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Oil spill dispersants*

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INTRODUCTION

The purpose of any oil spill response is to minimise the damage that could be caused by the spill. Dispersants are one of the limited number of practical responses that are available to respond to oil spills at sea.

When oil is spilled at sea, a small proportion will be naturally dispersed by the mixing action caused by waves. This process can be slow and proceed to only a limited extent for most situations. Dispersants are used to accelerate the removal of oil from the surface of the sea by greatly enhancing the rate of natural dispersion of oil and thus prevent it from coming ashore. Dispersed oil will also be more rapidly biodegraded by naturally occurring microorganisms. The rationale for dispersant use is that dispersed oil is likely to have less overall environmental impact than oil that persists on the surface of the sea, drifts and eventually contaminates the shoreline.

The development of modern dispersants began after the *Torrey Canyon* oil spill in 1967. Many lessons have been learned since that spill, and consequently the modern dispersants and application techniques in use today have become an effective way of responding to an oil spill. For example, the dispersant response to the *Sea Empress* spill in 1996 demonstrated that dispersants can be very effective and prevent a much greater amount of environmental damage from being caused [6,14].

This paper describes the chemistry and physics of dispersants, planning and decision-making considerations, and finally their practical application and operational use in oil spill response.

THE CHEMISTRY OF DISPERSANTS

Dispersants are liquid blends of surfactants (surface active agents) and solvents, designed to hasten break-up of oil slicks into fine droplets that disperse naturally in the sea. The surfactants, which are the active components, are 'soap-like' molecular structures that have both water-seeking hydrophilic and oil-seeking lipophilic sections. Surfactants are commonly used in the cosmetic and food industries also. Because of their dual nature, the surfactant molecules in oil spill dispersants reach their lowest energy state by positioning themselves at oil–water interfaces, thereby lowering the oil-water interfacial tension and significantly lowering the energy required to generate oil droplets in water. In addition, droplets generated with dispersants are typically much smaller than would otherwise form by the natural energy of the sea.

The composition of dispersant products have evolved a long way from the aromatic solvent-based degreaser products originally used on the *Torrey Canyon* spill over 30 years ago off the coast of England. Early generations of acceptable dispersants were either water-based surfactant systems or nonaromatic hydrocarbon solvent-based systems. These generally required high application rates, e.g. a 1:3 dispersant:oil ratio (DOR), and additional mechanical agitation, such as by ship propellers, fire monitors or 'breaker boards.' Modern dispersants use solvent systems that allow much higher surfactant content, ranging up to about 65% surfactant. These modern 'concentrate' dispersants therefore are effective at lower application rates, e.g. 1:20 DOR or less. For example, at breaking wave sea conditions, application ratios of less than 1:100 DOR can be adequate for effective dispersion with a 'concentrate' dispersant [16].

The actual compositions of the specific dispersant products can, of course, differ significantly.

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However, based on a review of patent literature, the surfactants used in modern dispersants are generally blends of nonionic and anionic types. The nonionic types include sorbitan esters of fatty acids, polyalkoxylated sorbitan esters of fatty acids, polyalkoxylated fatty alcohols, polyethylene glycol esters of oleic acid and tall oil esters. Anionic type surfactants include salts of dialkyl sulfosuccinates and of alkyl benzene sulfonic acid. Specific examples of surfactants used are: sorbitan monolaurate, ethoxylated sorbitan trioleate, ethylene/propylene oxide condensates, ethoxylated tridecylphosphate, sodium dioctyl sulfosuccinate, sodium lauryl sulfate, and isopropylamine dodecyl benzene sulfonate.

A frequent approach used to formulate the blend of surfactant components is based on the hydrophilic-lipophilic balance (HLB) system [3]. This system uses a coding scale ranging from 0 to 20, based on solubility characteristics of the dispersant in water and oils. Lower HLB values are predominantly soluble in the oil phase and higher HLB values are predominantly soluble in the water phase. The surfactants are blended to an optimum dispersant HLB value (typically 10–11); in general, blends are more effective than a single surfactant at a given HLB value. While not thermodynamically rigorous, nor universally used, this approach can provide a useful starting basis for developing improved dispersant product formulations.

The solvent content of a dispersant has many important functions. First, of course, it must solubilize the blend of surfactant components and yield a liquid viscosity suitable for the various dispersant application systems. Secondly, it must penetrate into the oil when applied, and assist in the diffusion of surfactants through the oil slick to the oil–water interface. Low toxicity solvents used in modern dispersants include oxygenated compounds such as glycols and glycol ethers and petroleum-derived nonaromatic hydrocarbons. Specific examples include ethylene glycol monobutyl ether, dipropylene glycol monomethyl ether, de-aromatized kerosene and isoparaffinic solvents, some of which are also used in cosmetics and household cleaners. Components such as alcohols and water are sometimes used as cosolvents or cosurfactants to help solubilize the surfactants and modify viscosity.

THE PHYSICS OF DISPERSANT ACTION

A detailed description of the mechanism by which dispersants function is illustrated in Fig. 1 [8]. Dispersant is sprayed as fine droplets onto the oil slick. Preferably, the dispersant is used neat (undiluted) for highest effectiveness, although it can be applied in aqueous carrier systems such as used on boats. The dispersant droplets penetrate and mix into the slick, aided by the action of the solvent and the momentum of the droplet spray. As dispersant reaches the lower part of the oil slick, the surfactant molecules spread along the oil–water interface and lower the interfacial tension. Small droplets of oil then begin to break away and disperse into the upper zones of the water column. As surfactant is carried off with the oil droplets, additional surfactant in the oil phase replenishes the slick oil–water interface. Thus, the oil slick tends to be gradually depleted as droplets break away and more surfactant reaches the interface. The dispersed oil droplets are stabilized by the surfactant layer which prevents coalescence and resurfacing.

Neat dispersant drops in the 300–800 μm range are generally considered to be optimum for application efficiency and coverage of the slick. Finer droplets can be blown off-target by winds, and larger droplets may break through the oil slick too rapidly, without mixing efficiently into the oil slick. Dispersant formulations with more oleophilic characteristics will more readily coalesce and mix with the oil slick, thus providing a higher overall application efficiency. Water-based carrier systems tend to be less effective due to their lower affinity to the oil slick and consequent loss to the sea water, and are generally most effective on freshly spilled and low viscosity oils.

WHAT AFFECTS DISPERSANT EFFICIENCY/EFFECTIVENESS?

Clearly, the composition of the dispersant product and the application system are important factors in determining the effectiveness of the dispersant. Other important factors are the composition and state of the oil being dispersed, the ratio of dispersant to oil, and the amount of mixing energy in the system. Oil composition can vary considerably, from light crude oils which will evaporate to a significant degree, to medium crude oils with different amounts of aromatics, saturates, resins and asphaltenic and polar compounds, to heavy crude oils and fuel products with lower volatility and higher viscosity. In addition, the oil can become emulsified with water, causing a significant increase in volume and viscosity.

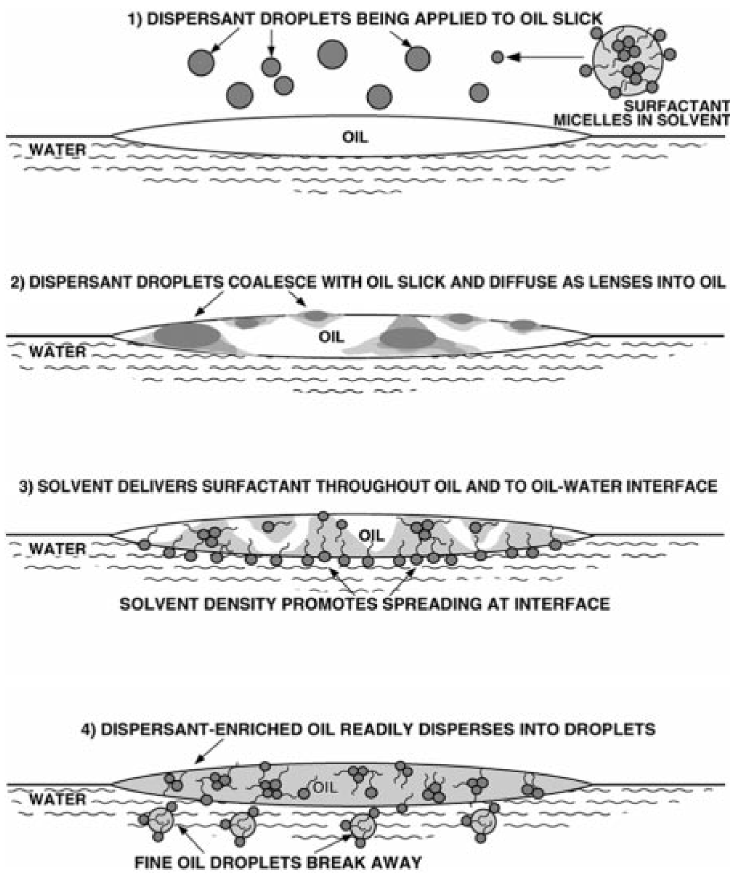

Fig. 1 Detailed mechanism of chemical dispersion.

In general, increasing the ratio of dispersant to oil (DOR) will increase the rate and degree of oil dispersion. A DOR of about 1:20 is generally suggested as a target for response planning purposes and is used in many standard laboratory effectiveness tests to compare dispersant performance. The actual DOR occurring in an oil spill response at sea, however, depends primarily on two factors, specifically the oil slick thickness and the dispersant application rate, i.e. the amount of dispersant sprayed per oil slick area (e.g. mL/m^2; L/hectare; gallons/acre). Slick thickness can vary over a wide range. For example, when oil emulsifies, the wind and currents can cause it to concentrate in patches that are several millimetres thick. In other areas of the same oil slick, e.g. sheen, the oil layer thickness may only be a few microns. While the dispersant application rate can be set by the spraying ship or aircraft, the oil thickness can generally only be estimated. Thus the treatment ratio (DOR) actually resulting at a particular area of an oil slick is not precisely determinable.

Higher energy conditions will increase the rate of oil dispersion, or, alternatively, allow effective dispersion at lower DORs. Thus, depending on circumstances, the overall treatment ratio of dispersant used to oil dispersed at some spills can be lower than that normally used in laboratory tests. For example, DORs from about 1:60–1:100 were found to be effective at the *Sea Empress* spill [6]. On the other hand, for difficult-to-disperse oils, such as viscous or emulsified oils, greater DORs (e.g. up to about 1:5) may be needed for effective dispersion.

An important feature of dispersants is the ability to break water-in-oil emulsions that form naturally as the oil slick weathers and tosses about on the sea surface. Recent laboratory and field experience have demonstrated the ability of some dispersants to break emulsions formed at sea, particularly before the extremely viscous and stable ‘mousse’ stage of emulsion forms [9,13]. This demulsification activity promotes coalescence of the water droplets in the emulsion, which in turn causes separation of water and lowering of viscosity. This step will slow down the dispersion process and can make effectiveness monitoring more difficult since oil releases more slowly into the water column. In addition, since a portion of the dispersant can be used up in the demulsification step, application of additional dispersant may be needed to increase the dispersion rate.

As mentioned, viscous difficult-to-disperse oils can require more than the typically targetted 1:20 DOR treatment. It should be noted that models for predicting the window of opportunity for dispersant use on a spill do not always account for specific differences between dispersants, such as the demulsification capability of the dispersant. The models may also not account for the possibility of higher dispersant treat rates and/or energy conditions other than those used in the standard laboratory testing. As such, models may predict a shorter window than actual for some oils and dispersants, and in practice, still require the judgement of oil spill responders experienced in their use.

EFFECTIVENESS TESTING OF DISPERSANTS

Over the years, a large number of laboratory tests have been developed by oil spill researchers to assess the effectiveness of oil spill dispersant formulations [5]. For approval purposes, various laboratory effectiveness tests have been adopted by government authorities generally on the basis of simplicity and cost factors. While some tests attempt to simulate sea application conditions, all aim primarily to simply rank the relative performance of dispersant products under a specific set of laboratory conditions, rather than to predict the actual percentage dispersion that will be experienced at sea with use of a specific dispersant product. In effect, these short-term laboratory tests are at best a ‘snap-shot’ in time of a much longer-term process.

Thus, the principal value of a laboratory test is to compare the performance of dispersant formulations under similar conditions, for the purpose of screening out less effective dispersants and approving the best performers for field applications. The different laboratory tests use a variety of test conditions, including the method of dispersant addition, type and duration of mixing energy, settling times (if any) after mixing, and ratio of water to oil; therefore, the magnitude of percentage oil dispersed in each of the tests will differ. Although there appears to be a rough correlation between tests for ranking, attempts to date to strictly correlate these laboratory test values with field experience have had limited success. The problem continues to be addressed by oil spill research scientists [15].

Laboratory tests are also useful to assess the relative dispersibility of specific crude oils and oil products [9] as well as to provide input to numerical weathering models that estimate the effective ‘time window’ for dispersant use on a specific oil. Here again, in view of the limitations of many of the laboratory tests, the data on percentage oil dispersed should be viewed as a relative guide to dispersibility rather than indicative of the absolute values to be expected in field applications.

THE DISPERSANT OPTION IN OIL SPILL RESPONSE

Mechanical recovery is generally considered as the primary option for responding to oil spills. However, oil spills on water rapidly spread into relatively thin surface slicks, making mechanical recovery of the oil difficult and inefficient in most cases, even under relatively calm sea conditions. For example, typical efficiencies cited for mechanical recovery are in the range of 10–20% of the spilled oil. Therefore, assuming 40% of the oil evaporates, as much as 40–50% may end up on shorelines, even after a typically effective mechanical recovery response. Dispersants, on the other hand, are well suited for treating oil slicks which cover large areas, and can prevent all or most of the oil from coming ashore. Also, whereas surface oil tends to be driven by winds into shorelines, dispersed oil is typically carried away from shorelines by water currents.

In some conditions, dispersant use may be the only practical response method. For example, at sea states above Beaufort Force 3 (i.e. winds above about 10 knots and wave heights above 1–2 m), mechanical containment and recovery becomes very difficult. The limit for effective dispersant treatment is considered to be above Beaufort Force 7 sea state (i.e. 30–35 knot wind speed and 6–8 m wave height). At very low wind speeds there will only be slow dispersion when dispersants are applied, although the dispersant will stay with the oil and more rapid dispersion will occur when the wind picks up. At very high wind speeds it will difficult to ensure accurate spraying of dispersant, however, lower dispersant treat ratios (DORs) and/or natural dispersion may be sufficient in these conditions. Thus, dispersants extend the weather conditions during which an effective response can be undertaken.

Although many reasons exist in support of dispersant use, dispersants have continued to be controversial in many parts of the world, with the main issues being effectiveness and environmental acceptability [12]. A detailed review by the US National Research Council, however, concluded that the use of dispersants as a first response option should be considered along with mechanical measures [21]. Also, an extensive study on ecological issues in dispersant use concluded that limited success in communicating existing scientific information to decision-makers and interest groups is the key obstacle to dispersant use [4]. (The section on the Debate on Dispersant Use also discusses this in more detail.)

Characteristics of dispersant use

Dispersants have many characteristics that make them attractive for use in oil spill response. Effective dispersants do the following:

- Greatly enhance the rate of natural dispersion and biodegradation by creating much finer oil drops and increased surface area [21,24];
- Decrease exposure of marine birds, mammals and shorelines to surface oil;
- Reduce coalescence and re-surfacing of dispersed oil;
- Delay/avoid formation of stable water-in-oil 'mousse' emulsions and, in some cases, break (demulsify) emulsions already formed.

Dispersants tend to work more slowly on thick and weathered oil slicks, thus more gradually releasing oil drops into the water column, as opposed to an instantaneous release. Also, released droplets will be carried along and diluted by water currents which may be flowing in a different direction than the wind-driven surface slick. A net effect of this is lower magnitude of local oil concentration to which fish are exposed.

Another consideration regarding dispersant use is that, if dispersion efficiency is less than initially projected, the options of using other oil spill response techniques, such as mechanical containment/recovery and burning, are still open. For example, oil that is not dispersed due to inefficient dispersant treatment is still amenable to recovery by skimming devices, including disc skimmers [23]. Of course, in addition to the possibility of sequential use of different response techniques, there is also the possibility of using an effective dispersant response on one part of the spill, while simultaneously using mechanical and/or burning response techniques at other parts of the spill.

THE DEBATE ON DISPERSANT USE

The debate on dispersant use has sometimes been cast as a 'fish vs. shoreline and birds' debate; use of dispersants favours sea birds and shorelines whilst threatening fish. This is an over-simplification of a complex issue, but the environmental acceptability of dispersants is still an important issue. Although there have been many advances in dispersant formulations and application methods in the last 30 years, planning for dispersant use also needs to overcome some obstacles of perception [12]. An example of arguments that have been used for and against are summarised in Table 1.

The specifics of the debate have been described in many references [e.g. 12,21] and only general points are addressed here.

Impact of dispersant use

The function of dispersants is to greatly enhance the rate at which oil is removed from the sea surface; it is transferred as fine droplets into the water column, where it can then more readily biodegrade. The potential environmental effects of doing this must be compared to the likely effects of permitting the oil to remain on the sea surface for a much longer time. The key issue in any spill response should not be whether there will be any environmental impact from using the response, but how to minimise the overall impact of the oil spill.

Successful use of modern, low toxicity dispersants causes a temporary increase in the dispersed oil concentration in the water column. Any marine organisms that are present in the locality may be exposed to locally elevated dispersed oil concentrations. A significant amount of data are available regarding the

Table 1 The dispersant debate

Those opposed to dispersant use argue:	Those in favour of dispersant use argue:
—It is better to remove spilled oil from the surface of the sea rather than force it into the water.	—Environmental damage is caused by exposure to spilled oil. The damage cannot be reversed, but can be minimised by rapid action. Rapid and total removal of spilled oil by mechanical means is rarely feasible.
—The use of dispersants ‘hides’ the problem rather than solving it.	—Dispersants accelerate a natural process and can provide a net environmental benefit by rapidly removing oil from the surface and thus preventing or minimising surface and shoreline impacts.
—Addition of chemicals into the environment is undesirable. —Dispersants are toxic, or their use causes the oil to have greater toxic effects than if dispersants were not used.	—Many oils exhibit toxic effects whether they are dispersed or not. Modern dispersants have low toxicity and when combined with oil do not add measurably to the environmental effects caused by the oil alone.
—Oil will disperse naturally, given enough time.	—Natural dispersion slows or even stops altogether when the oil emulsifies. —Emulsified oil poses a long-term hazard to the environment. Dispersants can remove the oil from the surface before it emulsifies and can retard emulsification.
—Dispersants are an unreliable technique because they do not always work	—Like every other response technique, dispersant use cannot be guaranteed to be effective in all circumstances
—Dispersants are used to avoid the expense of ‘better’ response options.	—Practical experience has shown that dispersants are one of the few effective response options available.

dispersed oil concentrations and exposure duration that can be expected after dispersant use, as well as the effects of this exposure on marine life [10,21]. In general, the data indicate that only shallow waters with poor circulation would be likely to reach oil concentrations of significant concern. While research work and experience are continuing to increase the knowledge and understanding of these exposures, experience to date indicates that the level of potential impact can be acceptable, and indeed preferable in many cases, to the alternative of not using dispersants. The recent well-monitored experience from the *Sea Empress* oil spill response [6,14] is a good example of this.

Toxicity of modern dispersants

The chemical cleaners used at the *Torrey Canyon* were toxic to marine life because they contained solvents composed of aromatic compounds, such as benzene, toluene and xylene. These solvents were especially suited for the primary purpose of these products; to remove oil, grease and dirt from surfaces such as dirty engines and garage floors. None of these components are used in modern dispersants; however, oils, particularly light distillate fuels, can contain a fair proportion of aromatic compounds. Although most of these rapidly evaporate, some will transfer into the sea where they may exert toxic effects, depending on the peak concentration reached. This can happen whether or not the oil is treated with dispersants. As an extreme example, the *North Cape* spill [20] of No. 2 fuel oil, used for domestic heating, demonstrated that oil with a high aromatics content, naturally dispersed by very rough seas into very shallow water, can exert narcosis-inducing or toxic effects, particularly to creatures such as lobsters and crabs. Dispersants were not and would not be recommended for this type of oil spill situation.

Modern dispersants are much less toxic than the oils they are used to disperse. Dispersants do have the potential to increase the rate of dissolution of the toxic low molecular weight aromatic components of the crude oil into the water column. In practice, however, most or all of these components will have already evaporated during the few hours prior to the application of dispersant. Thus, the increase in dissolution of these components because of dispersant use is likely to be very limited in the case of crude oils.

Natural dispersion and the use of dispersants

The forces of nature tend to spread and disperse spilled oil. Some oils, such as light distillate fuels (e.g. gasoline or kerosene) and very light crudes, will evaporate rapidly for the most part. Some crude oils will naturally disperse at a rapid rate in turbulent sea conditions. For example, almost all of the 84 000 tonnes of Gullfaks crude oil spilled at the *Braer* incident dispersed naturally in the very rough sea conditions [7]. The majority of crude oils, however, will not readily disperse under normal sea conditions; they emulsify and become very persistent on the sea surface and may eventually contaminate the shore. The judicious use of dispersant permits these oils to be more rapidly dispersed and more readily biodegraded at sea. Dispersant use can prevent or reduce the amount of damage that the surface oil would otherwise cause if driven ashore by winds.

Net environmental benefit analysis

The Net Environmental Benefit Analysis (NEBA) approach should be used to assess the overall effects of dispersant use or nonuse [10,11,14] (See also the paper by Baker in this issue). The NEBA should be conducted on a scenario-specific basis for all of the oil spill response methods. The essence of NEBA is to consider the overall effects of a response action, rather than concentrating on one particular issue. As stated earlier, the application of dispersants to oil spilled at sea may cause a temporary increase in dispersed oil concentration which can pose a threat, in a very limited volume of water, to sensitive marine life that may be present. In waters with good circulation, the dispersed oil concentration will rapidly drop to a very low, nontoxic level. In shallow water with poor circulation, the concentration of dispersed oil may be high enough and persist long enough that some localised damage to marine organisms occurs. Note that in many cases some damage to marine organisms can also occur even in a response where no dispersants are used.

More typically, effective dispersant use will minimize or prevent the exposure of marine birds and mammals to surface oil, and avoid subsequent stranding of oil on sensitive shorelines, where it could pose a longer term threat to sensitive resources. Thus, the NEBA-based decision on whether to use or not use dispersants would depend on the relative priority of protection of sensitive resources, the degree of impact and the time-scale for recovery of the particular resources and habitats involved.

PLANNING FOR DISPERSANT USE

Where dispersants are to be considered as part of the response strategy it is essential that the oil spill contingency plan (local or national) gives a clear policy statement on their use, on the procedures in place for prior approval, and on the resources available for a rapid response.

The following points should be considered when preparing an oil spill contingency plan in which dispersant use has a role.

Risk assessment

While prevention of oil spills should be of the highest priority, the risk of spills is ever-present and must be considered. Oil spills are caused by a variety of incidents; from relatively minor events such as the overfilling of tanks during crude oil loading, through ship and oil tanker accidents of varying degrees of severity, up to very large events such as blow-outs at offshore oil exploration and production facilities. Each spill scenario will have different characteristics, such as the type of oil released, the size of spill, the release rate and the location. These factors will influence the choice of the most appropriate response method, including dispersant use.

For example, the ‘window of opportunity’ for dispersant use, during which dispersants will be most effective, will depend on the type of oil released and the prevailing environmental conditions of temperature, wind speed and sea state (see paper by Tedeschi in this issue). The quantity of oil likely to be spilled and the release rate will determine how much dispersant and application equipment will be needed. The likely spill location, and the distance from prepositioned stockpiles of response equipment, will determine the most suitable dispersant application system and the time available for response.

Sensitivity mapping

The aim of any oil spill response is to minimise the damage (environmental, amenity or economic) that would be caused by an oil spill. The resources that could be impacted by an oil spill need to be identified and their location mapped. Sensitive natural resources include sea birds and sea mammals, specific habitats such as mud flats, salt marshes or coral reefs or locations such as fish nurseries [2]. Economic resources that could be impacted by oil pollution include fishing grounds, water intakes and tourist beaches.

Consequence analysis

Having identified the risks of oil pollution and having mapped the sensitive resources, a consequence analysis of different oil spill response scenarios should be undertaken. This will require information about the wind and current data in the region so that oil slick trajectories and response method effectiveness can be predicted/estimated. Computer models are usually employed to predict the trajectory of the spilled oil and the changes in the properties and behaviour that will be caused by weathering. The probable damage that would be caused by an oil spill without any response or with a low effectiveness response should be considered.

Evaluation of the effectiveness of alternative response strategies

Once the potential for damage caused by a particular oil spill scenario has been established, the potential reduction in the amount of damage achievable by each of the response options (e.g. mechanical recovery, dispersants, *in-situ* burning and do nothing at sea) can be assessed [22]. This involves an evaluation of the expected effectiveness of each option within the constraining time limits. Since the purpose of the response is to minimise the damage caused by the oil spill, a quantitative set of criteria or measure of success will need to be defined so that alternatives can be compared. In some cases the measure of success can be quite simple; the amount of oil predicted to reach a particularly sensitive shoreline resource or habitat may be a sufficient guide to probable benefit. In other cases, more complex ‘trade-offs’ between accepting damage to some resources, while protecting more sensitive or economically important resources according to the NEBA process, will have to be made.

Approval procedures

Time is always of the essence in responding to an oil spill. Dispersant products that are approved or certified by government authorities should be available from stockpiles. The approval/certification procedures generally require particular testing procedures selected by the government authorities to evaluate the relative effectiveness of the dispersant and ensure that the dispersant is of acceptably low toxicity. Procedures for government approval for the use of these dispersants at the time of a spill should be streamlined to allow a speedy response. To the extent possible, preapproval agreements for use of dispersants should be in place before an oil spill occurs, as there is very little time for discussion, consideration and decision making when a spill is in progress.

Setting up a dispersant response capability

Oil spill planning for dispersant use should of course include the equipment and personnel needed to carry it out. For large spills this may include the call-out of centralised oil spill response centres, such as Oil Spill Response Ltd (OSRL) in the UK, East Asia Response Ltd (EARL) in Singapore and Clean

Carribbean Cooperative (CCC) in the USA. These are supported by the oil industry and have significant dispersant application system capabilities to cover most parts of the world.

The challenge of mounting a successful dispersant operation is principally one of logistics. Adequate quantities of dispersant and specialised spraying equipment (see the section on Operational Use of Dispersants) must be purchased and stockpiled at appropriate locations. It is normal to stockpile a quantity of dispersant that is equivalent to about 5–10% of the likely oil spill volume. For example, if the oil spill response is dimensioned to deal with a 1000 tonne spill, a stockpile of 50–100 tonnes of dispersant should be readily available. These can be located near the site or close to ports or airstrips that will be used by the dispersant spraying ships or planes. Planing considerations should include training and activation of trained crews, as well as transportation means and infrastructure to support an extended operation if necessary. Sensitivity maps which identify where and when dispersant use is acceptable and where and when it is not should be readily accessible.

DECISION-MAKING AT THE TIME OF A SPILL

While many of the general decisions concerning dispersant use can be made during the preparation of the oil spill contingency plan, decisions that are specific to the incident can only be made at the time of the spill. Adequate preplanning at earlier stages should ensure that a range of options is available and decisions can be made rapidly. Decision trees, such as the one shown in Fig. 2 [adapted from 10], identify the relevant steps/considerations and can be helpful in this regard.

Information on the spill

When a spill has occurred it will be necessary to find out the location, size and identity of the oil spilled plus the prevailing and forecast weather. This information should be used to determine whether any sensitive resources are threatened and, through an application of Net Environmental Benefit Analysis, which response options should be taken.

Is an active response needed?

If no active response action is deemed necessary (e.g. because the spill is very small, is expected to evaporate rapidly or is drifting away from sensitive resources), its location should be monitored. Since conditions such as wind direction and speed may change, equipment and personnel should be prepared to respond appropriately if needed.

If sensitive resources are likely to be threatened by the oil as its drifts, and if dispersant use is deemed the most appropriate response, the dispersant response should be initiated as soon as possible and as far out at sea as possible to maximize effectiveness and avoid impacts.

OPERATIONAL USE OF DISPERSANTS

The purpose of any spray operation used to apply dispersant, irrespective of the boat, ship or aircraft on which the system is mounted, is to efficiently apply the required amount of dispersant in the optimal ratio as evenly as possible over the area to be treated. All dispersant spray systems consist of a dispersant storage tank, a pump to transfer dispersant (typically to spray arms), and nozzles to convert the dispersant into a spray that deposits on the spilled oil. The size of the dispersant droplets produced by the nozzles is important, and the individual nozzles should spaced so that there is a slight overlap as the spray hits the oil. The size and capability of each of these components varies with the type of spraying unit (boat, ship or aircraft) used.

Rate of dispersant to be sprayed

The dispersant spraying rate needed to achieve the desired treatment ratio (DOR) is a function of the thickness of the oil slick. Typically, an average thickness of the area of oil slick to be treated with dispersant is assumed, e.g. 0.1–0.2 mm. To illustrate the application rate relationship, a 0.1-mm thick oil layer is equivalent to 100 mL/m^2 (1000 L/hectare; 100 US gallons/acre) of oil and therefore requires the spray system to deliver 5 mL/m^2 (50 L/hectare; 5 US gallons/acre) of dispersant to achieve a DOR of 1:20, or 5% of the oil volume. Although this is a frequently targeted treatment rate for modern dispersants, it

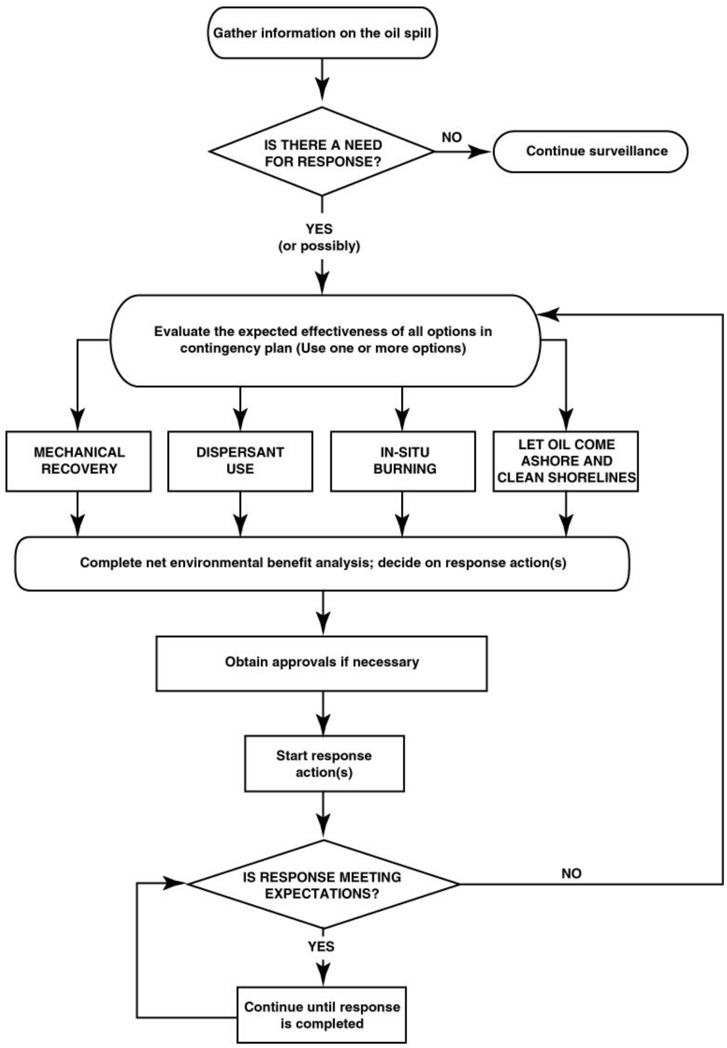

Fig. 2 Oil spill response decision tree.

should be noted that freshly spilled, low viscosity crude oils can be effectively dispersed at lower treatment rates. At the *Sea Empress* incident treatment rates as low as a DOR of 1:100 were reported to have been effective [6]. In practice it is also known that thickness can vary over a very large range. Within the thickest areas of the slick, the average thickness ranges to several millimetres, and, in some cases, up to several centimetres. Thick areas of oil, e.g. emulsion, generally need to be treated using multipass dispersant spray applications to achieve the proper DOR.

Dispersant spraying equipment for ships and boats

Modern concentrate dispersants were developed primarily for aerial application from fixed-wing planes or helicopters, but they can also be applied from boats and ships equipped with the appropriate spray systems. Power for the dispersant pump can be from the ship's electrical supply if the spray system is permanently installed, or from gasoline or diesel powered engines for portable systems than can be rapidly deployed on any boat or ship.

Ship spray arms are made as long as possible, consistent with the strength of the material used to manufacture them or consistent with the complexity of rigging systems required to support them. Large ships can have individual spray arms up to 12 m long (producing an overall spray width of nearly 30 m). Small boats have smaller spray arms, typically 5 or 6 m long.

Some modern dispersants, as well as the older water-dilutable dispersants, can be sprayed as a mixture with sea water. Although this is now not a recommended practice, there are many ships still fitted with the spray equipment to do this. The spraying equipment allows seawater (to a recommended maximum of 90% volume) to be mixed with dispersant and the mixture is then applied to the oil at a rate equivalent to about 25% of oil sprayed. Fire monitors can be used to apply dispersant and seawater mixtures, but need to be of the smaller type and adapted for this use [17].

Dispersant spraying equipment for helicopters

Helicopters are useful dispersant spraying units for smaller oil spills [18]. Dedicated spraying helicopters are not necessary if suitable helicopters that can be rapidly equipped with easily mounted, underslung spray 'buckets' are readily available. The size of the bucket depends on the carrying capacity of the available helicopters. Smaller types, such as the MBB-105, can carry a bucket containing nearly one tonne of dispersant, while larger helicopters such as the Sikorsky S61-N and AS 322 Puma can carry a maximum of almost three tonnes. Dispersant should be sprayed directly into the wind at a bucket altitude of 30–50 feet with a ground speed of 25–50 knots. Spraying at a lower speed or lower altitude causes too much interference by the rotor downwash; spraying at faster speeds or higher altitudes can cause much of the spray to be carried away by the wind.

Dispersant spraying equipment for fixed-wing aircraft

Dispersant spraying from fixed-wing aircraft has evolved from modified small, single-engine crop-spraying aircraft, carrying less than one tonne of dispersant, to the use of bigger multiengine aircraft. The largest unit currently available is the ADDS™ (Airborne Dispersant Delivery System) pack by Biegert Aviation Inc. which can be rapidly deployed by the C-130 Hercules aircraft and is capable of carrying 5000 US gallons of dispersant (Fig. 3). Dispersant spraying requires robust, relatively slow aircraft that can be used with limited support. The DC-3, DC-4 and DC-6 have all been used for dispersant spraying. In the UK, the Marine Pollution Control Unit (MPCU) retains a fleet of DC-3 and DC-6 aircraft (Fig. 4) as part of the UK National Contingency Plan.

Fig. 3 C-130 with ADDS-Pack spraying dispersant.

Only modern concentrate dispersants should be sprayed from aircraft. Aircraft should be flown as low and as slow as possible, consistent with safety, during dispersant spraying. The precise spraying parameters will differ with aircraft type; large aircraft such as the Hercules are normally flown at a minimum of 50–100 feet and at 140 knots. MPCU's DC-3 aircraft flew at 15–30 feet altitude and at a speed of 100 knots during the spraying of oil at the *Sea Empress* incident. The spray width that is deposited on the oil is generally about 1.2–2.0 times the width of the spray arms on the aircraft. The spray arms may be on the wings or tail of the aircraft. The spray arms of the rapidly mountable ADDS™ pack and AIRSPRAY™ systems (which can be deployed by smaller aircraft such as the Aeritalia G222) are deployed out of the open rear ramps during flight.

Fig. 4 DC-3 spraying dispersant.

Selecting the most appropriate spraying unit

The relative advantages and disadvantages of ships, helicopters and fixed-wing aircraft as dispersant spraying units depend on the precise circumstances of a particular spill. Also, ships of various sizes and different types of aircraft have various advantages and disadvantages:

- Ships can carry large amounts of dispersant and can remain spraying dispersant on the oil for prolonged periods, including remaining on station (but not dispersant spraying) overnight and during rough weather. However, the transit speed of ships is low and they may not be able to reach the spill area until the ‘window of opportunity’ for dispersant use has passed. Smaller ships and boats carry less dispersant, but may be very useful for spraying near-shore spills, close to harbours.
- Fixed-wing aircraft can travel rapidly to remote spill sites, but their load carrying capacity is limited, compared to large ships, and they need additional support facilities (e.g. airstrips and fuel). Larger aircraft have a greater load-carrying capacity, but are less manoeuvrable when dealing with scattered and broken-up oil patches that occur. Single-engine aircraft should not be operated offshore. Larger helicopters, temporarily fitted with underslung ‘buckets’ can be useful at smaller spills.

Several computer models have been developed to assess the potential of using different dispersant spraying systems for user-specified oil spill scenarios [1].

Dispersant application tactics

The general principles of dispersant use are:

1 Dispersants should be applied as soon as possible after the oil has been spilled and preferably before substantial emulsification has taken place. In general, oil that is threatening sensitive resources should be of the highest priority. If an oil spill is continuous or occurs as a sequence of events over a prolonged period, treatment of the ‘freshest’ oil, as close as possible to the source, is preferable. Surveillance aircraft equipped with remote sensing equipment such as SLAR (Side Looking Airborne Radar) are recommended to rapidly locate and track the oil slick.

2 Dispersants should be applied only to the thickest patches of oil (brown or dull grey in visual appearance) and *not* on sheen (silver or rainbow coloured) where dispersant is wasted because it rapidly breaks through the oil film, over-treating that zone. Since the areas of different thickness within a slick are often difficult to see, surveillance aircraft equipped with IR (Infra-Red) scanners or cameras are often used to help locate the slick areas of greatest thickness.

3 Wherever possible, an aircraft should be used to guide and monitor dispersant spraying units (ships and aircraft). This should ensure that dispersants are applied to the main part of the slick and that an assessment of the effectiveness of dispersant in removing the oil from the surface can be provided.

Regular checks on the effectiveness of the dispersant and the required dispersant treatment rate should be made. When it is clear that the oil has been treated at the planned DOR treat rate but has become too difficult to disperse, the spraying operation should be called off. This can be a difficult call since the lack of visual confirmation (e.g. no visible plume) does not necessarily mean that the dispersant is not working. It is also possible that, because the oil has emulsified and the thickness of the slick is greater than expected, the DOR was inadequate. In general, where effectiveness is uncertain, it is better to continue spraying dispersant, rather than to prematurely end spraying. Visual 'spotting' from aircraft and, if available, subsurface UVF (Ultra-Violet Fluorescence) monitoring from boats should be used.

The dispersant spraying unit (ship or aircraft) is only one part of a successful dispersant operation. It will require assistance from at least one spotter or surveillance aircraft equipped with remote sensing equipment.

Aircraft dispersant spraying procedures.

A surveillance aircraft generally locates the oil slick and then guides the spray aircraft (helicopter or fixed-wing) to the areas of thick oil and emulsion within the slick. These areas may not be visible to the spray aircraft crew during spraying, either because they are not visible without remote sensing equipment or because of the very low altitude (e.g. below 100 feet and preferably 30–50 feet, the minimum dictated by safe flying for different aircraft types) required for accurate spraying.

Good communication between the surveillance aircraft and the spraying aircraft is obviously essential. In common with any operation that involves multiple aircraft, a system of local air traffic control with appropriate vertical and horizontal separation needs to be instituted. It should be noted that in the case of a helicopter spraying operation, the tasks of both thick oil area location and spraying can be achieved by the same helicopter if using an onboard FLIR (Forward Looking Infra-Red) camera.

On instructions from the surveillance aircraft, the spray aircraft starts to spray dispersant, beginning from the edge of the area of thickest oil and flying into the wind (Fig. 5, adapted from [19]). Spraying should stop, as instructed by the aircraft, when the far edge of thick oil is reached. After the first spray run is completed, the spray aircraft returns in a racetrack configuration to spray a second strip adjacent to the first. Spraying is conducted as a series of continuous and parallel strips.

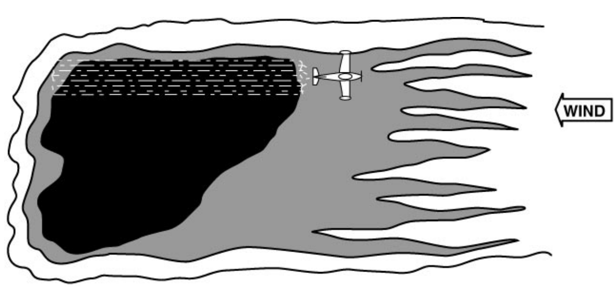

Fig. 5 Aircraft spraying dispersant into the wind on a thick area of oil slick.

Aerial spraying releases a long 'cloud' or 'carpet' of dispersant into the air at the spray altitude. This dispersant 'cloud' settles under the influence of gravity and the wind. It is recommended that the spray aircraft fly directly into the wind so that the dispersant drifts directly back along the aircraft track and onto the area to be treated. Spraying across the wind may be necessary if the distribution of thick oil dictates this, but it is much more difficult. If cross-wind spraying has to be undertaken, such as when the oil has formed relatively narrow strips aligned across the wind, the drift of the sprayed dispersant 'cloud' in the wind, before it hits the oil, must be allowed for (Fig. 6, adapted from [19]).

Ship dispersant spraying procedures.

As in aircraft spraying operations, a surveillance aircraft should be used to locate the oil slick and guide the spray ship. Again, good communications are essential. The ability to rapidly transfer IR images from the surveillance aircraft to the spraying ship by real time 'down-linking' is very useful.

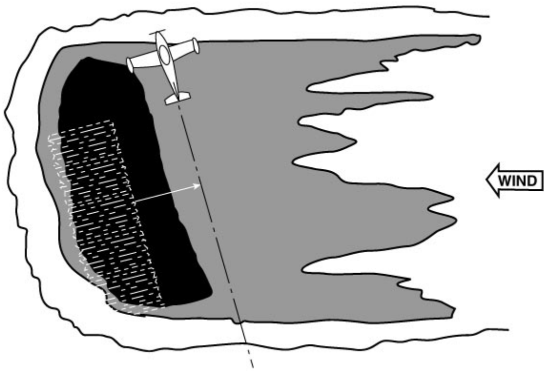

Fig. 6 Aircraft spraying dispersant cross-wind on thick area of oil slick.

The speed of the ship during spraying should be between 4 and 8 knots. Care must be taken to avoid pushing the oil away with the bow wave caused by excessive ship speed. Spray arms mounted on the bow of the ship reduce this tendency and permit faster spraying speeds. Breakup of the slick, caused by the spray ship or other ships sailing through it before dispersant spraying, should be avoided. Spraying into the wind is preferred; spraying with or across the wind may be necessary if the distribution of thick oil dictates this, but this may make spraying more difficult. Experience from field trials in Norway has shown that dispersant spraying with the wind can be successful. If cross-wind treatment has to undertaken, such as when the oil has formed narrow strips aligned across the wind, only the downwind spray arms should be used.

Monitoring effectiveness of the dispersant application

Monitoring of the dispersant application is needed to assess its effectiveness and to provide guidance both on whether any changes in dispersant application rate or strategy are needed and on when to end the operation. Visual and remote sensing observations made from the spotter or surveillance aircraft can give useful indications that the dispersant is being effective. The presence of a visible, light-coloured (grey or brown) dispersed oil plume is evidence that the dispersant is working. However, the absence of a visible plume does not necessarily indicate that the dispersant is not working. In some instances, this may simply be due to poor visibility conditions (e.g. lack of adequate sunlight); in other cases, it can be difficult to see because the oil is dispersing slowly. For example, the formation of a dispersed oil plume can take some time as the dispersant initially breaks the emulsion and then gradually disperses the oil. Under some conditions the dispersed oil plume may not be clearly visible because it is hidden under the rest of the oil slick.

Boats equipped with UVF detectors can also provide indications about the effectiveness of dispersant spraying, particularly if the UVF detectors are sampling water from two or three water depths, preferably two meters and deeper. It is not possible to calculate an accurate mass balance describing the quantity of oil being dispersed because this changes very rapidly with time and location. However, UVF measurements of oil concentrations significantly above background levels at depths of 3–5 m or more are the most definitive indicators of dispersant effectiveness at sea. These will be observed even when visual indications are not apparent, but adequate time must be allowed in the case of slowly dispersing oils. Simultaneous water samples should be taken for analysis for oil content and subsequent calibration of the UVF.

Regardless of the monitoring technique, it is not possible at present to quantitatively material balance the oil spill during a response, that is, to measure the total amount of oil on the surface (and how it decreases with time following effective dispersant application) or to measure the amount of dispersed oil (and how the concentration of dispersed oil increases with time at all points below the dispersant treated area). Measurements are also complicated by the fact that surface oil is primarily driven in the direction of the wind, whereas dispersed oil is typically driven in another direction by the current. Oil concentrations on and below the sea surface can also change rapidly and locally.

CONCLUSION

Modern dispersants can be an effective and overall beneficial oil spill response technique, and should be considered as a primary response option along with other available options. For many large oil spills, dispersants can be the only practical at-sea response. Over 25 years of studies and experience have shown that dispersant use can reduce the environmental and/or economic damage that would otherwise be caused by an oil spill.

Since a timely response is essential, dispersant use should be well-planned with due regard to local circumstances. The NEBA (Net Environmental Benefit Analysis) approach, comparing the consequences of the various response options, should be developed during the oil spill contingency planning process, to clearly identify conditions for dispersant use (or nonuse) prior to an oil spill incident. This approach should help to avoid unnecessary delays in the decision-making process during an actual spill while deliberations are made.

Just as prevention of oil spills is a important priority, so to should the minimization of environmental damage be, in cases where spills occur. Careful preplanning can streamline the approval process and assure that dispersant spraying operations are expeditiously and carefully undertaken. As with any response operation, monitoring should be carried out to assure the goals of the response are being met.

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