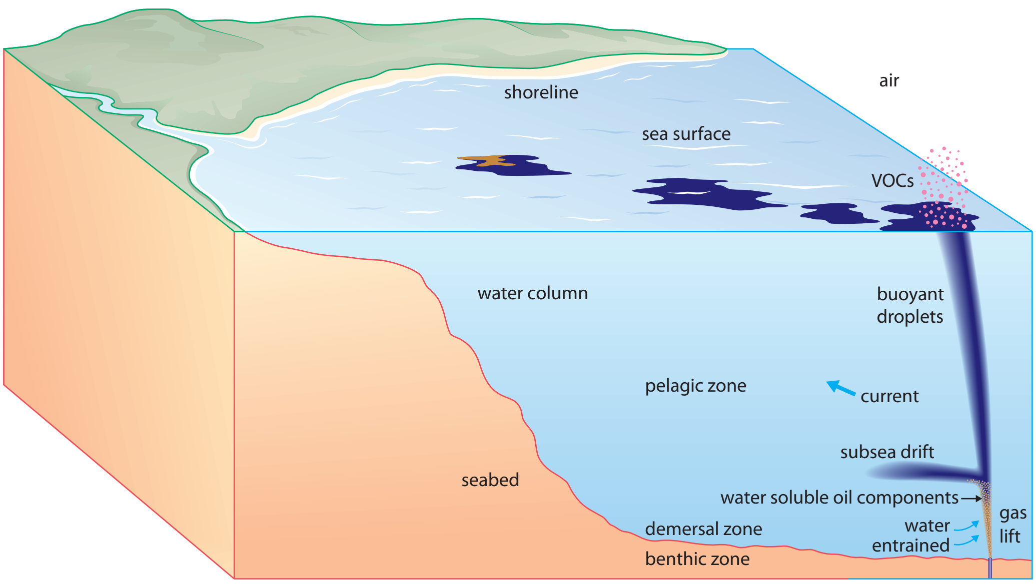


Table 2 *Potential effects of oil on environmental compartments*

Environmental compartment			Potential effects of oil
Seabed benthic zone			Subsea discharges of oil will either float to the surface or form part of underwater plumes that dilute and biodegrade as they move from the source of the release. The majority of the oil present as small oil droplets in the water will be biodegraded within days or weeks. The oil compounds that are slower to biodegrade are similar to those in bitumen or asphalt, and are largely biologically inert and of low toxicity. The proportion of a crude oil that is present as these compounds is typically small and this residue will be present at very low concentrations of a few ppb (parts per billion) in water as the remnants of the biodegraded dispersed oil droplets. Some of these compounds may eventually be deposited on the seabed at extremely low concentrations over a large area, posing no risk to marine life.
Water column	Near seabed demersal zone		
	Deep water pelagic		Deep ocean waters contain a relatively low density of biological life compared to the water closer to the surface. However, animals living in deep open waters may be exposed to dispersed oil plumes, and exposure may increase with dispersant usage. Potentially harmful concentrations would likely be limited to the area within a few kilometres of the release site. Free swimming fish would be likely to detect and avoid areas of relatively high oil concentration.
	Nearshore		Shallow nearshore habitats such as coral reefs may be susceptible to damage by exposure to naturally or chemically enhanced dispersed oil. Reefs more than 10 metres deep are at low risk of harmful concentration of oil due to dilution potential.
Sea surface			Spilled oil floating on the sea surface poses risks to ecological resources such as seabirds, marine mammals and fish eggs/larvae present in the uppermost water column. The plumage of seabirds that land in, or dive through, the oil will be contaminated with oil. This will reduce the insulation properties of the plumage and can lead to death by hypothermia. Floating oil may persist until it is removed by oil spill responders or weathering processes.
Nearshore sediments			Naturally dispersed oil droplets that become incorporated into nearshore sediments will continue to be subject to weathering processes such as biodegradation. However, this oil may result in longer-term exposure to the organisms that inhabit the mud and sediment.
Shoreline			Spilled oil on the sea surface can drift into shallow water and may contaminate coastal habitats including particularly oil-sensitive mudflats and wetlands. Photos or video of distressed and dying seabirds covered in oil that washed ashore are stark images of the effects of past oil spills. Spilled oil may smother shoreline organisms. Oil in shoreline substrates will continue to be subject to weathering and biodegradation processes, but at a much slower rate than occurs with dispersed oil, and may be a source of longer-term exposure for shoreline organisms. Whether these exposures will have toxic effects is dependent on a variety of factors, including the chemical composition and concentration of the oil.
Socio-economic			Oil on the sea surface can foul fishing vessels and their equipment; governments may prohibit fishing in oiled waters, potentially affecting the companies and people who fish in that area. Water recreation activities can be either prevented or disrupted by oil on the sea surface. Spilled oil drifting onto a tourist beach could also result in beach closures and have an impact on the income of those whose livelihoods depend on tourism. Shoreline economic features such as seawater intakes or ports and harbours can also be disrupted by oil drifting ashore.

Response to subsea oil releases

Deployment of any technique in the oil spill response toolkit should aim to minimize the damage that could be caused by spilled oil if no response were undertaken. The primary ecological threat from floating oil is considered to be when oil enters the nearshore or comes ashore. Shoreline environments typically have higher biological abundance and are often more sensitive to oil than open water environments. Keeping oil from drifting inshore is often key to minimizing the environmental impacts of an offshore oil spill.

The response to subsea oil releases could be undertaken:

- **at the source:** source control aims to stop the release or prevent the released oil from reaching the sea surface, either by subsea containment (with transfer to a surface recovery vessel) or by enhancing dispersion of the oil; and/or
- **on the sea surface:** after the oil released subsea has risen to the sea surface, where the primary aim of the response is to prevent the oil from drifting ashore.

An advantage of conducting a subsea response is that operations can be undertaken at a known and fixed location, as compared to the oil floating on the sea surface which in some cases may appear as fragmented patches scattered over a large area of the sea surface and drifting under the influence of the prevailing wind and currents.

Subsea response

Source control

Stopping the oil from being released subsea will always be the primary focus for response at such incidents. In the case of leaks or ruptures of subsea flowlines or oil export pipelines, engineering controls may be in place that can rapidly shut down the pipeline or isolate the section that has been damaged. Stopping the flow from a subsea blowout where the blowout preventer (BOP) has failed is a much greater challenge. Drilling relief wells to intercept and divert the oil flow far below the seabed well head will eventually be effective, but can take weeks to complete. Rapidly-deployable capping stacks to seal off an oil well in the unlikely event of the failure of all safety barriers, including the BOP, have been developed in recent years. The Marine Well Containment Company (MWCC), the Subsea Well Intervention Service (SWIS) and other providers now have capping stacks that can be rapidly deployed to all oil exploration, development and production regions.

Subsea containment and recovery

Recovery of some or all of the oil from the subsea release may be possible by the deployment of various subsea oil collection and recovery devices. After the Macondo well release and other incidents, the oil industry's Subsea Well Response Project (SWRP), MWCC and Helix Well Containment Group have developed toolkits of containment equipment and subsea well containment guidelines. International subsea containment and recovery equipment and services are now available through SWIS and other providers. The containment concept relies on existing drilling rigs and commercially-available well-testing equipment to capture fluids from an incident well and flow them to the surface for processing and disposal. If well shut-in is not possible, the subsea well containment toolkit can be deployed to enable the flow of well hydrocarbons from the capping stack to an offloading tanker.

Subsea dispersant injection

Subsea dispersant injection (SSDI) can prevent, or reduce the amount of, oil reaching the sea surface and subsequently drifting ashore. Further information is provided in subsequent sections.

Response to floating oil

Response techniques available for subsea oil releases that reach the sea surface and for releases that originate on the water's surface are identical and well established, and include:

- **mechanical containment** of spilled oil with floating barriers (booms) and **collection** using recovery devices (skimmers); recovered oil is collected in a vessel's tanks or other floating storage facility for subsequent offloading and either processing or disposal;
- **controlled (or in-situ) burning:** oil is corralled in fire-resistant booms and ignited. In-situ burning removes the floating oil by converting it into airborne combustion products (primarily as carbon dioxide and water vapour with small amounts of soot and other gases) which are rapidly diluted in the atmosphere; and
- **dispersant use:** disperses the floating oil into the upper layer of the water column as small oil droplets, which are rapidly diluted to low concentrations in the water. The majority of the oil in these droplets will subsequently be biodegraded by hydrocarbon-degrading organisms. The ultimate fate of most of the oil is to be biologically converted to carbon dioxide and water.

Each of these response techniques has capabilities and limitations that make it more or less suitable for a response in specific conditions (see Table 3).

Table 3 *Comparison of response techniques (note that surface operations are largely constrained to daylight hours)*

Factor	Containment and recovery	Controlled (in-situ) burning	Dispersant use
Rate at which spilled oil can be encountered	Low	Low	High
Spilled oil removal rate	Low	High during burn	High
Limiting prevailing conditions	Possible up to wind speed of 20 knots and wave height of 1 to 1.8 metres	Possible up to wind speed of 10 knots and wave height of 0.6 to 1 metre	Possible up to wind speed of 35 knots and wave height of 5 metres
Oil type and properties	Need to match skimmer to changing viscosity	Oils that have lost lighter fractions and emulsified oils are difficult to ignite	High-viscosity oil may be challenging to disperse, plus possible pour point limitation

Dispersants and how they work

Composition of modern dispersants

Dispersants are blends of surfactant in solvents.

Surfactants

Surfactants are surface active substances with numerous domestic and industrial applications. Surfactant molecules have two linked parts: a hydrophilic ('water-loving') part connected to an oleophilic ('oil-loving') part. Surfactants can be classified into various groupings such as anionic (with a negatively charged hydrophilic part), non-ionic (with a non-charged hydrophilic part), cationic (with a positively charged hydrophilic part) or amphoteric (combining cationic and anionic in the same molecule). There are thousands of commercially-available surfactants. They are the active ingredients in many household products such as soaps, shampoos, food additives, cosmetics, cleaners and detergents. No surfactants are manufactured specifically for use in oil spill dispersants.

The function of surfactants in most applications is to the lower the interfacial tension (IFT) between two fluids. Surfactants used in common cleaners reduce the surface tension of the water (also called the air/water IFT) so the water can more effectively wet the fibres and surfaces to be cleaned. They loosen and encapsulate the dirt and this ensures that the dirt will not be re-deposited on the surfaces.

Surfactants used in dispersants reduce the oil/water IFT by becoming orientated at the oil/water interface. The oleophilic part of the surfactant molecule is in the oil and the hydrophilic part is in the water. The surfactant forms a 'bridge' between the oil and water. The interface between the oil and the water is thus occupied by the surfactants and this reduces the oil/water IFT by around 30 times if a modern, well-formulated dispersant is used. This reduction in the oil/water IFT enables waves or other energy sources to break the oil into tiny droplets and disperse them into the water. Additionally, the droplets become surrounded by the surfactant thus preventing the droplets from sticking to each other to form bigger droplets that would be more likely to resurface.

Solvents

Solvents used in modern dispersants include glycol ethers, hydrocarbon and water (Fiocco *et al.*, 1995). A solvent is necessary to produce a liquid dispersant that can be easily sprayed. Many surfactants are high viscosity liquids and/or solids, so they need to be blended into a solvent to produce a dispersant of relatively low viscosity. The solvent also allows the dispersant to be positively buoyant and helps the surfactant to penetrate into the spilled oil.

The precise blends/formulations of most dispersants are proprietary information. However, the formulation details may be shared, in confidence, to national regulators as part of the dispersant listing or approval process. Most dispersants consist of a blend of two or three non-ionic surfactants (Brochu *et al.*, 1986) and sometimes include an anionic surfactant (Brandvik and Daling, 1998). All of the surfactants used in dispersants are also used in many other household products.

The ingredients list of the widely stockpiled COREXIT® dispersants has been published by their manufacturer, as shown in Table 4.

Table 4 *Composition of COREXIT® 9527 and 9500 dispersants*

Chemical abstracts service number	Name	Generic name	Examples of common, day-to-day use
1338-43-8	Sorbitan, mono-(9Z)-9-octadecenoate	Span	Skin cream, body shampoo, emulsifier in juice
9005-65-6	Sorbitan, mono-(9Z)-9-octadecenoate, poly(oxy-1, 2-ethanediyl) derivs.	Tween	Baby bath, mouth wash, face lotion, emulsifier in food
9005-70-3	Sorbitan, tri-(9Z)-9-octadecenoate, poly(oxy-1, 2-ethanediyl) derivs	Tween	Body/face lotion, tanning lotions
577-11-7	Butanedioic acid, 2-sulpho-, 1,4-bis(2-ethylhexyl) ester, sodium salt (1:1) [contains 2-Propanediol]	DOSS	Wetting agent in cosmetic products, gelatin, beverages
29911-28-2	Propanol, 1-(2-butoxy-1-methylethoxy)	Glycol ether solvent	Household cleaning products
64742-47-8	Distillates (petroleum), hydrotreated light	Hydrocarbon solvent	Air freshener, cleaner
111-76-2	Ethanol, 2-butoxy [NOT included in the composition of COREXIT® 9500]	Glycol ether solvent	Cleaners

Some of the most widely used non-ionic surfactants have a hydrophilic part based on sorbitan (derived from sorbitol—a sugar) and an oleophilic part based on a fatty acid (a vegetable oil) (Al-Sabagh *et al.*, 2007). These non-ionic surfactants have the generic trade name of 'Spans'. Other non-ionic surfactants used are ethoxylated sorbitan esters, and these are generically known as 'Tweens'. Spans and Tweens have applications in the pharmaceutical, cosmetic, food and agrochemical industries. The anionic surfactant used in many modern dispersants is sodium diiso-octyl sulphosuccinate (sometimes referred to as DOSS). This surfactant is also used in many household products, such as cleaners of various types. Its water retention properties can be useful and it is included in treatments for certain human health conditions.

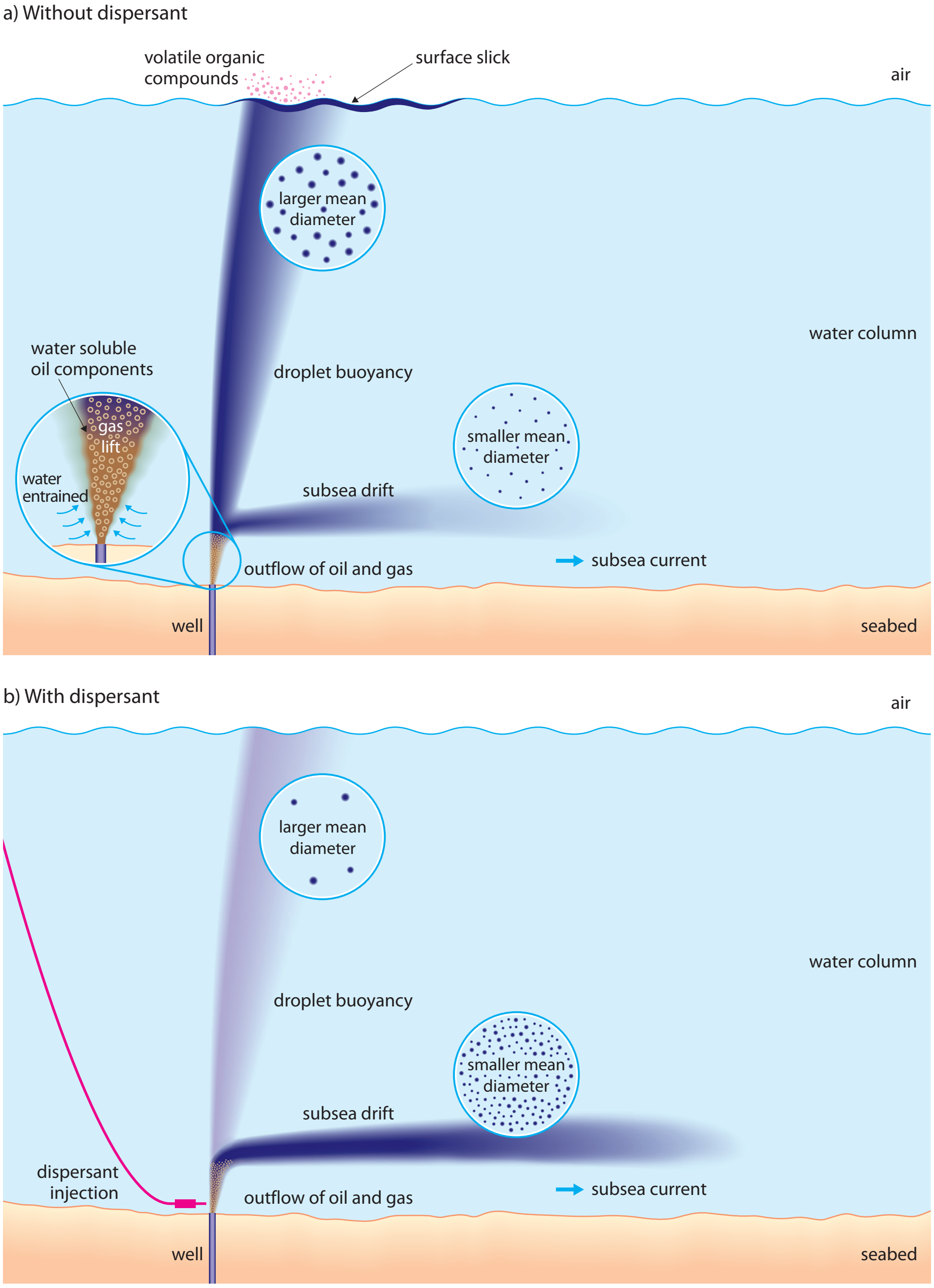
Mechanism of dispersant action subsea

Dispersants greatly reduce the IFT that exists between oil and water when they are added to the oil. The surfactants in dispersants 'bridge' the differences between the inherent properties of oil and water. This allows the prevailing mixing energy to produce a much higher proportion of smaller oil droplets when dispersant is added, than when it is not. When dispersant is used on floating oil the prevailing mixing energy is from wave action (IPIECA-IOGP, 2015).

When dispersant is used subsea on a blowout, the prevailing mixing energy is the turbulence produced at the point of the oil and gas release. If the oil release is a high-pressure, high-velocity event, particularly with a gas phase present, it will produce a plume of oil droplets and gas bubbles in the water. Even without dispersant application, a proportion of the released oil will be in the form of oil droplets that are too small to float to the sea surface and, in some circumstances, this portion may already be substantial.

Note: dispersed oil plumes in the water column are not visible; sensitive instrumentation is required to detect them as the dispersed oil is diluted into the water column.

Figure 4 *Schematic representation of subsea release with, and without, the addition of dispersant (not to scale)*



Dispersant that is added subsea to the oil release will cause a large reduction in the IFT, and the turbulence of the release conditions will convert a greater proportion of the oil into droplets that are small enough to be dispersed in the water column by the prevailing oceanographic conditions.

Benefits and potential risks of subsea dispersant use

The reason for using SSDI at a subsea blowout is the same as for any dispersant use: to prevent, or minimize, the amount of oil that may subsequently drift into shallow coastal waters or onto the shore, where it could cause damage to inshore habitats with relatively high biodiversity and abundance, as well as disruption to socio-economic activities. SSDI also provides a major health and safety benefit by greatly reducing the exposure of personnel responding near the release site to VOCs.

Benefits of dispersant use

The benefits of dispersant use include the following:

- It minimizes potential damages and disruption to sensitive wildlife, coastal habitats and socio-economic features that could occur if dispersant were not used and the oil either remained on the surface or reached coastal waters and shorelines.
- It increases the availability of oil for biodegradation and thereby speeds up its natural break-down and assimilation into the environment.
- It can reduce potentially harmful vapours in the vicinity of a spill and provide a safety benefit to responders undertaking vessel-based activities in the immediate area, as well as minimizing the exposure of responders and local communities to oil in the wider context. The VOCs present in dispersed oil will dissolve into the sea instead of evaporating into the air.
- The use of SSDI reduces the amount of dispersant required compared to surface application and can be operated day and night.
- It reduces the amount of oil that reaches the shore, which may reduce the extent and duration of shoreline clean-up operations.
- It avoids the creation of large volumes of waste material often associated with shoreline clean-up operations; such waste can present serious environmental challenges during its handling, storage and disposal.

In summary, an efficient subsea dispersant delivery system could potentially treat the vast majority of oil escaping from a single release point before it reaches the surface and forms a widely spread floating slick. Oil dispersed at depth as small droplets will not rise to the upper water column where there is generally a greater abundance of marine life.

Once deployed, SSDI is able to treat the oil released from a point-source with a high encounter rate, can continue day and night and is generally not limited by weather. However, when SSDI is applied from a ship on the surface, the ship may need to stop application and return to harbour if extreme weather conditions arise, such as a hurricane or typhoon. Unmanned or remotely operated SSDI systems may be able to continue operating in such conditions.

Potential risks of subsea dispersant use

Any successful dispersant use (on the sea surface or subsea) involves transferring more of the oil into the water column than would otherwise be the case. The potential risk of dispersant use is the increased exposure of marine organisms in the deep sea water column to dispersed oil droplets and water-soluble oil compounds released from these oil droplets.

At many subsea oil and gas blowouts, a substantial proportion of the released oil volume may already have been produced in the form of a plume of very small oil droplets in the water by the turbulence created by the high-velocity flow of oil and gas into the water. Adding dispersant to the oil being released will increase the proportion of oil dispersed as very small oil droplets, but from an already high value, not from zero.

Community perceptions of damage concerning the use of SSDI has a potential to impact fisheries market confidence.

A process for evaluating subsea dispersant use is further discussed in the context of net environmental benefit analysis (NEBA) on pages 29–34.

Capabilities and limitations

The capabilities and limitations of dispersant use on floating oil are described in the IPIECA-IOGP Good Practice Guide on the surface application of dispersants (IPIECA-IOGP, 2015).

Capabilities of subsea dispersant use

Subsea response techniques have the potential capability, once deployed, to deal with all the oil being released from the point source. This is in contrast to a response to floating oil, where the large area of fragmented and scattered oil on the sea surface is often a limiting factor. The rate at which any oil response can come into contact with oil is commonly called the encounter rate. The encounter rate of surface response techniques, particularly those involving containment of oil, can be low. However the encounter rate of all subsea response techniques is potentially very high; all of the released oil can be 'encountered' in a very small area, albeit that this limited area may be at some distance below the sea surface.

The potential capability of subsea dispersant use should therefore be initially compared with those of other subsea response techniques such as subsea capping and subsea containment and recovery. A limiting factor common to all these methods is the speed with which the required equipment and personnel can be deployed to the site of the oil release and the capability to conduct the response in the water depth at which the release is occurring.

The logistics involved with transporting bulky, heavy equipment associated with subsea capping and containment (a capping stack can weigh 300 tonnes) from where it is stored to where it is required can be formidable.

Table 6 *Comparison of the characteristics and limitations of subsea capping, containment and dispersant injection*

Factor	Subsea capping	Subsea containment	Subsea dispersant injection
Rate at which oil can be encountered	Very high		
Oil treatment rate	Prevents flow of well fluid	Captures well fluid	Very high
Deployment factors	Initial removal of debris may be required	Applicable in rare scenarios where capping is either not sufficient or not possible	Applicable while capping and containment systems are being deployed
Limitations	Current systems typically limited to a maximum water depth of 3,000 m and 15,000 psi pressure	Current systems typically limited to a maximum water depth of 3,000 m	Current systems typically limited to a maximum water depth of 3,000 m

Limitations of subsea dispersant use

The prevailing sea state and oil properties, principally oil viscosity, and the way that the viscosity increases as spilled oil 'weathers', determine the effectiveness of dispersant use on floating oil.

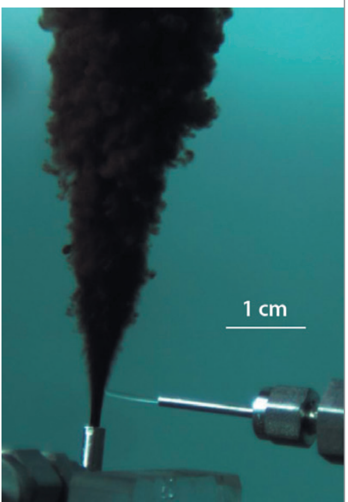
Subsea dispersant use will not be affected by the prevailing mixing energy provided by wave action at the sea surface or by the change in oil properties as it 'weathers'.

At a subsea blowout, there is a continuous 'supply' of crude oil and gas from the reservoir. Dispersant would be added to the oil as it flows into the water. Although the oil properties will change rapidly due to dissolution into the water of some of the water-soluble compounds in the oil, and the sudden drop in temperature as the oil enters the sea, it is unlikely that this will reduce the effectiveness of the dispersant in the case of most crude oils. Crude oil being released from a subsea well will often be at high temperature, although it will be rapidly chilled when it comes into contact with the cold water at deep releases. If a crude oil has a very high pour point due to a very high wax content, it is possible that it would become solid on entering the water, and take the form of a plume of solidified wax droplets.

A potential limitation of subsea dispersant use could be the effectiveness of its application at the release location. Dispersant needs to be added to the oil as the oil and gas enters the water. Studies (Brandvik *et al.,* 2014a and 2013 and Johansen *et al.*, 2013) have shown that the time available for the surfactants in the dispersant to influence droplet formation after the oil is released is very limited:

- If injecting dispersant into the oil and gas before the release, for example if injecting dispersant into a broken riser pipe, the dispersant should be injected no more than about six release diameters before the release.
- If the dispersant is to be added to the turbulent outflow from an oil and gas release, the dispersant should be added only slightly above the oil and gas release at a maximum of 10 diameters of the release.

Below: photograph from a test tank showing the injection of dispersant into a release; the dispersant is visible as a white line being sucked into the rising plume of oil.



Source: SINTEF

SSDI systems have been developed to take the above requirements into account to allow effective operations. Injecting dispersant into the oil before it is released at the discharge point may be better than spraying into the released oil jet near the discharge point. The injection point needs to be within the energetic jet before it begins to break into individual droplets. The distance outside the release point where this occurs will depend on the release conditions.

If the dispersant can't be injected into the oil and gas flow before it is released, the next best option is to get as close to the release point as possible. Dispersants have been shown to be effective under test conditions as long as they are injected into the energetic solid jet of oil before it breaks into droplets. A key requirement for injecting outside the release point will be to ensure that the dispersant is distributed around the jet and not just into one side. The most effective way to do this may be to use injection rings.

Toxicity and biodegradability of oil

Chemical compounds in crude oils

Crude oils are composed of a large number of individual chemical compounds. Almost all of these are hydrocarbons, composed of only hydrogen and carbon. Hydrocarbons can be classified by molecular weight, or carbon chain length, and the majority of hydrocarbons in crude oil contain from 5 to 35 carbon atoms. Hydrocarbons can also be classified according to chemical type; alkanes (paraffins), cycloalkanes (naphthenes) and aromatic compounds (containing one or more benzene rings). The relative proportions of these chemical compounds differ between crude oils and are responsible for the range of physical properties that crude oils exhibit. The majority of hydrocarbons in most crude oils are alkanes and cycloalkanes and they can range from volatile liquids to non-volatile liquids or solids (waxes) depending on their size (number of carbon atoms) and the prevailing temperature.

Potentially toxic chemical compounds in oil

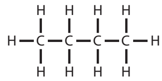
Most alkanes and cycloalkanes have a limited potential for toxic effects on marine organisms due to their low water solubility. Aromatic hydrocarbons are partly water-soluble and are generally considered to be the more potentially toxic component of crude and fuel oils with respect to aquatic organisms (Anderson *et al.*, 1974; Di Toro *et al.*, 2007).

Box 1 *Aromatic chemical compounds in oils*

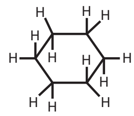
- **One-ring aromatic compounds:** these are benzene, toluene, ethylbenzene and xylenes and are often referred to as BTEX compounds. Crude oils contain from about 0.5% up to 5% BTEX. Gasoline can contain up to 40% BTEX. BTEX compounds are relatively soluble in water, but they also comprise the majority of VOCs and, if they reach the surface, will rapidly evaporate into the air from the floating oil.
- **Two-ring aromatic compounds:** naphthalene and alkyl-substituted derivatives. Different crude oils contain from 0% to 0.4% of naphthalene and from 0% up to 1% or more of substituted naphthalenes. These compounds are less water-soluble than BTEX and of moderate volatility.
- **3-, 4- and 5-ring polycyclic aromatic hydrocarbons (PAHs):** crude oils contain from 0 ppm to several hundred ppm of the 3-ring aromatic compounds, but much less, typically 1 to 10 ppm, of the individual 4-ring and 5-ring compounds. These PAH compounds are not volatile and the 3- and 4-ring compounds are slightly water-soluble.

Toxicity testing of dispersants and dispersed oil

Toxicity testing of dispersants and dispersant/oil mixtures (to produce dispersed oil) is carried out for different purposes and using a variety of toxicity test methods. The intention of toxicity testing of dispersants was to ensure that the use of toxic industrial detergents, such as those used in massive quantities at the *Torrey Canyon* oil spill in the UK in 1967 (Smith, 1968), would not be repeated. Currently, in order to be approved, most countries require dispersants to exhibit a toxicity less than a level deemed acceptable.

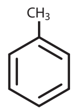


alkane

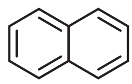


cycloalkane

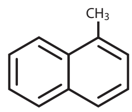
aromatic benzene



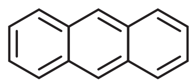
1-ring: toluene



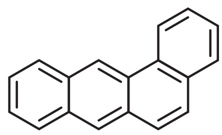
2-ring: napthalene



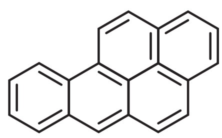
2-ring: 2-methylnaphthalene



3-ring: anthracene



4-ring: benzo(a)anthracene



5-ring: benzo(a)pyrene

Above: examples of aromatic compounds

A 96-hour or 48-hour LC_{50} (lethal concentration to 50% of the test population) toxicity test with a variety of test species was used to determine the toxicity of the dispersants. The purpose of the 48- or 96-hour LC_{50} toxicity test is to determine the concentration of dispersant in water that is lethal to 50% of the creatures exposed for the specified number of hours. The test can therefore be used to rank the comparative toxicity of different dispersants. The exposure regime (concentration of dispersant in the water and exposure duration) in an LC_{50} test does not simulate the exposure to dispersant that a marine organism would experience if the dispersant was used on spilled oil at sea.

In the USA, the toxicity tests required by the US Environmental Protection agency (EPA) for dispersants to be included on the NCP (National Oil and Hazardous Substances Pollution Contingency Plan) Product Schedule involves testing with two US EPA standard species: inland silverside fish (*Menidia beryllina*) and mysid shrimp (*Americamysis bahia*). The exposure regime of the LC_{50} toxicity testing procedure does not simulate dispersant use on spilled oil at sea because the concentrations used in the test are much higher, and the duration of exposure is much longer, than would occur at sea. However, LC_{50} toxicity testing provides a way of assessing the relative magnitude of toxic effects that could be caused by dispersants or dispersed oil under the test's exposure conditions.

At the time of the Macondo accident, eight dispersants on the NCP Product Schedule were tested for toxicity (Hemmer *et al.*, 2010).

The measured levels of toxicity in the LC_{50} tests were ranked on a five-level scale from 'very highly toxic' to 'practically non-toxic' as used by the US EPA for interpreting the results of LC_{50} tests (US EPA, 2012). This toxicity ranking scale is also used internationally (GESAMP, 2014).

Table 7 *Results of US EPA testing of eight dispersants on the NCP schedule*

EPA ecotoxicity categories (ppm = parts per million)	**Mysid shrimp 48-hour LC_{50}**	**Silverside fish 96-hour LC_{50}**
Very highly toxic: <0.1 ppm		
Highly toxic: 0.1–1 ppm		
Moderately toxic: >1–10 ppm		Dispersit SPC 1000
Slightly toxic: >10–100 ppm	Dispersit SPC 1000 Nokomis 3-AA COREXIT® 9500A Nokomis 3-F4 ZI-400	Nokomis 3-F4 Nokomis 3-AA ZI-400 Saf-Ron Gold Sea Brat #4
Practically non-toxic: >100 ppm	Saf-Ron Gold JD-2000	COREXIT® 9500A JD-2000

Source: US EPA, 2012

The majority of the dispersant used at the Macondo accident was COREXIT® 9500A, and was ranked as 'slightly toxic' to mysid shrimp and 'practically non-toxic' to silverside fish in the LC_{50} toxicity tests.

The same toxicity testing methodology used for listing on the NCP Product Schedule was used by the US EPA (US EPA, 2010) to determine the relative magnitude of the toxic effects that could be caused by:

- mechanically dispersed Louisiana Sweet Crude (LSC) oil;
- the dispersant used during the response to the Macondo accident—COREXIT® EC9500A; and
- LSC crude oil dispersed by using a mixture of 1:10 of COREXIT® EC9500A and LSC.

The results summarized in Table 8 show that the dispersant alone has a less toxic effect than the crude oil alone. The dispersant alone is considered to be 'practically non-toxic' to the fish species and only 'slightly toxic' to the shrimp, while the mechanically dispersed crude oil is rated as being 'moderately toxic' to both. The crude oil dispersed with the dispersant has the same rating as the mechanically dispersed crude oil of 'moderately toxic' to both species. In this case the measured toxic effects are caused by the oil, not the dispersant. Consequently, it is not appropriate to evaluate dispersant toxicity by conducting toxicity tests on dispersed oil.

Table 8 *US EPA's LC_{50} aquatic toxicity testing summary results for the spilled oil, dispersant and dispersed oil from the response to the Macondo accident*

	Louisiana Sweet Crude (LSC) oil		Dispersant (COREXIT® EC9500A)		Dispersed oil (LSC + COREXIT® EC9500A)	
EPA ecotoxicity categories (ppm = parts per million)	Mysid shrimp	Silverside fish	Mysid shrimp	Silverside fish	Mysid shrimp	Silverside fish
Very highly toxic: <0.1 ppm						
Highly toxic: 0.1–1 ppm						
Moderately toxic: >1–10 ppm	2.7 ppm	3.5 ppm			5.4 ppm	7.6 ppm
Slightly toxic: >10–100 ppm			42 ppm			
Practically non-toxic: >100 ppm				130 ppm		

Source: US EPA, 2010

The LC_{50} toxicity testing used a 1:10 mixture of dispersant to oil. This is more dispersant than would be used in subsea application, where ratios of 1:100 or 1:50 would be typical.

In actual dispersant use, on spilled floating oil or by subsea dispersant injection, the duration of exposure of marine organisms to dispersed oil, and the concentration of dispersed oil, will be dependent on a variety of factors, including environmental conditions and the circumstances of the oil release.

Exposure to oil, dispersed oil and water-soluble compounds from the oil

A fundamental basis of toxicology is that the magnitude of the effect of a chemical compound on an organism is dependent on the exposure of the organism to the chemical compound. Exposure is a function of exposure route, the concentration of the chemical to which the organism is exposed and the duration of exposure.

If a subsea oil release has occurred, some marine organisms may be exposed to elevated concentrations of dispersed oil droplets and water-soluble compounds from the oil in the water. At a subsea blowout of oil and gas at high pressure, all of the oil will likely be released into the water as oil droplets. A significant proportion of the released oil may be converted to very small oil droplets by the turbulence produced by the oil and gas release. In these circumstances, many of the lower molecular weight aromatic compounds (the BTEX and the 2- and 3-ring PAHs) will be rapidly transferred from the oil and into the water, where they will be subject to rapid dilution and biodegradation.

These compounds have the potential to harm marine organisms that are in the vicinity of the subsea blowout and are exposed to these dissolved compounds as well as to concentrations of dispersed oil in the water. The larger oil droplets, gas bubbles and the water-soluble oil compounds from the oil will rise rapidly through the water column, creating a potential risk to pelagic organisms (those in the water column), rather than to benthic organisms (those that live either in or on the seabed) or the demersal organisms that live near the seabed.

The concentrations of oil droplets and water-soluble compounds from the oil will rapidly decrease as the buoyant plume entrains water and is diluted as it rises through the water column. However, while the blowout continues, there will be a relatively high concentration of oil droplets and water-soluble compounds from the oil in the close vicinity of the release.

Effect of subsea dispersant use

If subsea dispersant use is effective, the oil droplets entering the water as a plume will be smaller in size. This will enhance the rate of transfer of the water-soluble compounds from the oil into the water because the oil/water surface area is increased with smaller oil droplets. This will result in higher concentrations of dispersed oil (very small oil droplets) and water-soluble compounds in the water in close proximity to the release. Although SSDI will increase these concentrations, they may already be relatively high close to the source without dispersant use. Hence, the potential for toxic effects on marine organisms present in the vicinity of the subsea oil and gas release is increased by subsea dispersant use, but from an already high 'baseline' condition. Oil that is dispersed by SSDI will generally become neutrally buoyant and create subsea plumes of dispersed oil at low concentration. These plumes will drift, dilute and biodegrade.

Exposure of marine organisms by ingestion of dispersed oil droplets

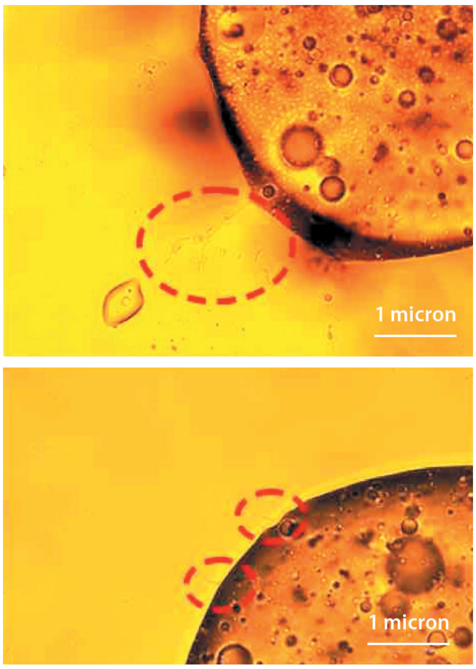
The ingestion of food provides marine organisms with a potential route of exposure to higher molecular weight PAHs. Filter feeding organisms that prey on plankton can ingest naturally- or chemically-dispersed oil droplets when they are of a similar size to some plankton. Relatively simple organisms, such as bivalves, cannot biochemically process the higher molecular weight PAHs in the oil, and these PAHs can build up ('bioaccumulate') in some organs (Neff and Burns, 1996). Predators that consume oil-contaminated bivalves can therefore be exposed to elevated concentrations of the higher molecular PAHs by this ingestion route. Organisms that possess livers, such as fish, can quickly metabolize PAH although some of these metabolites may be harmful. However, it is unlikely that bivalves will be exposed to subsea dispersed oil, as they are benthic organisms and are therefore more likely to be exposed to naturally dispersed surface slicks in shallow waters. Plankton and copepods may be found in the mid or deeper water column and are therefore at increased risk of exposure. The low concentration of dispersed oil, coupled with the abundance and rapid recovery of their populations, is likely to limit impacts on these organisms.

Biodegradation of oil

Oil droplets in the water column are rapidly colonized by petroleum degrading microorganisms that occur naturally in ocean environments (King *et al.,* 2014). All of the world's oceans have natural hydrocarbon seeps (Kvenvolden, 2003), and oil degrading microbes are found in all marine environments—even cold, dark environments—having evolved to degrade petroleum from these seeps. Most of the chemical components of crude oil in these droplets has only limited water solubility and the microorganisms must inhabit the interface between the oil and the water to biodegrade the oil. Oil dispersed as small droplets has a much greater oil/water interfacial area than an oil slick floating on the sea surface. This increase in interfacial area results in greater microbial attachment and faster biodegradation. A community of microorganisms (bacteria and fungi) consumes and degrades the oil as they grow and reproduce, and then larger protozoans and nematodes consume the bacteria. The oil is thereby assimilated into the environment (American Academy of Microbiology, 2011) and no longer poses any risks. Dispersed oil also dilutes rapidly. By the time an individual droplet is fully colonized by microorganisms and biodegradation becomes significant, concentrations of dispersed oil in the water are likely to be very low. At these low concentrations, most marine environments have sufficient oxygen, phosphorous, nitrogen and other nutrients to allow efficient aerobic biodegradation to proceed.

Figure 5 shows a photomicrograph of an oil droplet with marine oil-degrading bacteria attached. It can be seen that the microorganisms (i.e. a few microns in length) that degrade oil can be much smaller than the oil droplets themselves (i.e. a few tens of microns in diameter).

Figure 5 *Biodegrading microbes begin 'eating' the dispersed oil droplet*



Source: Hazen et al., 2010

Biodegradation proceeds principally by biochemical oxidation (Atlas and Bartha, 1992; Atlas and Cerniglia, 1995; Prince, 1997; Prince *et al.*, 2013). The different chemical compounds in crude oils will be biodegraded at different rates and to different extents (Singer and Finnerty, 1984; Lindstrom and Braddock, 2002; Campo *et al.*, 2013). Linear chain alkanes will be most rapidly biodegraded, followed by the single-ring aromatic compounds and then by branched chain alkanes and cycloalkanes. Many complex branched, cyclic and aromatic hydrocarbons, which otherwise would not be biodegraded individually, can be oxidized through co-metabolism in an oil mixture due to the abundance of other substrates that can be metabolized easily within the oil (Heitkamp and Cerniglia, 1987).

The ultimate fate of the majority of oil that is biodegraded is to be eventually converted into carbon dioxide and water (MacNaughton *et al.*, 2003). Some very heavy oil compounds, such as asphalt or bitumen, are slower to biodegrade. These are biologically inert and are non-toxic or practically non-toxic.

The concentration of dispersed oil in the water will progressively decrease to undetectable levels as the small oil droplets are further diluted into the water column. The surfactants and solvent in dispersants are biodegradable and the dispersant will therefore also be biodegraded, usually more rapidly than the oil. The oil compounds that cannot be readily biodegraded will initially be present at very low concentrations of a few ppb (parts per billion) in water as remnants of the dispersed oil droplets. This oil residue will eventually be deposited at these low concentrations over a wide area of the seabed.

To summarize, dispersing the oil by adding dispersants allows significant enhancement of the natural biodegradation process. Oil that is dispersed effectively will persist in the environment for days to weeks, while undispersed floating oil that weathers, emulsifies and ultimately strands on shorelines could persist in the environment for several years.

Net environmental benefit analysis

Net environmental benefit analysis (NEBA) is a process used by the response community for making the best choices to minimize the impacts of oil spills on people and the environment—see the IPIECA-IOGP Good Practice Guide on NEBA (IPIECA-IOGP, 2015c).

NEBA works at different stages in a spill:

- NEBA is an integral part of the contingency planning process, used to ensure that the response strategy for planning scenarios is well informed.
- During a response, the NEBA process is used to ensure that evolving conditions are properly understood and evaluated so that the response strategy can be adapted and adjusted as necessary.
- The NEBA process can also be used to ensure that longer-term response end points are defined and achieved.

NEBA involves consideration and judgment to compare the likely outcomes of using different oil spill response techniques and recommendations as to the preferred tactics, based on the considerations of experienced responders and consultations with stakeholders. NEBA typically involves the following steps for identified release scenarios, and should be carried out prior to an oil spill as an integral part of the contingency planning process.

Table 9 *Typical NEBA steps involved in the contingency planning process*

NEBA step	Description
Evaluate data	The first stage is to consider where the spilled oil is and where it will drift under the influence of currents and wind—various oil spill trajectory models exist to support this. It is also useful to know how an oil will 'weather' as it drifts. This is part of evaluating the available data.
Predict outcomes	The second stage is to assess what is likely to be affected by the spilled oil if no response is undertaken. This may include ecological resources offshore, nearshore and on shorelines, alongside socio-economic resources. The efficiency and feasibility of the response toolkit should also be reviewed. This covers the response techniques, the practicalities of their utilization and how much oil they can recover or treat. If areas under threat include oil-sensitive coastal habitats, the role of oil spill response at sea is to either prevent or limit the spilled oil from reaching these habitats. Previous experience can help to assess which oil spill response techniques are likely to be effective. Pragmatic, operational considerations should form a very important part of the NEBA process applied to all feasible response techniques.
Balance trade-offs	The advantages and disadvantages of the potential response options are considered and weighed against the ecological and socio-economic impacts of each to understand and balance the trade-offs.
Select best options	The process concludes with the adoption of response technique(s) within contingency plans that minimize the impact of potential spills on the environment, and promote the most rapid recovery and restoration of the affected area.

Step 1: Evaluate data

An important aspect of oil spill contingency planning is using realistic oil release scenarios (see the IPIECA-IOGP Good Practice Guide on contingency planning (IPIECA-IOGP, 2015d). Various subsea oil release scenarios, up to and including a worst credible case discharge, should be developed. The predicted prevailing conditions must be taken into account.

Modelling should then be conducted to help predict how the released oil will behave. Several computer models are available for modelling subsea oil and gas blowouts. A model needs to take into account the relevant factors such as the well's and metocean characteristics including currents, temperatures, etc. throughout the relevant depths.

Work is still under way to develop models that accurately predict the oil droplet size distributions produced under a wide range of release conditions.

Step 2: Predict outcomes

Combining sensitivity mapping (IPIECA/IMO/IOGP, 2012) with modelling can indicate which ecological resources and socio-economic resources (offshore, nearshore and on shorelines) are potentially at risk from oil if no response is undertaken. The ways in which oil can impact various ecological and socio-economic resources, and the factors that can influence these impacts, are described in the IPIECA-IOGP Good Practice Guides on marine ecology (IPIECA-IOGP, 2015a) and shorelines (IPIECA-IOGP, 2015b).

Feasibility of using a response technique

The likely effectiveness and feasibility of conducting the different response techniques under the range of likely prevailing conditions should be reviewed. This covers the response techniques, the practicalities of their utilization and how much oil they can recover or treat in the time that is likely to be available for their use. Pragmatic, operational considerations should form an important part of the NEBA process applied to all feasible response techniques.

In considering a response to a subsea oil release, the decision must be made as to whether the response should be conducted subsea (with subsea capping, containment and recovery or subsea dispersant use) or to wait until the released oil has risen to the sea surface where the response could be mechanical containment and recovery, controlled burning or surface dispersant use. The particular characteristics of the subsea oil release scenario and released oil and gas behaviour will inform this decision.

- At a subsea oil and gas blowout in deep water, where the gas will be dissolved in the water and not reach the sea surface, the use of surface vessels to deploy subsea capping stacks, subsea containment and recovery systems and subsea dispersant injection equipment may be a feasible response.
- However, at a subsea oil and gas blowout (with similar hydrocarbon flows and pressures) in shallower water, where the gas will not be totally dissolved in the water and will reach the sea surface, an offset subsea equipment system, deployed at a horizontal distance of up to 500 m from the well, should be considered as the fire and explosion risk will likely preclude the use of surface vessels above the well location.

The time taken to deploy any response equipment may also be a key factor in assessing the feasibility of conducting the response. Any oil spill response is often a race against time. Once a subsea oil release has occurred, the potential risks will be determined by the proximity of resources that could be damaged and by the prevailing conditions, such as wind direction and speed.

Mechanical recovery is generally the first oil spill response option considered for use. This will continue to be the case in the future because the vast majority of oil spills are small and located near stockpiles of equipment. As spills grow in size and move further away from stockpiles of equipment, mechanical recovery becomes less efficient due to the large surface area of the oil, lower oil encounter rates, and logistical issues of transporting recovered oil to shore for processing or disposal. This is why dispersants are needed that can be applied rapidly by air or applied subsea. Dispersants can treat remote oil spills quickly because they can be deployed by fast-moving aircraft. Aircraft deployment means that dispersants can treat large areas much more rapidly than in a boat-based response. Subsea dispersants treat the oil at a known location even more efficiently.

Step 3: Balance trade-offs

A decision to use or not use dispersants is not a black and white decision, despite being typically misconstrued as a 'birds versus fish' debate. Untreated oil slicks moving across the water surface may impact fish eggs and larvae in or immediately under the slick. Furthermore, nearshore and stranding oil may impact the juvenile life stages of many fish. If the oil is not dispersed, slicks may drift across the water surface and strand on shorelines to impact fisheries—possibly more so than dispersing the oil if the spill occurs during critical spawning periods or the oil moves into critical nearshore habitat for juvenile fish. As the potential harm to fish stocks from dispersed oil is low, there can be strong NEBA arguments that dispersant use can protect fisheries.

The trade-offs, or balance, of potential benefits and risks of subsea dispersant use at a subsea blowout are similar, but not identical, to those of dispersant use on spilled floating oil because the circumstances are different. The potential risks posed to marine organisms by dispersed oil are different in terms of scale, location and possible consequence.

The risk of toxic effects on marine organisms is related to their exposure to dispersed oil and the partially water-soluble components released from the oil. Exposure is a function of concentration and duration.

Exposure to dispersed oil caused by dispersant use on floating oil

Breaking waves passing through a localized area of an oil slick will cause the oil to be broken up into oil droplets with a range of sizes. The larger oil droplets will rapidly resurface, but the smaller oil droplets will be dispersed into the water column. The proportion of oil dispersed by natural dispersion is often low and decreases as the oil 'weathers'.

Dispersant use greatly increases the proportion of the oil that is converted into small droplets by the prevailing wave action. Localized plumes of dispersed oil droplets are produced as breaking waves pass through dispersant-treated floating oil. The concentration of oil (as droplets) in the upper water column rises rapidly, but then rapidly decreases as the oil is diluted into the surrounding water. As the oil slick drifts under the influence of the wind, further breaking waves will cause localized clouds of dispersed oil to be produced in the water column at locations some distance from where the previous clouds were produced and subsequently diluted. The peak concentrations of dispersed oil in water are low and of short duration, occurring at scattered locations over a period of time under the dispersant-treated oil.

Marine organisms inhabiting the upper layer of the water column (to a maximum depth of around 5–10 m) can be briefly exposed to increased concentrations of dispersed oil droplets and water-soluble oil compounds in the water column, compared to the situation if dispersants were not used. Some exposure will occur if dispersants are not used, due to natural dispersion—see the IPIECA-IOGP Good Practice Guide on the surface application of dispersants (IPIECA-IOGP, 2015).

Exposure to dispersed oil caused by SSDI at a subsea oil release

The continuous release of large amounts of oil and gas from a point source will produce high concentrations of dispersed oil, and of the water-soluble components from the oil, in the water close to the release. The concentration of dispersed oil in the water will be diluted and decrease as the plume rises and drifts away. The use of SSDI will cause a further increase in these already high concentrations of dispersed oil in water close to the release. These high concentrations of dispersed oil in water close to the source will be maintained for as long as the oil and gas release continues (as illustrated in Figure 4).

The exposure regime for marine organisms exposed to dispersed oil and water-soluble oil compounds in the water column will be dependent on their proximity to the release, the drift direction of the plumes, and the ability of the marine organisms to detect oil and move away to avoid the oil. Sessile organisms on the seabed that cannot move away may experience higher exposure to dispersed oil than those organisms that can swim away. Sessile organisms close to the release can be exposed to high concentrations of dispersed oil for prolonged periods.

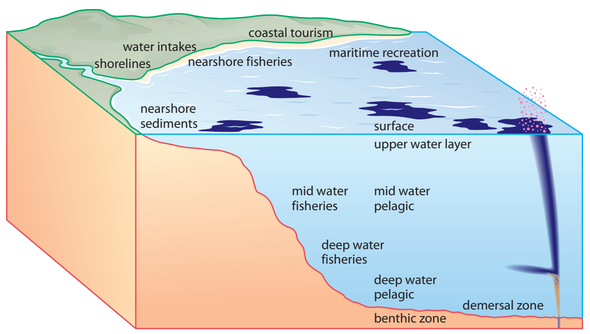
The actual effects of the dispersed oil exposure regime produced by SSDI will depend on the marine organisms that are present in the vicinity of the subsea oil and gas release or near the subsea plumes of dispersed oil that are drifting, diluting and biodegrading. In general, the population density in deep water is less than that present nearer to the sea surface.

The essential element of NEBA when considering subsea dispersant use and comparing its probable effectiveness to that of other response techniques, will be the need to consider the probable outcomes of:

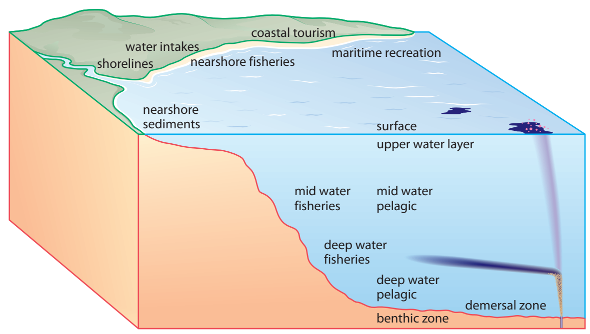
- no response, i.e. not using subsea dispersants or another response; compared with
- the use of subsea dispersants.

Any 'trade-off' consideration of subsea dispersant use should consider the amount of severe and long-lasting damage to oil-sensitive coastal habitats, and potentially to socio-economic resources, that can likely be prevented by dispersant use and compare that with the potential localized effects of dispersant use on the marine environment. Box 2 on page 33 provides an example scenario illustrating how the use of SSDI can achieve a net benefit compared to no response.

Box 2 *Example scenario to illustrate how the use of SSDI can achieve a net benefit compared to no response*



No-response scenario



Scenario with effective SSDI

This representative scenario indicates how the successful use of SSDI can reduce the overall consequences of a release and thereby achieve a net environmental benefit.

Note that this example is illustrative, and that individual contingency planning cases need to take into account the specifics of an operation, including the local environmental resources, their ecological, commercial and cultural value and their seasonality.

	Environmental compartment	Representative population/resources	Potential relative consequence* with no response	Potential relative consequence with SSDI
	Seabed benthic zone	Burrowing organisms	Insignificant	Insignificant
Water column	Near seabed demersal zone	Flatfish	Insignificant	Insignificant
Water column	Deep water pelagic (>400 m)	Round body fish	Small	Moderate
Water column	Mid-water pelagic (<400 m)	Round body fish	Small	Small
Water column	Upper water layer (<20 m)	Plankton	Moderate	Insignificant
Water column	Nearshore water (<10 m)	Coral reef	Moderate	Insignificant
	Sea surface	Seabirds/sea mammals	Very large	Small
Shoreline	Nearshore sediments	Seagrass	Moderate	Insignificant
Shoreline	Wetlands	Burrowing organisms	Very large	Insignificant
Shoreline	Rocky shores		Moderate	Insignificant
Shoreline	Sandy shores		Moderate	Insignificant
socio-economic resources	Coastal tourism		Very large	Small
socio-economic resources	Inshore fisheries and aquaculture**		Large	Small
socio-economic resources	Mid-water fisheries**		Small	Moderate
socio-economic resources	Deep water fisheries**		Insignificant	Large
socio-economic resources	Seawater intakes		Very large	Small
socio-economic resources	Maritime recreation		Very large	Small

* Relative consequence categories take into the account a variety of factors, including the sensitivity of habitats, species or populations, the geographic extent of an area that may be affected, the anticipated recovery time and socio-economic value of a resource, if applicable.

** Fisheries authorities are likely to impose a precautionary fishing ban or exclusion to protect perceived risks to human health and market confidence. A ban typically remains until there is evidence that fish are safe for consumption. Such bans can increase the consequence to fisheries through enforced loss of earnings, rather than through impacts on fish populations or stocks.

Step 4: Select best options

In Step 4 of NEBA, data, viewpoints and trade-offs are taken into account to select the optimum response strategy for the planning scenario or the prevailing incident conditions. This stage of NEBA relies on planners and stakeholders reaching consensus on the priorities for protection and the acceptable balance of trade-offs.

The key objective of planning for, and executing, a response is to implement those techniques that, at any moment in time, have the greatest net benefit. For example, in an offshore marine incident, treating or recovering as much oil as close to the source as possible, will have the greatest benefit, before it has had a chance to weather and spread out making other response options less effective and increasing the chances of more oil reaching sensitive areas, international boundaries or the shoreline.

Example release scenarios and the NEBA considerations associated with response planning are given in the Annex on pages 57–64.

Dispersant regulation principles

A report entitled, *Regulatory approval of dispersant products and authorization for their use* has been produced by the IPIECA-IOGP Oil Spill Response Joint Industry Project (JIP) (IPIECA-IOGP, 2014) to provide an overview of the principles of regulations concerning dispersants.

Dispersant regulations have been divided into the following two categories:

1. **Dispersant product approval regulation** that describes which dispersants would be approved for use in national waters.
2. **Dispersant use authorization regulation** that defines where and when approved dispersant products may be authorized for use on spilled oil in national waters.

Dispersant product approval regulations for subsea use

The same considerations for dispersant product approval apply to dispersants used subsea and on floating oil, namely that:

- A dispersant should meet or exceed a threshold for effectiveness (or 'efficacy').
- A dispersant should not exceed a maximum toxicity threshold to marine life. Care needs to be taken when considering dispersant toxicity versus the toxicity of the dispersed oil (dispersant plus oil). When approving a dispersant for use, the maximum toxicity threshold of a candidate dispersant is usually set at either:
  - a level where the oil and dispersant mixture is no more toxic than the oil alone at the same exposure levels; or
  - if the dispersant is tested alone, at a level which is significantly less toxic than a reference toxicant.

    Note: concerns over the toxicity of dispersed oil should be considered during dispersant use authorization (i.e. when and where dispersant use may be allowed).
- A dispersant should be readily biodegradable and not contain persistent harmful constituents. This may require additional information to be provided as part of the product approval process.

Subsea dispersant use at the Macondo accident employed the same dispersants that have been widely used around the world on floating oil.

Dispersant use authorization regulations for subsea use

To date, the USA is the only country that has had experience with regulating subsea dispersant injection as a response technique. Following the Macondo accident, the US National Response Team published guidance on environmental monitoring for atypical dispersant operations (NRT, 2013) and began the process of revising the National Contingency Plan. The American Petroleum Institute (API, 2013) has developed a similar monitoring guidance document that is focused more towards collecting information needed to make operational decisions regarding continued use of SSDI.

Experience: the Macondo accident

Subsea dispersant injection (SSDI) was used for the first time in response to the Macondo accident off the Gulf of Mexico in 2010. To understand the rationale for SSDI to be used it is necessary to consider the circumstances of the incident.

On the evening of 20 April 2010, a gas release and subsequent explosion and sinking occurred on the Deepwater Horizon oil rig working on the Macondo exploration well in the Gulf of Mexico, approximately 42 miles (68 km) south-east of Venice, Louisiana. As the drilling unit sank, the marine riser with the drill pipe inside connecting the unit to the blowout preventer and the well below separated from the sinking Deepwater Horizon rig and collapsed to the seafloor. Oil and gas continued to flow from the broken and buckled riser (a pipe previously connecting the well head on the seabed to the rig on the sea surface) after the Deepwater Horizon rig had sunk.

The accident involved a well integrity failure, followed by a loss of hydrostatic control of the well. The blowout preventer (BOP) failed to seal the well after the initial explosions. A major effort was undertaken to seal off and stop the continuing flow of oil and gas. Work quickly began on the drilling of two relief wells.

Within days of the accident occurring, the USA's federal government established a Unified Area Command to manage the response to the oil release. The biggest oil spill response operation in history was initiated. A wide variety of oil spill response techniques was used to try to prevent oil from reaching the shore, contaminating sensitive ecological resources and disrupting the local economy, particularly tourism and fisheries. Response techniques included:

- the use of large-scale offshore skimmers and shallow water equipment to skim the floating oil;
- controlled in-situ burning of oil conducted by the Unified Command where weather, sea conditions, distance from shore and other conditions made it safe and appropriate;
- dispersants applied in various ways; and
- physical protection of the shoreline, including the deployment of 3.8 million feet (1,160 km) of hard boom and 9.7 million feet (2,960 km) of absorbent soft boom. This was part of a comprehensive shoreline response programme.

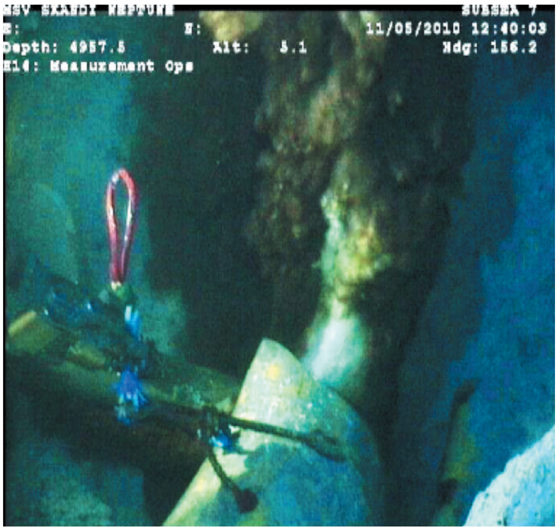
The well was capped on 10 July and the oil and gas release was stopped on 15 July. Oil and gas had flowed into the waters of the Gulf of Mexico for 87 days. In January 2015, the US District Court concluded that there was no way to know with precision how much oil was discharged into the Gulf of Mexico, but found that the evidence supported an estimated total of 3.19 million barrels (507,000 m^3).

Subsea oil and gas release at Macondo well

Several characteristics of the subsea oil and gas release that occurred at the Macondo accident determined the fate of the oil. Some parameters are not known with accuracy and some became the subject of much speculation and legal contest; proceedings continue at the date of preparation of this guide. Other facts are not disputed and are known with certainty.

After the Deepwater Horizon sank, the release of oil and gas was occurring at a water depth of approximately 5,100 feet (1,550 metres), where the pressure is 150 atmospheres. This precluded direct human intervention by divers to assess the oil and gas release rates and shut off the flows. All subsea operations were therefore conducted using remotely operated underwater vehicles (ROVs). Video cameras on the ROVs deployed to the seabed soon revealed that the oil and gas flow was continuing from two or three places along the broken and buckled riser.

Oil continued to arrive on the sea surface, and a variety of techniques were tried to regain control of the source of the oil and gas and to stop the flow or to contain and recover the oil.



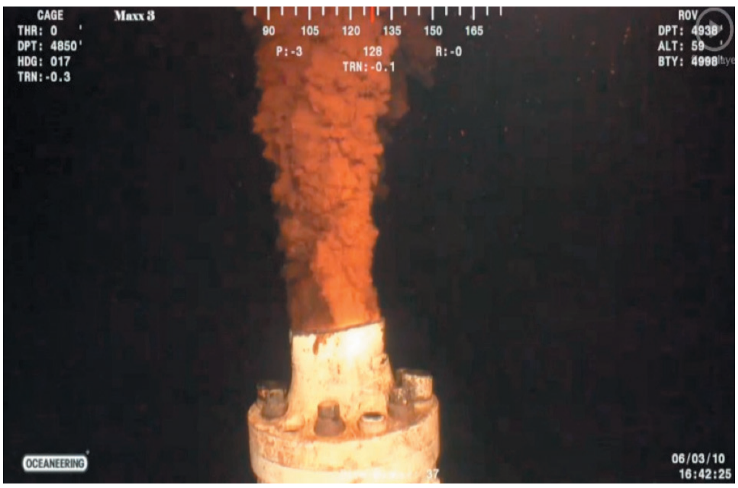
Modified from BP video from ROVs

Oil and gas being released from the broken riser on 11 May 2010

- A coffer dam was deployed on 7 May, but solid methane hydrate formed inside and increased the buoyancy causing it to float, hence it could not be placed in position over the leak to collect oil.
- A pipe, known as the RITT (riser insertion tube tool), was inserted into the broken riser on 14 May to collect some of the outflow and recover it to a vessel on the sea surface. The RITT collected an average of 2,000 barrels (320 m^3) of oil per day until it was removed to allow the 'top kill' (drilling mud pumped into the well) procedures to proceed.
- The 'top Kill' operation was unsuccessful on 29 May and preparations were made to proceed with the Lower Marine Riser Package (LMRP) Containment System Plan.
- The riser was cut off on 3 June and the LMRP/'top hat' containment system was put in place. This recovered oil and gas siphoned through a riser to the vessel *Discoverer Enterprise* at a rate of approximately 15,000 bbls (2,400 m^3) per day.
- A second containment system (subsea manifold) was attached to the BOP on 16 June and the recovered oil and gas was flared via the Q4000 platform at a rate of approximately 8,500 barrels (1,400 m^3) per day.
- The well was capped and the oil and gas release was stopped on 15 July.

Below: hydrocarbons (oil and natural gas) escaping from the end of the riser tube after it was severed on 3 June 2010 immediately above the Macondo well BOP stack

The amounts of oil and gas being released into the deep sea at the Macondo accident could not be measured directly at the time. Many estimates of the rate of oil and gas flow were made, both during and after the incident, but the precise amounts were uncertain. It was obvious that some of the oil that was being released was reaching the sea surface because the oil slick continued to form above the well when the SSDI system was not in operation, and some oil continued to reach the sea surface in close proximity to the release location (within a few kilometres) even when the SSDI system was in operation.



Modified from BP video from ROVs

The oil slicks and sheens on the sea surface then began to break up and drift away under the effects of the prevailing winds and currents. However, water sampling showed that a proportion of the oil released at the source did not subsequently arrive on the sea surface and was being dispersed into the water column, both by the inherent mixing energy of the release and by the SSDI system.

The oil was not being released as a continuous stream of liquid. Instead, due to the turbulence created by the release conditions, the oil and gas were being released into the water as a plume of small oil droplets and gas bubbles. The size distribution of the oil droplets and gas bubbles produced would have been a function of several parameters including:

- the flow rates of the gas and oil, and the gas-to-oil ratio;
- the pressures and temperatures of the released fluids (the Macondo well was being drilled into a high-pressure, high-temperature oil and gas reservoir);
- the size and configuration of the orifices through which the oil and gas was being released; and
- the pressure and temperature of the water into which the oil and gas were being released.

As noted above, some of these parameters are known with certainty and precision, but others can only be estimated with much less certainty or accuracy. Studies and modelling conducted after the Macondo accident (for example Socolofsky, 2012), plus measurements made at the time of the incident and in the months afterward (OSAT, 2010), confirmed the general characteristics of the oil behaviour previously shown in Figure 4.

Dispersant use at the Macondo well

Dispersant use on oil on the sea surface

Aircraft first sprayed dispersant on to floating oil on 22 April. This was done under the direction of the Federal On-Scene Coordinator (FOSC), and dispersant use had been pre-authorized in the Regional Response Team's (RRT's) oil spill contingency plan. Aircraft sprayed dispersant onto oil outside a five nautical-mile radius safety exclusion zone imposed around the vessels dealing with the source control efforts. Dispersant spraying was conducted closer to the source from ships and boats. The objective was to disperse the floating oil into the water column and also to suppress the build-up of VOCs in the air so that response personnel would not be exposed to them.

As the oil spill response operation grew, more aircraft were used for spraying dispersant onto the floating oil. The amount of dispersant sprayed from aircraft one week into the response was 138,024 US gallons (522.5 m^3) and was rising rapidly. As response operations continued, there was growing concern about the quantity of dispersant that might be needed to address surface slicks. This included concern about the ability to manufacture and buy the volume of dispersant that might be needed, as well as concern about the potential effects of dispersants on the environment. Some response workers and members of the public also expressed concern about the potential for people to be exposed to dispersant chemicals or dispersed oil.

Consideration of subsea dispersant use

More effective ways of using dispersant were evaluated. Adding dispersant subsea, directly to the oil as it was released, was considered. Subsea dispersant addition could have several possible advantages:

- It would enhance the safety of the oil spill response and source control efforts by reducing the amount of oil on the sea surface. This would reduce the potential exposure of response personnel on the surface vessels to VOCs evaporating from the oil.
- It would reduce the need for subsequent mechanical recovery, burning, surface dispersant use and shoreline protection/treatment by reducing the amount of floating oil.
- It would have a higher encounter rate compared to spraying dispersant onto floating oil. The dispersant would be effective at lower treatment rates and this could reduce the total amount of dispersant needed for the response.
- It would be able to proceed continuously day and night (24/7) while dispersant could only be sprayed from aircraft during daylight hours.
- It would not be affected by the majority of inclement weather and sea conditions that would prevent or limit other at-sea response techniques.

However, there were also many uncertainties and questions about subsea dispersant addition, including:

- Subsea dispersant addition had never been done before. Would it work? And if it did, what would be the consequences?
- What would be the long-term effects of subsea dispersant use?
  - What would be the effects of generating large amounts of dispersed oil near the source for prolonged periods of time?
  - How should a net environmental benefit analysis (NEBA) be conducted if the subsea environment has not been extensively studied?
- Would biodegradation of the dispersed oil occur in the low-temperature water at significant depth?
  - If biodegradation did occur, would oxygen be depleted to very low levels?

Testing subsea dispersant use

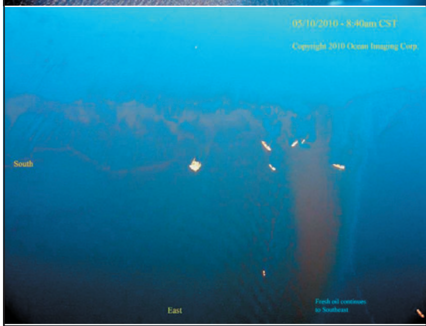
The regulators (the Federal On-Scene Coordinator for oil spill response (FOSC) and the US EPA) authorized BP to conduct tests of this new subsea dispersant approach. A series of tests with limited amounts of dispersant were conducted on 30 April, 2–4 May and 10–11 May.

A series of aerial photographs taken during the tests with subsea dispersant injection conducted from 9–12 May are presented and discussed in Box 3 on page 40. Although it is difficult to accurately quantify the total amount of oil on the sea surface from such photographs, they supply good qualitative evidence of the effect of subsea dispersant use. The photographer was able to confirm that the observed reduction in surface expression of oil extended beyond the area covered by the images.

Box 3 *Visual evidence of the effectiveness of SSDI*

9 May, 08:52

This photograph was taken prior to dispersant injection. The floating oil above the release source forms a continuous layer. Oil being released from the broken riser is constantly rising up through the water column and arriving on the sea surface.



10 May, 08:40

The same aerial view three hours after dispersant started to be injected into the oil and gas flowing out of the end of the broken riser through a pipe guided in by the ROV.

The area of floating oil is clearly a lot less than that in the previous photograph. A reasonable interpretation is that most of the oil was no longer arriving at the sea surface.

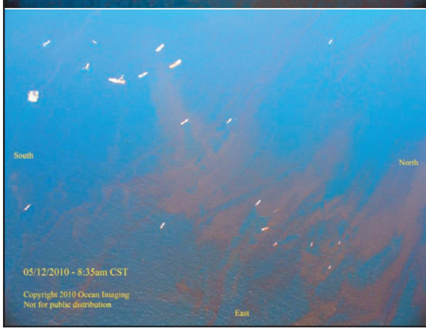
10 May, 17:05

The floating oil after eleven hours of dispersant being injected subsea. Only scattered remnants of oil are visible on the sea surface.

Subsea dispersant injection was then stopped.

11 May, 09:10

This photograph was taken five hours after the subsea dispersant injection was stopped, and shows that the extent of the floating oil had increased significantly. This indicated that oil that had previously been dispersed subsea by the dispersant injection was now reaching the sea surface.



12 May, 08:35

Taken 28 hours after dispersant injection had ceased, this image shows that the extent of floating oil is similar to that before subsea injection was tested, although the oil is now drifting to the north due to changes in the wind.

Subsea dispersant application

Subsea method

Dispersant was injected into the oil and gas flowing out of the end of the broken riser through a pipe guided in by the ROV until 3 June when the broken riser was removed. Dispersant was then added to the oil and gas flowing from the well head and then the LMRP, until the oil flow was stopped on 15 July.

Modified from BP video from ROVs

The dispersant was added by a 'lance' or 'wand' held by a ROV and guided by the ROV operator. The live video feeds showed that the lance was being moved around into the release of oil and gas, plus the water that was being entrained in the plume, a few feet (around 1 m) above the well head or LMRP. Dispersant addition using lances, or wands, of various configurations was tried (see photographs on right).

Subsea dispersant treatment rate

Since the oil and gas flow rates were not known and could not be measured, it was not possible to specify a dispersant treatment rate in terms of the dispersant-to-oil ratio (DOR) that needed to be achieved. In early tests of the SSDI system in May 2010, dispersant was added at rates ranging from an average of 4.6 to 10 gal/min (17.4 to 37.9 l/min).

Tests were conducted to determine the most effective application rate within the tested range, and to evaluate whether the addition of subsea dispersant could reduce the total amount of dispersant that would be required in the response. These tests considered whether the addition of dispersant directly into the oil flowing out of the well head would be effective, and whether it could be effective using a substantially smaller volume of dispersant than the aerial dispersant team was spraying onto scattered floating oil on a daily basis. These test showed that subsea application could prevent oil from reaching the sea surface above and in the vicinity of the well. However, the tested application rate was not sufficient to disperse all of the oil subsea. Some partially degraded and weathered oil continued to reach the sea surface several kilometres away from the well, and dispersant spraying from aircraft continued to address that surface oil.

On 26 May, the US EPA and the US Coast Guard (USCG) issued a directive (US EPA, 2010a) requiring that the total volume of dispersant applied (on oil on the sea surface and subsea) be reduced by 75% from the maximum daily amount being used. The directive ordered the responsible party to stop using surface dispersants in the absence of prior written authorization from the USCG. It allowed subsea dispersant use to continue, but only at a maximum of 15,000 gal/day, equivalent to 10.4 gal/min (39.4 l/min, equivalent to 357 barrels of dispersant/day).

Amount of dispersant used

A total of just over 1.8 million gallons (nearly 7,000 m^3) of dispersant was used during the response to the Macondo accident.

More than 40% (771,272 gallons or 2,920 m^3) of the total amount of dispersant was injected subsea.

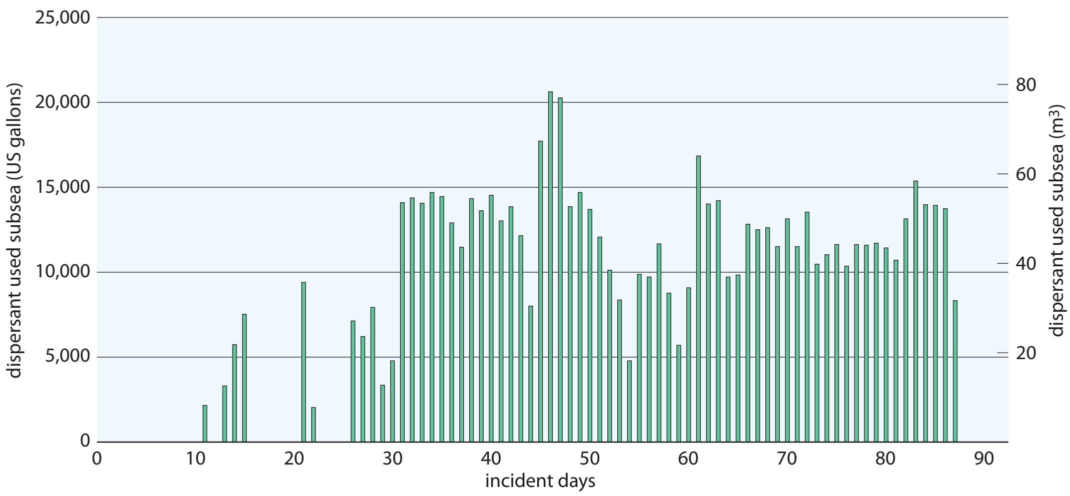
Table 10 *Dispersant used at the Macondo accident*

Dispersant used	US gallons	m^3
Sprayed from aircraft	976,249	3,696
Sprayed from ships	93,751	355
Applied subsea	771,272	2,920
Totals	**1,841,272**	**6,971**

After the test applications conducted at the end of April and during early May, the daily amount of subsea dispersant used rose to 15,000 gal/day (55 m^3/day) with an average dispersant pump rate of 10 gal/min (37.9 l/min) (Figure 6).

After the EPA's Directive of 26 May, there was a substantial decline in the average daily volume of dispersant used in the incident response. Surface spraying of dispersants was prohibited on some days, and authorized at substantially lower daily volumes on other days when it was needed. During 3–5 June, at the time the riser was removed and the LRMP was fitted, the subsea dispersant application rate was briefly increased to 20,000 gal/day (76 m^3/day), equivalent to 14 gal/min. At other times, the daily dispersant subsea usage continued at an average rate that varied between approximately 8,000 to 15,000 gal/day (30 to 55 m^3/day), equivalent to 6 to 10.4 gal/min (22.7 to 39.4 l/min), until the oil flow stopped on 15 July.

Figure 6 *Dispersant application subsea during the Macondo accident*



Water column monitoring requirements

Subsea dispersant use had never been attempted as an oil spill response technique prior to the Macondo accident, and the use of dispersants in such large quantities as a response was without precedent. Monitoring of the water column was required to address the questions and concerns about subsea dispersant use, namely:

- Would the subsea addition of dispersant to the oil and gas release work?
- If subsea dispersant addition did work, what would be the consequences?
  - Where would the plumes of dispersed oil be transported to by the prevailing currents?
  - What would be the concentrations of dispersed oil in these plumes?
  - Could these concentrations of dispersed oil cause harm to the marine organisms exposed to them?
  - Would biodegradation of the dispersed oil occur in the cold, deep water?
  - If biodegradation did occur, would it deplete the oxygen in the water to very low levels and cause harm to marine organisms?

The US EPA required monitoring of subsea dispersant during the response to indicate the overall effectiveness of the dispersant added. They also wished to have indications of the transport of dispersed oil in the water column.

On 10 May the US EPA issued a Directive (EPA, 2010b) establishing a three-part monitoring plan required for subsea dispersant use to proceed. Part 1 monitoring was required to indicate whether subsea dispersant use was being successful, i.e. dispersing the oil subsea, and employed:

- the use of towed fluorimeter (Turner Designs C3 fluorimeter) used at 1 m water depth to measure the concentrations of oil in water;
- particle size analysis using a LISST (laser in-situ scattering and transmissometry) analyser (Sequoia Scientific, Inc.) at various intervals from the surface to a water depth of 550 m to measure oil droplet size distributions;
- measurements of dissolved oxygen at various intervals from the surface to a water depth of 550 m to detect any oxygen depletion due to biodegradation of oil;
- use of a CTD device to measure conductivity, temperature and depth at various intervals from the surface to a water depth of 550 m;
- water sampling from the surface to a water depth of 550 m for PAH (polycyclic aromatic hydrocarbon) analysis; and
- aerial visual observation (weather permitting).

Part 2 monitoring was required when the Part 1 monitoring indicated that subsea dispersant use was being effective. This extended the required monitoring of Part 1 to be undertaken to the sea floor at a water depth of 1500 m. In addition, some extra monitoring requirements were added:

- cast (i.e. lowered, not towed) fluorimeter measurements, from the surface to the sea floor;
- Rototox™ toxicity testing; and
- UV-fluorescence testing to detect higher molecular weight (> 3-ring) PAH fractions.

Part 3 outlined the operational procedures for subsurface injection of the dispersant and included parameters such as the types of dispersant to be used, the rate of dispersant injection, how the pumping rate will be monitored, and procedures for the FOSC to start and stop injection.

The addition of the requirement to conduct Rototox™ toxicity testing was to evaluate the risk posed by SSDI in its early form, and to determine whether the SSDI process should be stopped, or altered, to reduce the risk of harm to marine species. Two thresholds were specified:

1. A significant reduction in dissolved oxygen from background to below 2 mg/l; or
2. Excessive exertion of a toxic response, revealed by the toxicity tests.

In the event that either threshold was reached, and taking into account all the relevant factors including shoreline, surface water, and other human health and ecological impacts, government agencies would have considered whether the risk of subsea dispersant application exceeded its potential benefits, and whether the SSDI system should be modified or shut down.

The monitoring requirements were subsequently modified to include monitoring of unaffected waters to provide background data, and a combined CTD and water sampling rosette package[1].

Results of monitoring

The water column monitoring and sampling undertaken was designed to reveal:

- measurable indications of the effectiveness of subsea dispersant addition, such as the location and concentrations of dispersed oil in the subsea plumes; but also:
- potential risks and adverse consequences of subsea dispersant use such as a toxic response in test organisms, or a large decrease in the dissolved oxygen content of the water.

The results of the monitoring and water sampling carried out were summarized and included in a report prepared for the Unified Command, entitled *Summary Report for Sub-Sea and Sub-Surface Oil and Dispersant Detection: Sampling and Monitoring*, often referred to as OSAT1 (OSAT, 2010). This report presents results on 10,000+ samples from 25 research vessels on more than 125 cruises and 850 ship days at sea. OSAT1 includes a summary of data collected in the SSDI process, but it is not about SSDI. It reports on water sampling results to determine whether response activities in the water are complete. It allowed the FOSC to shift its focus to the response on shore, and in any tidal areas alongside the shore.

The data in Figure 7 are taken from a report produced by the Joint Analysis Group (JAG) for Surface and Sub-Surface Oceanography, Oil and Dispersant Data (JAG, 2010a) and are examples of the measurements made during monitoring of the water column at different times, dates and locations. The figure shows:

- fluorimeter response, fluorescence (ppb QSDE—quinine sulphate dehydrate equivalence) in black;
- dissolved oxygen content of the water (ml/l) in red; and
- water density anomaly (kg/m^3) in blue.

The figures are raw data and are used only to illustrate the results obtained during the monitoring.

[1] The most common design for a water sampling package, which generally includes from 12 to 36 sampling bottles, typically ranging from 1.2 to 30 litres capacity, clustered around a central cylinder where the CTD or similar sensor package can be attached.

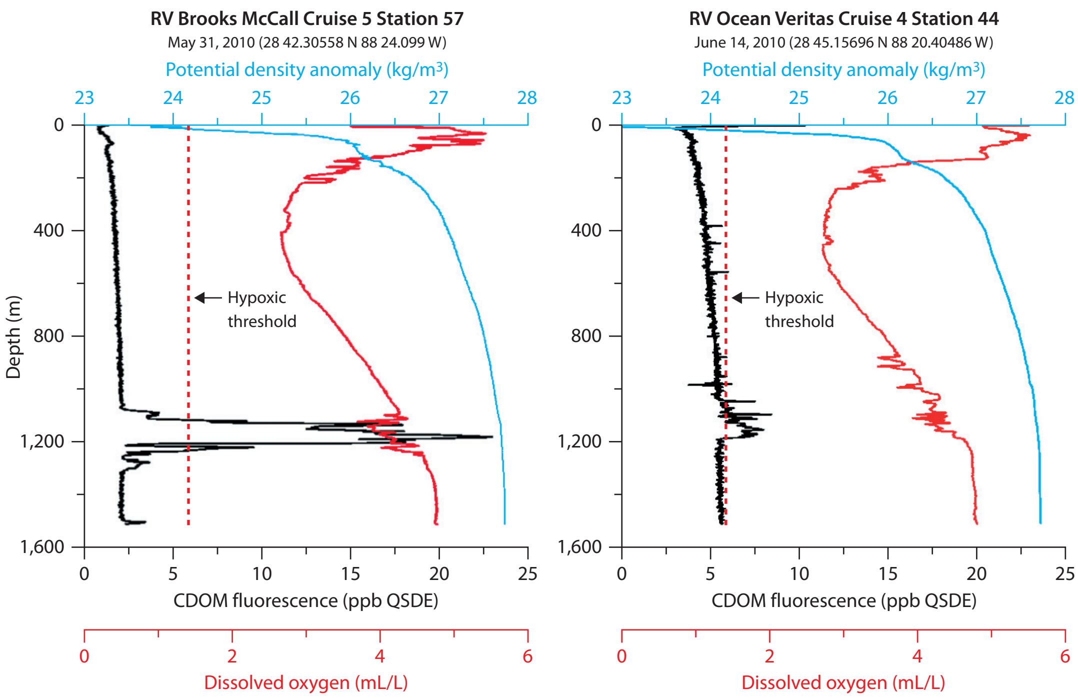
Fluorimetry measurements and water chemical analysis

As reported by the JAG, dispersed oil (including both oil that is physically dispersed by the turbulence of the release conditions and oil dispersed as a result of chemically enhanced dispersion caused by subsea dispersant addition) was detected by fluorimetry as a dilute plume of dispersed oil at a water depth of approximately 1,200 m, i.e. 300 m above the oil and gas release. The readings were highest near the release site, generally decreasing with distance, and trending primarily southwest to the north-east, consistent with the measured water current (JAG, 2010a).

A further JAG report (JAG, 2012) concluded that:

- The oil that was detected was classified into volatile fraction hydrocarbons (partly water soluble) and semi-volatile fraction hydrocarbons. Separately reporting these two classes of hydrocarbons allowed differences in the fate of these fractions observed early in the spill to be distinguished. Some evidence shows that the most easily biodegraded fractions of the oil, the volatile fraction hydrocarbons, were preferentially consumed.
- The observed decreases in hydrocarbon concentrations with increasing distance from the well head were likely due to multiple factors, primarily dilution and biodegradation; other factors, such as particulate adsorption, could have also contributed to the decreases.
- The highest concentration of volatile hydrocarbons detected in water between the depths of 900 m and 1,300 m was 2,112 parts per billion (ppb) found in a sample 1.2 km from the well head. Beyond 20 km from the well head, volatile hydrocarbon concentrations were below 100 ppb and values beyond 100 km from the well head were below analytical method detection levels.
- The levels of semi-volatile fraction hydrocarbons at depths between 900 m and 1,300 m were primarily in the 1–10 ppb range at distances of >10 km from the well. The highest semi-volatile

Figure 7 *Examples of the many measurements made during monitoring of the water column*



hydrocarbon level in a water sample was 485 ppb, also found in a sample 1.2 km from the well head. Measurable amounts of semi-volatile hydrocarbons were found 400 km from the well head; values above 10 ppb were found up to about 275 km from the well head.

Dissolved oxygen measurements

The dissolved oxygen content of the water was depleted to some degree in the vicinity of the dispersed oil plume, but the subsea dispersant operation did not create any oxygen-depleted zones that would harm the marine organisms.

Water column sampling and analysis results

Water samples were collected in the locations where fluorimetry had indicated the highest dispersed oil concentrations, and these water samples were analysed for specific hydrocarbons.

Human health benchmarks
Human health benchmarks developed by the US EPA in coordination with the US Department of Health and Human Services are used to assess potential human health risks from exposure to oil-contaminated water. The benchmark consists of screening levels for a number of compounds, including VOCs, PAHs and metals.

A total of 11,634 (6,090 nearshore, 750 offshore and 4,794 in deep water) samples were analysed for comparison to the human health benchmark. None of samples exceeded the EPA benchmark.

Aquatic life benchmarks
The EPA established benchmark 'levels of concern' for PAH concentrations in water and sediment to screen for potential adverse impacts on aquatic life. The water samples were analysed for a total of 41 oil chemical compounds, including 7 volatile organic compounds, 16 parent PAHs and 18 alkylated homologues of the parent PAHs. Each of the individual chemical compounds were assigned a potential toxicity so that the cumulative toxicity (acute or chronic) of the mixture of compounds in each sample could be calculated. These aquatic life benchmarks were established on the basis of a suite of laboratory toxicity evaluations using contaminated water and various species, life stages, end points and exposure durations.

A total of 10,578 (6,090 nearshore, 749 offshore and 3,739 in deep water) samples were analysed for comparison to the aquatic life benchmark. As reported (OSAT, 2010 and OSAT, 2011) approximately 1% of the total samples were consistent with Macondo oil and above US EPA benchmarks, with 1% from sediment locations and <1% from water locations.

Dispersant benchmarks
The water samples were analysed for four dispersant constituents:
- 2-butoxyethanol (found only in COREXIT® 9527 that was used until May when supply ran out);
- dipropylene glycol n-butyl ether (DPnB);
- propylene glycol; and
- di-iso-octylsulphosuccinate (DOSS).

Benchmarks, based on dissolved seawater concentrations for the individual compounds, were used to establish 'levels of concern' based on available biological effects data and were conservatively designed to protect aquatic life.

A total of 10,178 (5,262 nearshore, 682 offshore and 4,334 in deep water) samples were analysed for comparison to the dispersant benchmark. As reported by OSAT, no exceedances were observed

Toxicity testing

Laboratory testing done using the standard Rototox™ protocols and Macondo crude oil dispersed with COREXIT® 9500A indicated that the LC_{50} value for the rotifer, *B. plicatilis* was in the range of 10 to 17 ppm. The highest observed total petroleum hydrocarbons (TPH) values in the field where toxicity tests were conducted were considerably less than this. It is therefore not surprising that no signs of toxic response were revealed in the Rototox™ toxicity testing conducted as Part 2 of the required water column monitoring.

In addition, toxicity tests were also conducted on various benthic and pelagic species (Table 11).

Table 11 *Tests carried out on various benthic and pelagic species during the Macondo accident*

Sample type	Test type	Duration	End point	No. of tests
Water	Fish	96 hours	Survival	126
		7 days	Survival, growth, biomass	36
	Mysid shrimp	96 hours	Survival	93
		7 days	Survival, growth, fecundity, biomass	30
	Pink shrimp	7 days	Survival	88
	Sea Urchin	120 minutes	Fertilization	2
	Mollusc	48 hours	Survival, embryo development	20
	Diatom	96 hours	Growth	68
	Algae	96 hours	Growth	68
Sediment	Amphipod	96 hours	Survival, growth	74
		10 days	Survival, growth, reburial	505
	Worm	10 days	Survival	112
	Mysid	48 hours	Survival	256
		96 hours	Survival, growth	65
	Sea Urchin	60 minutes, 48 hours	Fertilization, embryo development	66

A total of 3,548 toxicity tests were conducted during the spill and the associated response, making it the most extensive testing programme ever conducted to characterize the effects of an oil spill in the marine environment. Overall, 90% of these tests showed no statistically significant effects. None of the concentrations of dispersant-related constituents found in the sediment and water samples collected after 3 August 2010 in the nearshore zone exceeded the US EPA's chronic aquatic benchmarks (OSAT, 2011).

Addressing concerns over seafood

To address concerns about the potential effect of oil and dispersants on seafood, in June 2010, the National Oceanic and Atmospheric Administration (NOAA) and the US Food and Drug Administration (FDA), in consultation with the US EPA and the Gulf states, agreed to an extensive sampling and testing procedure. Areas once closed to fishing were reopened only when all seafood sampled in the area passed both the established sensory and chemical testing. While initial testing was focused on oil contaminants, in October 2010, the FDA and NOAA created a new test that could detect traces of dispersant constituents in fish tissue (US FDA, 2010). Every sample tested was well below FDA levels of concern, with 99% of the samples showing no detectable residue.

To date, none of the seafood tested by the FDA, NOAA and the Gulf states has exceeded the FDA's human health thresholds. Gulf of Mexico seafood is among the most rigorously tested sources of seafood on the US market. Since May 2010, the FDA, NOAA and the Gulf states have tested more than 10,000 finfish and shellfish specimens, and levels of PAH in seafood have consistently tested 100 to 1,000 times lower than FDA safety thresholds (US FDA, 2012).

Natural Resource Damage Assessment

In the USA, the Oil Pollution Act of 1990 addresses environmental impacts from a spill through two types of activities:

- **Response:** actions taken to contain and remove oil from the water and shoreline, and minimize damage to the public health and welfare.
- **Restoration:** actions taken to restore or replace injured natural resources and compensate the public for temporary lost use of those resources.

Scientists working on response and natural resource assessment and restoration actions were in the field within days after the accident occurred, collecting data that would be used to evaluate the potential impact of oil and dispersants on wildlife and habitats, as well as lost recreational use of these resources. This was the start of the Natural Resource Damage Assessment (NRDA)—the largest such environmental assessment ever performed. By early 2015, NRDA scientists had conducted more than 240 studies including investigations of potential benthic impacts. Data analysis and potential injury assessment were still under way at the time of preparation of this guide.

Operational aspects—an overview

The basic operations of subsea dispersant use are as follows:

- A surface vessel is used to transport a supply of dispersant and the required application equipment to the site of the subsea oil release.
- The equipment is deployed and, if possible, subsea monitoring is conducted to characterize the subsea oil release.
- Dispersant is pumped from the surface to a subsea manifold. A jumper from the manifold is connected to a nozzle held by a remotely operated vehicle (ROV) located close to the release.
- The ROV positions the nozzle to inject dispersant directly into the flow of oil or as close to the release point as possible.
- Dispersant is pumped at a controlled rate from the deck of the surface vessel through the nozzle and into the oil.
- The subsea dispersant use is monitored to assess whether it is being effective and to provide information about the locations of dispersed oil plumes in the water column and their potential risk to marine organisms.

Equipment needs

The first step is to mobilize the necessary equipment to the well source-control location. Table 12 presents an example preparedness checklist to assist in mobilizing the appropriate resources.

Table 12 *Example preparedness checklist for subsea dispersant injection*

Resource type	Specific equipment, supplies or other items
Vessel	• Offshore construction vessel to transport and deploy subsea dispersant injection system, and dispersant supply shuttle vessel(s) to transport dispersant supply
Chemical supplies	• Dispersant
Operating equipment	• Multiple ROVS to assist in installation/operation • Coil tubing unit • Subsea manifold • Dispersant pumping system • Vessel-to-vessel hose and equipment for refilling dispersant storage tanks
Subsea dispersant monitoring kit	• Research vessel • Specialized instrumentation for conducting monitoring of subsea dispersant injection operation • Science team to support monitoring operation
Procedures	• Installation/operation procedures customized for the responder's vessel(s)
Planning/procedures	• Dispersant deployment plan (ISO tanks to vessel) • Dispersant injection plans (ratio of oil flow to dispersant injection or DOR) • Transfer plan for restocking pumping operations • Dispersant monitoring planning • Contingency planning for installation
Planning	• Staging/sequencing plan for arrival of dispersant tanks at shore base • Ensure vessel charter agreements include dispersant
Agreements	• Agreement with dispersant supplier to purchase additional dispersant

Courtesy of MWCC

Dispersant stockpiles

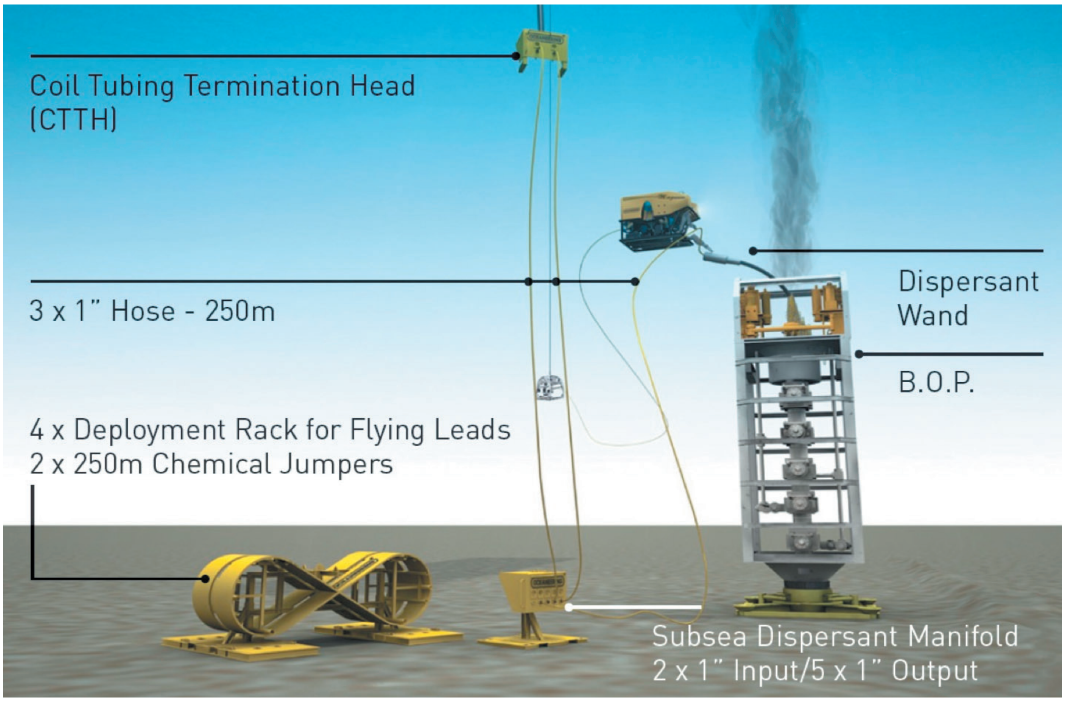
Dispersant stockpiles are maintained worldwide as part of Oil Spill Response Limited's (OSRL's) global dispersant stockpile (GDS) of 5,000 m^3 (or 5 million litres) of dispersant. The stockpiles are positioned to enable quick access to dispersants and to ensure that sufficient stock can be mobilized for an individual spill response incident. Access to the GDS is available to all of OSRL's members who sign the GDS supplementary agreement. Other response organizations such as the Marine Well Containment Company (MWCC) in the Gulf of Mexico and the Australian Marine Oil Spill Centre (AMOSC) in Australia have also developed site-specific dispersant stockpiles.

Deployment of SSDI equipment

Once the SSDI equipment arrives on-scene at the source-control area, the dispersant supply vessel is positioned on the surface above the well head. Due to other operations that may be occurring near the well head (e.g. cap and containment activities, debris removal, relief well drilling, etc.), all vessels and activities must be carefully coordinated through a central command system known as Simultaneous Operations command (SIMOPS). SIMOPS exists to coordinate all activities on the ocean surface and subsea to ensure the safety of all vessels that are operating in close proximity.

After the vessel is in position, surface dispersant hoses are attached to the dispersant supply tanks. The dispersant manifold and clump weights with the coiled tubing are then deployed from the vessel. ROVs are used to connect the various components of the subsea dispersant injection system.

Figure 8 *The SWIS subsea first response toolkit*



Source: SWRP/SWIS

Once fully assembled and checked, the ROV then inserts the dispersant applicator (or application wand) into the flowing oil plume. A second ROV would assist the first ROV by providing lighting and video surveillance at the sea floor. Once the application wand is in position, dispersant pumping is initiated from the dispersant vessel. The pumping rate and dispersant operation is adjusted to maximize dispersant effectiveness, as indicated by in-situ operational monitoring.

The mobilization and assembly time described here would likely take several days. Once operational, however, the system can be sustained 24 hours per day since it is not constrained by daylight or anything but extreme surface weather. Even then, it may be possible to deploy a self-contained dispersant pumping system to the seafloor that could operate without any human intervention from the surface. One such system was developed by MWCC and is known as the Subsea Autonomous Dispersant Injection (SADI) system. The SADI system could be used to provide SSDI in the event that an emergency site evacuation of personnel was needed. It consists of a dispersant storage bladder, manifold and injection pump system that can be self-powered at the seafloor without any surface vessel support.

Subsea dispersant treatment rate

The dispersant treatment rate will depend on the precise circumstances of the oil release. The rate is most often expressed as a dispersant-to-oil ratio (DOR), being the required dispersant to produce a significant increase in the proportion of oil droplets that are small enough to be dispersed in the water column.

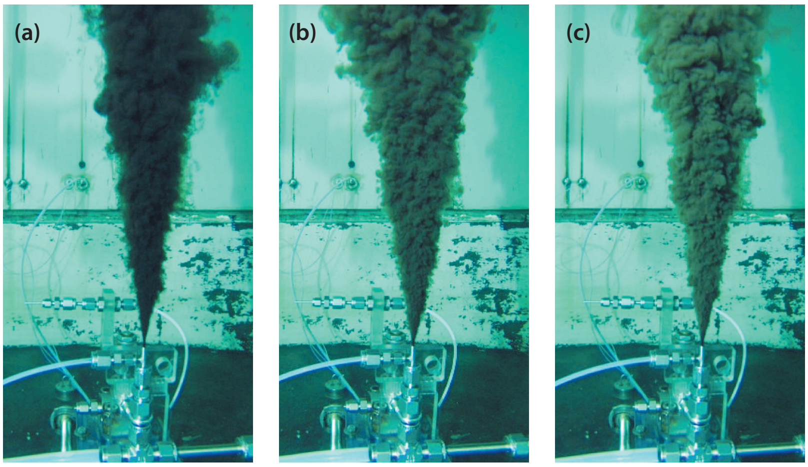
As noted in a previous section, it is not possible to know the subsea DOR that was used at the Macondo accident because the oil and gas flow rates were not known with any degree of accuracy.

Subsequent research (Brandvik *et al.,* 2014b) using scaled-down oil and gas releases has indicated that DORs of 1:50, 1:100 or less may be sufficient to cause substantial additional dispersion. During an incident the DOR would be based on observations from field monitoring. The dispersant pumping rate would be adjusted to achieve the minimum DOR needed for effective dispersion at the prevailing oil flow rate. See Table 13.

Table 13 *Dispersant pump rates required to achieve DORs of 1:50 and 1:100 for a range of oil flow rates*

Oil flow rate	Dispersant pump rate to achieve a DOR of 1:50		Dispersant pump rate to achieve a DOR of 1:100	
Barrels/day	US gallons/minute	Litres/minute	US gallons/minute	litres/minute
20,000	12	44	6	22
40,000	23	88	12	44
50,000	29	110	15	55
60,000	35	132	18	66
100,000	58	221	29	110

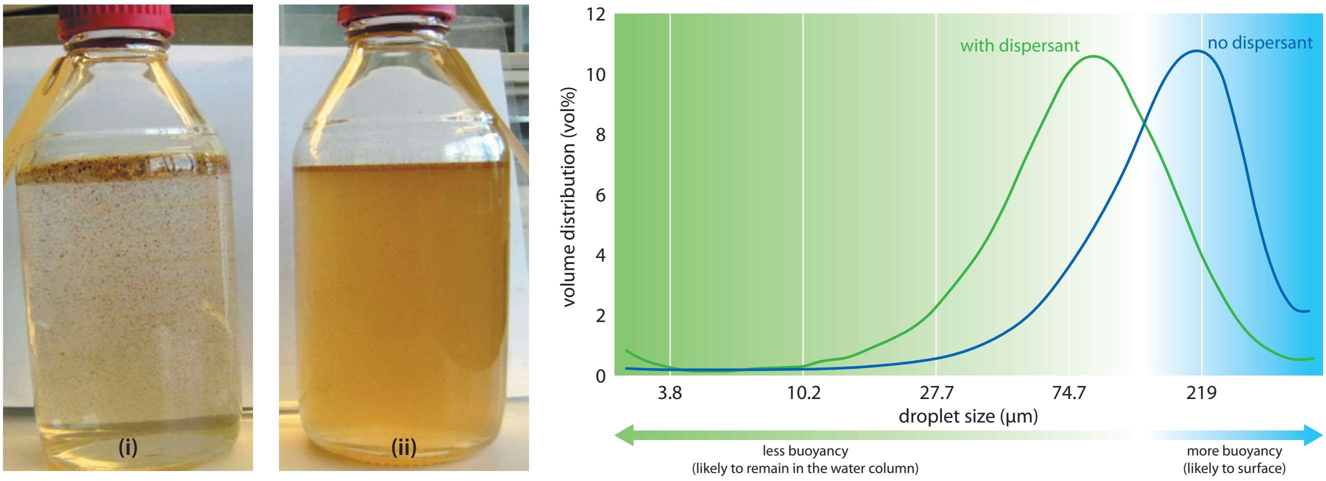
Figure 9 *Testing of Oseburg crude oil with, and without, dispersant added*



Left: testing of Oseburg crude oil with:
(a) no COREXIT® 9500 dispersant
(b) a DOR of 1:100
(c) a DOR of 1:50

The jars show the sampled water with:
(i) no dispersant
(ii) a DOR of 1:100

The graph below compares droplet size (a) when no dispersant is used; and (b) with a DOR of 1:100.



Purposes of subsea monitoring and sampling

Monitoring of a subsea dispersant operation

Although SSDI is an effective response technique, some of the oil may rise to the surface where more traditional oil spill monitoring techniques, such as the use of the SMART (Special Monitoring of Applied Response Technologies) protocols, can be used. Subsea monitoring programmes, therefore, will likely be implemented in conjunction with surface oil monitoring programmes.

The API has developed guidance for industry that is concerned primarily with operational monitoring (API, 2013). Its focus is to collect real-time or near real-time monitoring data that can be used to inform operational decisions for the current day or the next day. Monitoring data that takes days to collect and analyse does not support operational decision making. The API guidance groups monitoring activities into three phases which address:

- the assessment of subsea dispersant use effectiveness;
- characterization of the nature and extent of subsea, or near-surface, dispersed oil plumes; and
- an initial assessment of potential ecological effects as they relate to operational response decision making.

These phases are initiated in the order listed below, but each phase is based on information produced by the one that preceded it. Each phase is intended to be implemented on a time line that parallels the deployment of subsea dispersant injection resources during the response phase.

Phase 1: Assessment of subsea dispersant effectiveness

The initial question that must be answered by the subsea monitoring programme is, 'Is SSDI likely to be effective?'

Initially, monitoring at the release point is required to characterize the nature of the subsea oil release, estimate the oil and gas flow rates, and determine the properties and behaviour of the released oil. This information serves as pre-dispersant application background data and is used to guide the selection of dispersant injection methods and application rates.

Dispersant effectiveness can be estimated by comparing baseline data collected prior to dispersant application (i.e. visual appearance, air and water quality data) with data collected after initiation of dispersant application. Dispersant effectiveness can be assessed:

- Visually, by examining the output from video cameras on ROVs to assess whether the shape or colour of the oil discharge changes with dispersant addition.
- Acoustically, by analysing backscatter data generated from a ROV-mounted sonar. Sonar imaging of the jet of oil before and after dispersant injection can also give an indication of dispersant effectiveness. This is because sonar at the appropriate wavelength should give a strong backscatter signal prior to injection of dispersant and a much weaker backscatter signal after injection.
- Visually, by analysing the area of oil on the sea surface in aerial photographs. Aerial photography should be conducted before and during the subsea injection of dispersant to determine whether the use of dispersant is reducing the amount of oil reaching the surface.
- By air monitoring for VOCs and percentage lower explosive limit (LEL) on vessels in close proximity to the well site before and after dispersant addition.

None of these techniques taken individually can directly quantify dispersant effectiveness, but collectively, the data produced can provide sufficient evidence to support operational decisions to continue or modify dispersant use. Note that changes in surface expression of the oil will take time to express depending on surface winds/currents and the expected rise time of oil through the water column.

Phase 2: Characterization of the nature and extent of subsea, or near surface, dispersed oil plumes

Once it is assessed that SSDI is effective, the next phase of monitoring seeks to define the magnitude and behaviour of subsea dispersed oil plumes. The purposes of this monitoring phase are to:

- determine the location, extent, and characteristics of the dissolved and dispersed oil within the water column;
- characterize the lateral and vertical movement of the dissolved and dispersed oil; and
- document changes in the concentration of oil as it moves away from the source.

Local oceanographic data together with hydrodynamic models, if available, will determine the likely direction of movement of the subsurface oil.

Water column monitoring

The primary monitoring strategy involves using a research vessel outfitted with an A-frame and winch to conduct sampling casts using a CTD instrument and rosette sampler. The CTD is outfitted with a fluorimeter, dissolved oxygen sensor, and a deep-water laser-light scattering particle size analyser (e.g. LISST).

Using this strategy, water samples are collected and stored for subsequent detailed chemical analysis from depths determined by the results of the CTD casts for selected stations. Water samples for shipboard dissolved oxygen measurements should be collected at depths above, in and below any observed increase in fluorimetric response.

A laser-light scattering particle size analyser provides real-time in-situ measurements of the dispersed oil droplet size distribution. A significant shift from larger to smaller droplets sizes is indicative of dispersion of the oil.

Water sampling

The determination of water sampling site locations should be based on information from a reliable 3-D subsea oil spill model. If no such models are available, a sampling grid should be developed and centred on the spill location. Stations should be established in a radial pattern moving out from the centre, and fluorimeter readings from CTD casts and light scattering measurements should be used to determine the path of the dispersed oil.

Following retrieval of the instruments, the water samples should be transferred into suitable containers and stored until subsequent analysis.

Phase 3: Initial assessment of potential for ecological effects

This phase of monitoring seeks to fully characterize all water samples collected by CTD casts, using state-of-the-art laboratory analytical techniques for petroleum analytes and dispersant marker analysis. Once water samples are collected, they must be returned to land for rapid transfer to a certified, accredited laboratory utilizing appropriate chain-of-custody procedures. Vessel transit time, sample transfer time and laboratory processing can equate to a minimum of five days to process a sample, depending on the incident location. In the case of a larger spill event where significant numbers of samples are collected, it could take at least 7–10 days to receive detailed analytical results that have met quality assurance and control (QA/QC) standards. It is unlikely that many locations in the world would have sufficient laboratory facilities to sustain the level of toxicology and analytical chemistry required during the water sampling and monitoring phase of the dispersant response to the Macondo accident.

Conclusion

The reason for using dispersants, whether applied to oil floating on the surface or to a subsea release, is the same: to minimize the overall ecological and socio-economic damage, by preventing the released oil from drifting into nearshore or coastal habitats and onto the shore. Dispersant use on floating oil causes it to disperse into the upper layer of the water column where it is rapidly diluted and subsequently biodegraded. Subsea dispersant injection (SSDI) aims to prevent the oil released subsea from reaching the sea surface by dispersing it into the water close to the release. This provides a major health and safety benefit by greatly reducing the exposure of personnel responding near the release site to volatile organic compounds (VOCs).

The experience of subsea dispersant use gained at the Macondo accident in 2010 has shown that SSDI can be an effective response technique for subsea oil and gas blowouts. More oil would have come ashore if subsea dispersant use had not been undertaken. The challenges of conducting a response to oil released 5,100 feet (1,550 m) below the sea surface with a technique that had never been used before were considerable. A great deal of ingenuity and expertise were required to develop subsea dispersant injection (SSDI) into a viable response during the largest oil spill response ever conducted.

As a response to a subsea oil release, SSDI has many advantages over the strategy of responding to the released oil after it has reached the sea surface. Using SSDI:

- treats the oil at the point of release;
- uses less dispersant compared to surface application;
- reduces the potential exposure of responders to VOCs and oil;
- can be conducted continuously, day and night and in practically any weather conditions, unlike response techniques on the sea surface.

Using SSDI to disperse released oil into the water column has capabilities and limitations plus potential benefits and risks. When considering the use of SSDI, or any other response technique, the associated benefits and risks need to be addressed by conducting a net environmental benefit analysis (NEBA). The addition of dispersant will cause more of the released oil to be produced as smaller oil droplets that will be diluted in the water column and subsequently biodegraded to a very large extent. The use of SSDI has the following benefits:

- Effectively dispersing the released oil into the water column prevents the oil from reaching the sea surface, from where it could drift ashore, potentially causing serious damage to oil-sensitive coastal habitats and disrupting socio-economic activities.
- Dispersing the oil into the water as small oil droplets permits rapid colonization by petroleum degrading microorganisms that occur naturally in ocean environments. These microorganisms will substantially biodegrade the majority of the oil within days and weeks. The dispersant will also be biodegraded.

However, increasing the amount and concentrations of dispersed oil in the water increases the risk of potential harm to marine organisms by exposure to dispersed oil, particularly in the vicinity of the source.

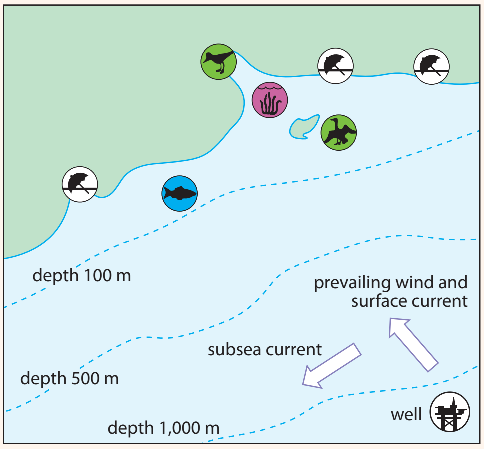
The trade-offs involved in using SSDI need to be understood by all concerned and, ideally, should be addressed during contingency planning.

The logistics of conducting SSDI require considerable specialist equipment, trained personnel and support. Multiple ROVs will be required with dedicated offshore supply vessels. Subsea dispersant use requires subsea monitoring to assess whether it is effective and where the subsea plumes of oil would be transported by the prevailing deep water currents. To address concerns about the possibility of toxic effects on marine organisms from the dispersed oil, it may be appropriate to conduct extensive water monitoring and water-sampling surveys with subsequent chemical analysis and toxicity testing. This was done at the Macondo accident. Although research is still under way at the time of preparation of this guide, available data indicate that concerns about substantial toxicity to marine organisms, oxygen depletion in the water due to biodegradation and the persistence of dispersant in the water column were demonstrated to be unfounded, and subsea dispersant use proved to be a very effective spill response tool.

Annex: Outline of NEBA for four subsea release planning scenarios

Scenario 1

An exploration well suffers loss of control including failure of the blowout preventer. Crude oil and gas are released, with the oil estimated to be flowing at 3,000 m^3 (19,000 bbls) per day.



- The well is in a water depth of 1,100 m.
- Surfacing oil slicks are drifting towards the shore under the influence of a prevailing 15-knot wind and surface current.
- A subsea current runs parallel to the coast
- Wave height is around 1.5 m.
- There are fishing grounds closer to the coast and seagrass beds in shallow water.
- Coastal resources that could be impacted by the oil include an estuarine mudflat that supports a large population of wading birds. An offshore island supports a seabird colony. There are three popular tourist resorts in the vicinity.

Summary of NEBA

Evaluate data

With no intervention and under prevailing conditions, modelling predicts an 80% probability that surfacing spilled oil would reach the shore, with oil reaching the coast after four days. During this time the spilled oil would become progressively 'weathered' and emulsified. The spilled oil volume would initially decrease due to evaporative loss, but then increase due to emulsification. This could result in up to 10,000 m^3 per day of emulsified oil threatening the coast after four days. Gas released within the well fluids would dissolve before reaching the surface.

Predict outcomes

The nearshore and coastal sensitivities are very high and their protection from oil would result in high environmental benefit. The estuarine mudflat is biologically productive and difficult to either protect with booms or clean up if oiled. The seabird colony does not contain threatened species but adds to the attraction of the area for tourists, with daily boat trips. The tourist resorts are a major part of the regional economy, relying on popular sandy beaches and watersports. The tourism is seasonal but this scenario falls within the main season. The threat to beaches would cause significant immediate disruption and has the potential to dent confidence in the area and reduce future reservations. The inshore fishery is locally important but economically small in relation to tourism.

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Balance trade-offs

At-sea mechanical recovery or in-situ burning alone could not deal with the amount of spilled oil in the time available. Surface use of dispersant is possible; the crude oil is tested to be amenable to dispersant use prior to emulsification, with a window of opportunity of around 24 hours. The prevailing conditions of a 1.5-metre wave height and 15-knot wind are good for dispersant use. However, the surfacing oil would rapidly spread and fragment, presenting challenges for targeting and encountering the floating oil even using a combination of vessels and aerial systems. Approximately 150 m^3 of dispersant would need to be applied each day, based on a dispersant-to-oil ratio (DOR) of 1:20. An aerial application system is available within 24 hours, capable of applying up to 100 m^3 of dispersant per day. First response is available from a standby vessel with a boat spray system and stock of 5 m^3 of dispersant.

Mobilizing a subsea dispersant injection system as part of a capping system would allow treatment to commence within seven days, with dispersant supplied from the global stockpile. Injection at the well head would greatly increase both the targeting of the dispersant operation and the volume of oil surfacing. The DOR could be decreased to 1:50 or less, reducing the volume of dispersant used per day by more than 50%. Surface dispersant application could then be scaled down or stopped.

Enhancing the subsea dispersion of oil by using dispersant injection would pose a heightened risk to pelagic marine life, primarily within a few kilometres of the well location. However, dilution of dispersed oil would (i) reduce concentrations to below toxicity levels in the wider area, (ii) enhance biodegradation and (iii) greatly mitigate gross oiling of the sensitive coastal zone.

It is anticipated that the well would be capped within 15 days.

Select best options

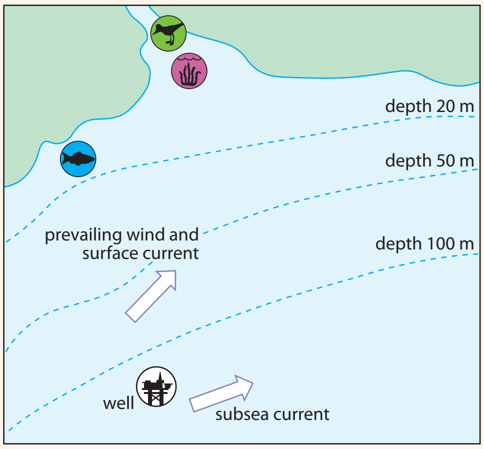
Initial surface dispersant use on the floating spilled oil, followed by subsea injection as soon as it can be mobilized, would be effective, and would be the primary response tool.

Inshore containment and recovery operations would be mobilized and targeted around the ecologically-sensitive areas.

Shoreline clean-up would be carried out around the sandy tourist beaches.

Scenario 2

An exploration well suffers loss of control including failure of the blowout preventer. Crude oil and gas are released, with the oil estimated to be flowing at around 3,000 m^3 (19,000 bbls) per day.



- The well is in a water depth of 130 m.
- Surfacing oil slicks are drifting towards the shore under the influence of a prevailing 10-knot wind and surface current.
- A subsea current runs parallel to the coast.
- Wave height is around 0.5 m.
- There are fishing grounds closer to the coast and seagrass beds in shallow water.
- Coastal resources that could be impacted by the oil include an estuarine mudflat that supports a large population of wading birds.

Summary of NEBA

Evaluate data

With no intervention and under prevailing conditions, modelling predicts a 95% probability that surfacing spilled oil would reach the shore, with oil reaching the coast after approximately two days. During this time the spilled oil would become progressively 'weathered' and emulsified. The spilled oil volume would initially decrease due to evaporative loss, but then increase due to emulsification. This could result in up to 10,000 m^3 per day of emulsified oil threatening the coast after two days.

Predict outcomes

The nearshore and coastal sensitivities are high and their protection from oil would result in high environmental benefit. The estuarine mudflat is biologically productive and difficult to either protect with booms or clean up if oiled. The inshore fishery is locally important.

Balance trade-offs

The gas included in the well fluids would not have time to fully dissolve and would surface at the well site. This would severely restrict operations in the vicinity of the site due to safety concerns. Surface pollution response would be limited to sea areas away from the site.

At-sea mechanical recovery or in-situ burning alone could not deal with the amount of spilled oil in the time available. Surface use of dispersant is possible; the crude oil is tested to be amenable to dispersant use prior to emulsification, with a window of opportunity of around

continued …

24 hours. The prevailing conditions of a 0.5-metre wave height and 10-knot wind are good for dispersant use. However, the surfacing oil would spread rapidly and fragment, especially under the influence of gas within the well fluids, presenting challenges for targeting and encountering the floating oil even using a combination of vessels and aerial systems. Approximately 150 m^3 of dispersant would need to be applied each day to treat all the oil, based on a dispersant-to-oil ratio (DOR) of 1:20. An aerial application system is available within 24 hours, capable of applying up to 100 m^3 of dispersant per day. First response is available from a standby vessel with a boat spray system and stock of 5 m^3 of dispersant. Spraying would be allowed up to the 20-m depth contour in line with national regulations.

Mobilizing a subsea dispersant injection system may be delayed or restricted by the presence of gas at the surface. Specific assessments would be carried out to investigate the feasibility of deploying a subsea injection system. If it was considered feasible, injection at the well head would greatly increase the targeting of the dispersant operation and reduce by a large amount the volume of oil surfacing. The DOR could be decreased to 1:50 or less, which could also lead to a reduction in the volume of dispersant used per day by more the 50%. In this circumstance, the gas lift may bring dispersed oil into the upper water column, rather than creating a subsea plume. Surface dispersant application could be greatly scaled down or stopped.

The enhancement of subsea dispersed oil through dispersant injection would pose a heightened risk to pelagic marine life, primarily within a few kilometres of the well location. Dilution of dispersed oil would (i) reduce concentrations to below toxicity levels in the wider area, (ii) enhance biodegradation and (iii) greatly mitigate gross oiling of the sensitive coastal zone.

Depending on the circumstances, the well would either be capped within 15 days or the flow stopped when a relief well could be drilled.

Select best options

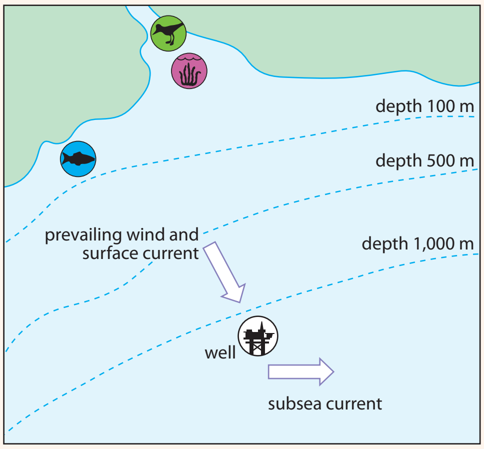
Initial surface dispersant use on the floating spilled oil, followed by subsea injection if it can be safely mobilized and deployed, would be an effective part of the response.

Inshore containment and recovery operations would be mobilized and targeted around the ecologically sensitive inlet. As the area is remote from major population and habitations, inshore in-situ burning would be mobilized.

Shoreline clean-up options would be considered in the light of the extent and type of coastal habitats affected.

Scenario 3

An exploration well suffers loss of control including failure of the blowout preventer. Crude oil and gas are released, with the oil estimated to be flowing at around 2,000 m^3 (12,500 bbls) per day.



- The well is in a water depth of 1,200 m.
- Surfacing oil slicks are drifting away from the shore under the influence of a prevailing 20–25 knot wind and surface current.
- A subsea current runs parallel to the coast.
- Wave height is around 2.5 m.
- There are fishing grounds closer to the coast and seagrass beds in shallow water but these are currently not being threatened.
- However, coastal resources that could be impacted by the oil if the wind changed direction include an estuarine mudflat that supports a large population of wading birds. An offshore island supports a seabird colony. There are three popular tourist resorts in the vicinity.

Summary of NEBA

Evaluate data

With no intervention and under prevailing conditions, modelling predicts a 0% probability that surfacing spilled oil would reach the shore. The modelling predicts that a significant proportion of the subsea release will disperse naturally. Furthermore, surfacing oil will break-up and dissipate under the prevailing rough sea conditions resulting in only transient surface oil slicks. Gas released within the well fluids would dissolve before reaching the surface.

Predict outcomes

The nearshore and coastal sensitivities are very high and their protection from oil would result in high environmental benefit. However, the current prevailing weather conditions indicate that the coastal resources are not under immediate threat of oiling.

Balance trade-offs

Prevailing rough sea conditions would preclude the use of any on-water containment techniques (mechanical recovery and in-situ burning), leaving subsea dispersant injection and surface dispersant application as the only viable active response options to treat any floating oil.

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The current predictions are for continuing offshore prevailing winds between 20–25 knots for the next 3–5 days. Modelling indicates that this will continue to break up any surfacing oil, without the formation of persistent slicks.

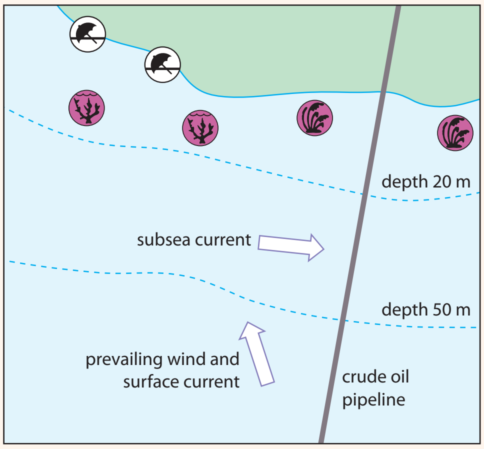
Select best options
Aerial surveillance and monitoring of the offshore area around the release is required to assess and verify modelling predictions, including the rapid dissipation of any surfacing oil slicks.

The mobilization to a standby condition of subsea dispersant injection and surface application capability would be undertaken as a precaution. The dispersant option would only be utilized if the weather abated to the extent that observed persistent surface slicks began to form. The initial preference would then be to inject dispersant subsea, to provide the most efficient means to reduce or prevent oil from reaching the surface.

Continual monitoring of the 5–10 day weather forecast would inform any decisions to mobilize other response tools, including offshore containment systems and shoreline protection capability. However, the locality has persistent offshore winds during the season in which this incident has occurred, and it is therefore unlikely that these resources will be needed in the medium term.

Scenario 4

A crude oil pipeline suffers damage due to a vessel dragging its anchor. The line is shut down but oil is detected on the sea surface.



- The incident occurs in a water depth of 50 m.
- Surfacing oil slicks are drifting towards the shore under the influence of a prevailing 10-knot wind and surface current.
- A subsea current runs parallel to the coast.
- Wave height is around 0.5 m.
- There are mangroves along the coast and tourist resorts with offshore coral reefs to the west.

Summary of NEBA

Evaluate data

With no intervention and under prevailing conditions, modelling predicts a 98% probability that surfacing spilled oil would reach the shore, with oil reaching the coast after approximately 24 hours. During this time the spilled oil would become progressively 'weathered' and emulsified. The volume of spilled oil would initially decrease due to evaporative loss, but then increase due to emulsification. The maximum volume in the pipeline is approximately 2,000 m^3.

Predict outcomes

The coastal ecological sensitivities are high and their protection from oil would result in high environmental benefit. The mangroves are biologically productive and difficult to either protect with booms or clean up if oiled. The tourist resorts are luxury style and rely heavily on pristine beaches and scuba diving clientele.

Balance trade-offs

Depending on the extent of pipeline damage, an initial release of oil would be expected to be followed by lower volume leakage.

Preference would be given to inshore mechanical recovery, and systems would be mobilized. Surface use of dispersant is possible; the crude oil is tested to be amenable to dispersant use prior to emulsification. The prevailing conditions of a 0.5-metre wave height and 10-knot wind

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are good for both recovery and dispersant use. An aerial application system is available within 6 hours, capable of applying up to 15 m^3 of dispersant per day. Spraying would be allowed up to the 20 m depth contour and more than 2 km away from coral reefs in line with national regulations.

Mobilizing a subsea dispersant injection system would not be feasible, as there is no suitable subsea mixing energy from such a pipeline release.

Select best options
Initial surface dispersant use on the floating spilled oil would provide the most rapid response and provide the best option for protection of the critically important mangrove habitat. This would be supported by the use of mechanical recovery operations inside the 20-m contour. Preparations would be made for clean-up of tourist resort beaches where appropriate.

References

Adams, E. E., and Socolofsky, S. A. (2005). *Review of Deep Oil Spill Modeling Activity Supported by the DeepSpill JIP and Offshore Operators Committee*. December 2004, revised 2005. www.researchgate.net/publication/265031649_DEEP_OIL_SPILL_MODELING_ACTIVITY_SUPPORTED_BY_THE_DEEPSPILL_JIP_AND_OFFSHORE_OPERATORS_COMMITTEE

Al-Sabagh, A. M., El-Hamouly, S. H., Atta, A. M., El-Din, M. R. N. and Gabr, M. M. (2007). Synthesis of some oil spill dispersants based on sorbitol esters and their capability to disperse crude oil on seawater to alleviate its accumulation and environmental impact. In *Journal of Dispersion Science and Technology*, Vol. 28, Issue 5, pp. 661-670.

American Academy of Microbiology. (2011). *Microbes & Oil Spills FAQs.* A report from the American Academy of Microbiology, 1752 N Street, NW Washington, DC 20036. www.asm.org.

Anderson, J., Neff, J., Cox, B., Tatem, H. and Hightower G. M. (1974). Characteristics of dispersions and water-soluble extracts of crude and refined oils and their toxicity to estuarine crustaceans and fish. In *Marine Biology*, Vol. 27, Issue 1, pp. 75-88.

API (2013). *Industry Recommended Subsea Dispersant Monitoring Plan. Version 1.0*. American Petroleum Institute (API) Technical Report 1152, September 2013. 20pp.

Atlas, R. M. and Bartha, R. (1992). Hydrocarbon Biodegradation and Oil Spill Bioremediation. In *Advances in Microbial Ecology*, Vol. 12, pp. 287–338.

Atlas, R. M. and Cerniglia, C. E. (1995). Bioremediation of Petroleum Pollutants: Diversity and environmental aspects of hydrocarbon biodegradation. In *BioScience*, Vol. 45, Issue 5, pp. 332-338.

Brandvik, P. J. and Daling, P.S. (1998). Optimisation of oil spill dispersant composition by mixture design and response surface methods. In *Chemometrics and Intelligent Laboratory Systems*, Vol. 42, pages 63-72. ISSN:0169-7439. DOI:10.1016/S0169-7439(98)00009-4

Brandvik, P. J., Johansen, Ø., Leirvik, F., Farooq, U. and Daling, P. S. (2013). Droplet breakup in subsurface oil releases – Part 1: Experimental study of droplet breakup and effectiveness of dispersant injection. In *Marine Pollution Bulletin*, Vol. 73, Issue 1, pp. 319-326. doi:10.1016/j.marpolbul.2013.05.020

Brandvik, P. J., Johansen, Ø. and Farooq, U. (2014a). Subsea Release of Oil & Gas – A Downscaled Laboratory Study Focused on Initial Droplet Formation and the Effect of Dispersant Injection. *International Oil Spill Conference Proceedings:* May 2014, Vol. 2014, No. 1, pp. 283-298.

Brandvik, P. J., Johansen, Ø., Farooq, O., Angell, G. and Leirvik, F. (2014b). *Subsurface oil releases - Experimental study of droplet distributions and different dispersant injection techniques Version 2*. A scaled experimental approach using the SINTEF Tower basin. SINTEF report no. A26122. Trondheim, Norway.

Brochu, C., Pelletier, É., Caron, G. and Desnoyers, J. E. (1986). Dispersion of crude oil in seawater: the role of synthetic surfactants. In *Oil and Chemical Pollution*, Vol. 3, No. 4, 257-279.

Campo, P., Venosa, A. D. and Suidan, M. T. (2013). Biodegradability of COREXIT 9500 and Dispersed South Louisiana Crude Oil at 5 and 25 °C. In *Environmental Science & Technology*, Vol. 47, No. 4, pp. 1960-1967.

Chevron, 2012. *Frade Response: Updates and Information on Our Work to Resolve the Frade Field Incident in Brazil's Campos Basin*. www.chevron.com/fraderesponse

Di Toro, D. M., McGrath, J. A. and Stubblefield, W. A. (2007). Predicting the toxicity of neat and weathered crude oil: Toxic potential and the toxicity of saturated mixtures. In *Environmental Toxicology and Chemistry*, Vol. 26, Issue 1, pp. 24-36.

Farrington, J. (1980). *NOAA Ship RESEARCHER/Contract Vessel PIERCE Cruise to IXTOC-I Oil Spill: Overview and Integrative Data Assessment and Interpretation.* A summary and assessment report of data collected during research cruises in the Gulf of Mexico during the Ixtoc I oil spill. Woods Hole Oceanographic Institution. www.whoi.edu/oil/ixtoc-I

Fiocco, R. J., Lessard, R. R., Canevari, G. P., Becker K. W. and Daling, P. S. (1995). The Impact of Oil Dispersant Solvent on Performance. In *The use of Chemicals in Oil Spill Response*. ASTM STP 1252, P. Lane, Ed., American Society for Testing and Materials, Philadelphia, USA.

GESAMP (2014). Revised GESAMP Hazard Evaluation Procedure for Chemical Substances Carried by Ships, 2nd Edition (IMO/FAO/UNESCO-IOC/WMO/IAEA/UN/UNEP/UNIDO/UNDP) Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection, Rep. Stud. GESAMP No. 64. www.gesamp.org/publications/publicationdisplaypages/rs64

Hazen, T. C., Dubinsky, E. A., DeSantis, T. Z., Andersen, G. L., Piceno, Y. M., Singh, N., Jansson, J. K., Probst, A., Borglin, S. E., Fortney, J. L., Stringfellow, W. T., Bill, M., Conrad, M. E., Tom, L. M., Chavarria, K. L., Alusi, T. R., Lamendella, R., Joyner, D. C., Spier, C., Baelum, J., Auer, M., Zemla, M. L., Chakraborty, R., Sonnenthal, E. L., D'haeseleer, P., Holman, H-Y. N., Osman, S., Lu, Z., Van Nostrand, J. D., Deng, Y., Zhou, J. and Mason, O. U. (2010). Deep-Sea Oil Plume Enriches Indigenous Oil-Degrading Bacteria. In *Science*, Vol. 330, No. 6001, pp. 204-208. DOI:10.1126/science.1195979.

Heitkamp, M. A. and Cerniglia, C. E. (1987). Effects of chemical-structure and exposure on the microbialdegradation of polycyclic aromatic-hydrocarbons in freshwater and estuarine ecosystems. In *Environmental Toxicology and Chemistry*, Vol. 6, Issue 7, pp. 535-546.

Hemmer, M J., Barron, M. G. and Greene, R. M. (2010). *Comparative Toxicity of Eight Oil Dispersant Products on Two Gulf of Mexico Aquatic Test Species*. U.S. Environmental Protection Agency Office of Research and Development. U.S.EPA/ORD Contributors: National Health and Environmental Effects Research Laboratory.

IPIECA/IMO/IOGP (2012). *Sensitivity mapping for oil spill response*. IPIECA-IOGP Good Practice Guide Series, Oil Spill Response Joint Industry Project (OSR-JIP). IOGP Report 477. http://oilspillresponseproject.org/completed-products

IPIECA-IOGP (2014). *Finding 2: Regulatory approval of dispersant products and authorization for their use*. Finding 2 of the IOGP Global Industry Response Group (GIRG) response to the Deepwater Horizon incident in the Gulf of Mexico in April 2010, Oil Spill Response Joint Industry Project (OSR-JIP). http://oilspillresponseproject.org/completed-products

IPIECA-IOGP (2015). *Dispersants: surface application. Good practice guidelines for incident management and emergency response personnel*. IPIECA-IOGP Good Practice Guide Series, Oil Spill Response Joint Industry Project (OSR-JIP). IOGP Report 532. http://oilspillresponseproject.org/completed-products

IPIECA-IOGP (2015a). *Impacts of oil spills on marine ecology*. IPIECA-IOGP Good Practice Guide Series, Oil Spill Response Joint Industry Project (OSR-JIP). IOGP Report 525. http://oilspillresponseproject.org/completed-products

IPIECA-IOGP (2015b). *Impacts of oil spills on shorelines*. IPIECA-IOGP Good Practice Guide Series, Oil Spill Response Joint Industry Project (OSR-JIP). IOGP Report 534. http://oilspillresponseproject.org/completed-products

IPIECA-IOGP (2015c). *Net environmental benefit analysis (NEBA)*. IPIECA-IOGP Good Practice Guide Series, Oil Spill Response Joint Industry Project (OSR-JIP). IOGP Report 527. http://oilspillresponseproject.org/completed-products

IPIECA-IOGP (2015d). *Contingency planning for oil spills on water*. IPIECA-IOGP Good Practice Guide Series, Oil Spill Response Joint Industry Project (OSR-JIP). IOGP Report 519. http://oilspillresponseproject.org/completed-products

JAG (2010a). *Review of Preliminary Data to Examine Subsurface Oil In the Vicinity of MC252#1, May 19 to June 19, 2010*. Joint Analysis Group (JAG) for Surface and Sub-Surface Oceanography, Oil and Dispersant Data. http://service.ncddc.noaa.gov/rdn/www/activities/healthy-oceans/jag/reports/documents/JAG_Data_Report_2_FINAL.pdf

JAG (2010b). *Review of* R/V Brooks McCall *Data to Examine Subsurface Oil.* Joint Analysis Group (JAG) for Surface and Sub-Surface Oceanography, Oil and Dispersant Data. http://www.noaa.gov/sciencemissions/PDFs/JAG_Report_1_BrooksMcCall_Final_June20.pdf

JAG (2012). *Review of Subsurface Dispersed Oil and Oxygen Levels Associated with the Deepwater Horizon MC252 Spill of National Significance*. NOAA Technical Report NOS OR&R 27, pp. 95. Joint Analysis Group (JAG) for Surface and Sub-Surface Oceanography, Oil and Dispersant Data.

Johansen, Ø., Brandvik, P. J. and Farooq, U. (2013). Droplet breakup in subsea oil releases – Part 2: Predictions of droplet size distributions with and without injection of chemical dispersants. In *Marine Pollution Bulletin*, Vol. 73,Issue 1, pp. 327-335. doi:10.1016/j.marpolbul.2013.04.012

Johansen, Ø., Rye, H. and Cooper, C. (2003). DeepSpill—Field Study of a Simulated Oil and Gas Blowout in Deep Water. In *Spill Science & Technology Bulletin*, Vol. 8, Issues 5–6, pp. 433–443. doi:10.1016/S1353-2561(02)00123-8.

Johansen, Ø., Rye, H., Melbye, A. G., Jensen, H. V., Serigstad, B. and Knutsen, T. (2001). *Deepspill JIP experimental discharges of gas and oil at Helland Hansen*. SINTEF Technical Report, June 2000.

King, G. M., Kostka, J. E., Hazen, T. and Sobecky, P. (2014). Microbial Responses to the Deepwater Horizon Oil Spill: From Coastal Wetlands to the Deep Sea. In *Annual Review of Marine Science*, Vol. 7, pp. 377-401. DOI:10.1146/annurev-marine-010814-015543. www.annualreviews.org/doi/abs/10.1146/annurev-marine-010814-015543

Kvenvolden, K. A. (2003). Natural seepage of crude oil into the marine environment. In *Geo-Marine Letters*, Vol. 23, Issues 3-4, pp.140-146.

Lindstrom, J. E. and Braddock, J. F. (2002). Biodegradation of petroleum hydrocarbons at low temperature in the presence of the dispersant COREXIT 9500. In *Marine Pollution Bulletin*, Vol. 44, Issue 8, pp.739-747.

MacNaughton, S. J., Swannell, R. P. J., Daniel, F. and Bristow, L. (2003). Biodegradation of dispersed Forties crude and Alaskan North Slope oils in microcosms under simulated marine conditions. In *Spill Science and Technology Bulletin*, Vol. 8, Issue 2, pp. 179-186.

Neff, J. M. and Burns, W. A. (1996). Estimation of Polycyclic Aromatic Hydrocarbon Concentrations in the Water Column Based on Tissue Residues in Mussels and Salmon: An Equilibrium Partitioning Approach. In *Journal of Environmental Toxicology and Chemistry,* Vol. 15, Issue 12, pp. 2240–2253.

NOAA (2010). *Analysis of Hydrocarbons in Samples Provided from the Cruise of the R/V* WEATHERBIRD II*, May 23-26, 2010*. National Oceanic and Atmospheric Administration (NOAA), Silver Spring, Maryland, USA. www.noaanews.noaa.gov/stories2010/.../noaa_weatherbird_analysis.pdf

NRT (2013). *Environmental Monitoring for Atypical Dispersant Operations: Including Guidance for: Subsea Application; Prolonged surface Application.* U.S. National Response Team (NRT). www.nrt.org/production/NRT/NRTWeb.nsf/PagesByLevelCat/Level3Oil?Opendocument

OSAT (2010). *Summary Report for Sub-Sea and Sub-Surface Oil and Dispersant Detection: Sampling and Monitoring*. Report prepared by the Operational Science Advisory Team (OSAT), Unified Area Command, for the US Coast Guard, 17 December 2010. www.restorethegulf.gov/sites/default/files/documents/pdf/OSAT_Report_FINAL_17DEC.pdf

OSAT (2011) *Summary Report for Sub-Sea and Sub-Surface Oil and Dispersant Detection: Ecotoxicity Addendum*. Report prepared by the Operational Science Advisory Team (OSAT), Gulf Coast Incident Management Team, for the US Coast Guard, 8 July 2011. www.restorethegulf.gov/sites/default/files/u306/FINAL%20OSAT%20Ecotox%20Addendum.pdf

Prince, R. C. (1997). Bioremediation of marine oil spills. In *Trends in Biotechnology,* Vol. 15, Issue 5, pp. 158-160.

Prince, R. C., McFarlin, K. M., Butler, J. D., Febbo, E. J., Wang, F. C. Y. and Nedwed, T. J. (2013). The primary biodegradation of dispersed crude oil in the sea. In *Chemosphere*, Vol. 90, Issue 2, pp. 521-526.

Singer, M. E. and Finnerty, W. R. (1984). Microbial metabolism of straight-chain and branched alkanes. In Atlas, R. M. (Ed.) *Petroleum Microbiology*, pp. 1-59. Macmillan Publishing Company, New York.

Smith, J. E. (1968). *Torrey Canyon Pollution and Marine Life*. Cambridge University Press, New York.

Socolofsky, S. A. (2012). *Integral plume modeling of subsea accidental oil-well blowouts*. Presentation to the Nearfield Modeling ListServe, 11 June 2012.
https://ceprofs.civil.tamu.edu/ssocolofsky/nfm/Downloads/socolofsky_Jun_11.pdf

US EPA (2010). *Comparative Toxicity of Louisiana Sweet Crude Oil (LSC) and Chemically Dispersed LSC to Two Gulf of Mexico Aquatic Test Species*. August 2010 and the updated report of September 2010. Environmental Protection Agency, Office of Research and Development. Available at:
www.epa.gov/bpspill/dispersants-testing.html

US EPA (2010a). *Dispersant Monitoring and Assessment Directive—Addendum 3*. US Environmental Protection Agency Archive Document, 26 May 2010. www.epa.gov/bpspill/dispersants/directive-addendum3.pdf

US EPA (2010b). *Dispersant Monitoring and Assessment Directive for Subsurface Dispersant Application*. US Environmental Protection Agency Archive Document, 10 May 2010.
www.epa.gov/bpspill/dispersants/subsurface-dispersant-directive-final.pdf

US EPA (2012). Ecotoxicity categories for terrestrial and aquatic organisms. (Website—updated on 10 February 2015). www.epa.gov/oppefed1/ecorisk_ders/toera_analysis_eco.htm

US FDA (2010). *NOAA and FDA announce chemical test for dispersant in Gulf seafood: all samples test within safety threshold*. US Food and Drug Administration (FDA) website archives. 29 October 2010.
www.fda.gov/NewsEvents/Newsroom/PressAnnouncements/2010/ucm231653.htm

US FDA (2012). *Gulf Seafood is Safe to Eat after Oil Spill*. 'FDA Voice' — the official blog of the US Food and Drug Administration (FDA), 11 January 2012. http://blogs.fda.gov/fdavoice/?tag=gulf-seafood

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IPIECA

IPIECA is the global oil and gas industry association for environmental and social issues. It develops, shares and promotes good practices and knowledge to help the industry improve its environmental and social performance; and is the industry's principal channel of communication with the United Nations. Through its member led working groups and executive leadership, IPIECA brings together the collective expertise of oil and gas companies and associations. Its unique position within the industry enables its members to respond effectively to key environmental and social issues.

www.ipieca.org

IOGP International Association of Oil & Gas Producers

IOGP represents the upstream oil and gas industry before international organizations including the International Maritime Organization, the United Nations Environment Programme (UNEP) Regional Seas Conventions and other groups under the UN umbrella. At the regional level, IOGP is the industry representative to the European Commission and Parliament and the OSPAR Commission for the North East Atlantic. Equally important is IOGP's role in promulgating best practices, particularly in the areas of health, safety, the environment and social responsibility.

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