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SINTEF REPORT

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Revision of MMS Offshore Continental Shelf Oil-Weathering Model : Evaluation

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ABSTRACT

This report identifies needs and potentials for improvements in the Offshore Continental Shelf (OCS) Oil Weathering Model (OWM). Key tasks in the project have been conducting a teleconference with users of the OCS model, reviewing existing oil weathering models, surveying recent developments in model concepts of oil weathering processes, and establishing an overview of available data sets for model calibration and testing.

The teleconference clearly demonstrated that the present OCS model has fallen behind the needs of its users, the state-of-the-art in terms of computational hardware and software, and the scientific developments in oil spill weathering. These shortcomings are in general validated by the review of the OCS model presented in this report. The reasons for the most frequent problems reported by the users of the model are also explained.

The review of recent developments in oil weathering modeling has been organized according to the major processes accounted for in the OCS model – spreading, evaporation, natural dispersion, emulsification, and oil-ice interactions. On this basis, potential modification or replacement of existing algorithms is discussed.

A global overview of field data sets has been achieved as part of this project. Although the existing data sets are highly variable in quality and content, some of the more recent data sets appear useful for purposes of model calibration and testing.

The report concludes with recommendations for potential improvements of the OCS model, with acquisition of an existing model and empirical oil weathering database as the preferred alternative in terms of both cost and quality.

	ENGLISH	NORWEGIAN
GROUP 1	Environment	Miljø
GROUP 2	Numerical oil weathering model	Numerisk olje forvitringsmodell
SELECTED BY AUTHOR	Oil spill weathering models	

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Revision of MMS Offshore Continental Shelf Oil-Weathering Model: Evaluation

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Øistein Johansen	Literature Review, Review of OCS Model
Per Johan Brandvik	Review of Data Sets
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1. Introduction

The purpose of this report is to identify needs and potentials for improvements in the Offshore Continental Shelf (OCS) Oil Weathering Model (OWM). Key tasks in the project have been conducting a teleconference with users of the OCS model, reviewing existing oil weathering models, supplemented with a survey of recent developments in model concepts of oil weathering processes, and establishing an overview of available data sets for model calibration and testing.

The behavior and fate of oil spill at sea is governed by a suite of inter-related physical and chemical processes, including

- advection,
- spreading,
- horizontal dispersion,
- vertical dispersion (entrainment),
- evaporation,
- emulsification,
- photo-oxidation,
- dissolution, and
- degradation.

Should the oil drift ashore, an additional group of processes associated with surf zone dynamics, coastal sediments and environments comes into play.

Oil weathering models are generally designed to simulate the physical-chemical changes and over-all mass balance of an oil slick on the open sea. Explicit consideration of the geographical position of the slick is not included in the analysis, nor are coastal zone processes. Weathering models thus attempt to separate the spatial advective processes from the other processes listed above.

Surface advection and vertical dispersion combine to produce the spreading patterns observed in actual spill situations, as discussed further in the following report. The question of whether or not oil weathering can be represented adequately without physical advection is therefor worth considering.

A weathering model does not attempt to reproduce the complex physical distribution of a surface slick, but only the state of a "typical" square meter, or perhaps the distribution of states within the surface oil. Whether an entrained droplet will resurface within or separate from the existing surface slick is not readily answered with a classical weathering model. Weathering models tend to parameterize these processes by identifying a threshold droplet size or a threshold rise time below which droplets are assumed permanently entrained, rather than following the entrainment and resurfacing of oil droplets, as in a full trajectory and weathering model.

The user accepts certain limitations when choosing to employ a weathering model without an associated trajectory model. For example, no geographical maps of the evolution of the slick are usually expected, although a geographical information system (GIS) could easily produce such maps. Reasonable expectations are a reliable mass balance of the slick over time, and information on the physical-chemical state of the oil. Viscosity and water content are of interest because of their importance in spill response strategy development. Appropriate parameterizations of the advective spreading processes mentioned above, backed by laboratory weathering studies, appear to reproduce observed weathering in the field on a consistent basis in both warm and cold weather (Daling et al, 1997; Sørstrøm et al, 1994). The absence of laboratory weathering data results in significantly less reliable predictions (Hudon, 1998). This theme is followed further in the ensuing report.

2. Summary of MMS uses and needs

The model is used in Alaska primarily for pre-lease environmental analyses, and for evaluation of oil spill contingency plans for exploration activities. In the Gulf of Mexico, the model is also used for post-lease assessments of lease sites in environmentally sensitive areas, and for evaluation of site-specific contingency plans. The users in general have access to other models for trajectory analyses, and use the OCS model mainly for assessment of the mass balance and lifetime of specific oil spills.

Current uses require:

- Modeling crude oils of interest;
- Modeling fuel oils used in OCS operations;
- Calculation of area covered by slick over time;
- Specific density of slick over time;
- Weathering for 30 to 90 days or until slick is dispersed to 10-percent;
- Weathering of oil in ice;
- Viscosity as a function of time;
- Calculation of mass balances.

Discussions with MMS users clearly demonstrated the extent to which the model has fallen behind both the needs of its users, the state-of-the-art in terms of computational hardware and software, and the scientific developments in oil spill weathering. The main shortcomings may be summarized as follows:

The quality of the predictions is questionable:

- Persistence (lifetime) seems to be too high, particularly for light oils (diesel);
- Slick thickness does not increase with water content, but appears to thick in long model runs;
- The model appears to behave questionably outside the narrow range of oils and conditions for which it was developed;
- Recent advances in oil spill modeling should be incorporated (spreading, natural dispersion).

An updated version of the model must meet new needs:

- Scenarios with variable wind and temperature;
- More realistic ice scenarios;
- Continuous releases;
- Subsurface leaks (pipeline ruptures, blowouts).

An updated version of the model could meet additional secondary interests:

- Incorporation of algorithms for high total suspended solids;
- Incorporation of cleanup into algorithms;

- Representation of slick over time in Geographical Information System (GIS);
- Minimum and maximum thickness for emulsification;
- Thick and thin slick thickness.

The model must be made easier to use:

- Outdated user interface – input line by line, and inflexible;
- Much experience required to change input parameter values in the Alaska version;
- Data necessary for identification of input parameters not readily available;
- Difficult to add new oils, requested data not readily available;
- No graphical output;
- No simple links to frequently used applications (spread sheets, word processors).

These shortcomings were in general validated by a review of the OCS oil weathering model description and user's manual (Kirstein and Redding, 1987; Payne et al., 1987), as presented in the next section.

3. Review of the OCS Oil Weathering Model

The OCS model predicts the changes in mass balance and composition of oil remaining in the slick as a function of time due to the following weathering processes:

- Spreading,
- Evaporation,
- Dispersion (oil into water), and
- Emulsification (water into oil).

The presence of sea ice is also represented in the model, although in an extremely primitive fashion.

The parameters reported from the model are primarily:

- Mass balance and slick area as a function of time:
  - Remaining oil mass (totals and mass fractions for each cut)
  - Mass dispersed
  - Mass evaporated
  - Slick area
  - Slick thickness

- Oil properties as a function of time:
  - Specific gravity
  - Water content
  - Viscosity

3.1 Characterization of oils

Six oil types are predefined in the original version of the OCS model:
- Prudhoe Bay Crude, Alaska
- Cook Inlet Crude, Alaska
- Murban Crude, Abudhabi
- Lake Chicot, Lousiana
- Light diesel

Five additional oils are available in the Gulf of Mexico version (Kirstein, 1992):
- Sugar Creek
- Chandeleur Sound
- Main Pass Block 290
- Gibson Terminal Composite
- High Island Offshore Composite

The following standard parameters are used to characterize these oils:
- Bulk properties:
  - API gravity
  - Viscosity (cP) at 25°C
  - Oil-water surface tension (Dynes/cm)

- True boiling point cut data:
  - Volume fraction (%) for specified boiling point intervals (degree Fahrenheit).
  - API gravity for the same cuts

In addition, some model-specific parameters are specified for each of the oils:
- Emulsification constants:
  - Maximum weight fraction of water in the oil
  - Water incorporation rate
  - Emulsion viscosity constant
- Viscosity-weathering constant
- Temperature-viscosity scaling constant

The emulsification constants are used to compute the water content in the oil as a function of time at different wind speeds. The viscosity-weathering constant is used to calculate the change in viscosity due to evaporation of volatile fractions. The temperature-viscosity scaling constant is used to adjust the viscosity from the standard temperature (25°C) to the specified sea temperature. These constants are as described in Mackay et al., (1980a).

For oils not already incorporated in the model, the user must enter these parameters during the first model run. The data entered by the user is stored in a data file, and may be recovered from this file during subsequent runs. Some of the oil parameters listed above (i.e. the bulk properties, true boiling point data) may be obtained from standard crude assays reported from the relevant oil production company, while no standard procedures are available for obtaining the model-specific parameters (i.e. emulsification and viscosity constants). These latter parameters must be measured empirically in the laboratory, or fit empirically from field observations.

Similar constants are required by the ADIOS model, and default values for each oil are supplied in the database which accompanies the model. The SINTEF OWM relies on a standardized set of parameters, derived from a standardized set of laboratory procedures. The parameters reflect the physical-chemical properties of the various stages of weathering each specific oil undergoes. The under-lying procedures are well defined, and are in place at both SINTEF and Battelle Duxbury laboratories.

3.2 Spreading

The change in the slick area with time is calculated in the OCS model with the Mackay et al., (1980a) thick slick spreading algorithm (Kirstein and Redding, 1987; Kirstein, 1992). Mackay et al. (1980a) proposed a spreading model including a thick and thin portion of the slick, where the thick portion fed oil into the thin layer. This combined spreading model was introduced to include observed spreading behavior not accounted for in the conventional Fay spreading models, Fay (1969, 1971).

The OCS model only includes the equation for the thick part of the slick. According to Mackay et al. (op. cit.), this equation is a modified (finite difference) version of Fay's equation for radial spreading of instantaneous spills in the gravity-viscous spreading regime. However, an important difference should be observed:

- The term representing the effect of the density difference between water and oil in the original Fay equation is included in a general spreading constant in Mackay's modified model.

In the OCS model, this spreading constant has a fixed value as given by Mackay et al. (op. cit.). The computed spreading rates are therefore independent of the initial oil density and insensitive to subsequent changes in density caused by evaporation and emulsification. The computed slick thickness does not incorporate the water content due to emulsification. The same equation is used for oil in broken ice, but the spreading constant is reduced by a factor depending on the ice coverage.

Neither the Fay equations nor the Mackay versions explain many observed aspects of oil spreading at sea. The major factors of concern are:

- formation of elongated slicks, with a thin film trailing behind the thick slick;
- reduced spreading rate of viscous oils cannot be explained by conventional spreading formulas;
- conventional spreading formulas do not apply after break-up of the oil slick into small patches;
- rate of spreading depends strongly on discharge conditions (surface/sub-sea leaks, instantaneous/continuous spills).

A more comprehensive discussion of alternative solutions to the spreading problem will be given in the review of recent advances in weathering processes.

3.3 Evaporation

The oil is presumed to be a well-mixed multi-component liquid, with the composition described in terms of components that are obtained by fractionating the oil in a true boiling point column. This procedure yields cuts, or "pseudo-components", of the oil, which are characterized by boiling point and density. This information is then used to calculate other parameters of the cut, such as saturation vapor pressures and molecular weights. The total equilibrium vapor concentration and a wind-dependent mass transfer coefficient drive the evaporation process. The equilibrium concentration of vapor above the oil layer is derived from the vapor pressures and the molecular fractions of each cut in the oil mixture by the use of Raoult's law.

The pseudo-component approach to representation of oil relies in most cases on the establishment of distillation temperature intervals to define the pseudo-components, as described above. This approach uses readily available crude assay distillation curves, and is used in the MMS OCS, ADIOS, and SINTEF oil weathering models. We note in passing that there exists a second method of identifying pseudo-components, based on ranges of carbon numbers in the molecules, and/or hydrocarbon types (e.g. Cornillon et al, 1979; Sebastiao and Soares, 1998). This approach requires detailed chemical analysis of each oil to be modeled, and is therefore not appropriate for models that may have to simulate a wide variety of crude oils and petroleum products. (One possible advantage of this more complicated methodology may be that it could allow more accurate toxicological assessments of dissolved components.)

The Alaska version of the model provides three options for computation of the mass transfer coefficient:

1) the user may specify a constant, overall mass transfer coefficient;
2) the program may calculate a wind-dependent mass transfer coefficient based on a correlation proposed by Mackay and Matsugu (1973).
3) the program may calculate an individual oil- and air phase mass transfer coefficient, with the air phase coefficient scaled with the wind.

Of these options, the second is the one recommended in the user manual. Mackay and Matsugu originally proposed this formula for the mass transfer coefficient in 1973. The same formula was chosen by Mackay et al. (*op cit.*), and is also applied frequently in evaporation models up to present. However, despite the apparent longevity of this formula, the formula is in disagreement with formulas for sea surface fluxes of momentum, heat and moisture commonly used in meteorological studies (ref. Amorocho and DeVries, 1980, Smith 1988).

In the pseudo-component concept generally, the vapor pressure for each cut is calculated from the average boiling point of the cut and the temperature of the oil. This temperature is often assumed to be the same as that of the surface seawater, although in the presence of sunlight the oil may be as much as 5 C warmer (Daling, 1998). Different empirical or semi-empirical formulas have been developed for this purpose, and the one used in the OCS model has recently been questioned (Jones

1997). For this reason, some minor revisions of the evaporation model may be justified (see Section 4.2).

It should also be noted that some major issues may still cause controversies among specialists, such as:

- formulation of the wind dependency of the mass transfer coefficient;
- validity of the well-mixed assumption, especially in cold climates;
- the extent to which emulsification will influence (reduce) evaporation rates.

We will return to these matters in the review of recent advances in modeling of oil weathering processes.

3.4 Natural dispersion

Loss of oil from the surface slick due to natural dispersion is also computed by equations originally proposed by Mackay et al. (op. cit.). This concept is based on an estimate of the fraction F of the sea surface subjected to dispersion per unit time, supplemented by an estimate of the fraction F_B of the entrained oil containing droplets with a size small enough to be permanently dispersed in the water column. The total rate of entrainment (volume of oil entrained per unit surface area per unit time; m^3/m^2-s) is obtained by multiplying F (m^2/m^2) by the oil film thickness (m). The rate of permanent dispersion is then found by multiplying this product with F_B.

Mackay et al. postulate that the fraction F depends on the sea-state, with an increase proportional to the wind speed squared. The fraction permanently dispersed is, on the other hand, supposed to be independent of the sea state, and influenced mainly by the oil film thickness and the properties of the oil (i.e., the viscosity and the oil/water surface tension). Thin oil films with low viscosity and low surface tension are thus postulated to disperse more rapidly than thick oil films with high viscosity and surface tension.

In the OCS model, only the thick portion of the slick is considered, whilst Mackay et al. applied the dispersion equations for both the thick and the thin portions of the slick. By neglecting transfer of oil from the thick to the thin portion of the slick — where the fraction of permanently dispersed oil will be enhanced — the OCS model may be expected to underestimate the overall dispersion rate. On the other hand, it should be noted that the water content in the emulsion is not included in the slick thickness applied in the dispersion equations in the OCS model. Due to the inverse thickness dependency postulated by Mackay et al. (op cit.), this is likely to cause an overestimation of the fraction permanently dispersed from emulsified oils.

The algorithm proposed by Mackay et al. (1980a) was presented as a crude and approximate representation of the dispersion process. The basic concept is in many aspects similar to the now more widely accepted concept proposed by Delvigne and Sweeney (1988). The major difference is that the more recent concept includes a prediction of the droplet size distribution in the entrained oil. This makes it possible to relate the permanently dispersed fraction to a threshold droplet size (or rise velocity). A discussion of this concept will be presented later in the review of recent advances in weathering models.

3.5 Emulsification

The computation of the rate of emulsification in the OSC model is also based on a model originally presented by Mackay et al. (1980a,b). Mackay et al. postulate that the emulsification is governed by a water incorporation rate, counteracted by a water removal rate. The former is presumed to increase with the sea-state and to decrease with the viscosity of the emulsion. The latter is presumed to increase with the water content, and to decrease with slick thickness and viscosity. The net water incorporation rate is then obtained as the difference between the two rates, and the water uptake will terminate when the two rates are equal. This concept leads to a differential equation with two constants to be determined empirically, i.e., the water incorporation constant K_i and the water removal constant K_T.

However, Mackay et al. (op cit.) did not recommend this differential equation as a model for emulsification, in view of "the doubtful basis in physical reality". Instead, they proposed an approximate implicit equation for the water content as a function of time, which had "the correct general properties". This implicit equation must be solved by trial and error and contains three empirical constants, where one is a constant also used in the equation for the viscosity of emulsions. The two remaining constants will determine the maximum water content and the water uptake rate.

A review of the original study by Mackay et al. (op cit.) has shown that the authors finally recommended a simpler equation for the emulsification. This equation was formulated in explicit form, and contained only two parameters, one representing the water uptake rate, and the other the maximum water content. Both models were found to be equally able to reproduce the same set of observations. Since the explicit model also could be put into a differential form, the authors preferred this model.

The emulsification parameters in both equations must be derived from experimental studies of the actual oil, and these parameters have been found to vary considerably among different oils. More recent studies also indicate that the emulsification rate, as well as the maximum water content, also depends on the degree of weathering of the oil (Daling et al., 1997, Neff et al. 1997). Some crude oils, which have been shown to be unable to form stable emulsion in the fresh state, may produce stable emulsions after some hours of evaporative exposure. This observed dependency on the degree of weathering also implies that the differential form of the emulsification equation should be preferred, in that the rate will change as a function of time

3.6 Oil-in-Ice

The effects of sea ice on the weathering processes discussed above are addressed by allowing the user to define three successive stages ("compartments") of oil weathering:

- Oil weathering in pools on top of ice
- Oil weathering on the ocean surface in a broken-ice field
- Open ocean oil weathering

In the first compartment (oil on ice), only evaporation is considered in the model. The initial thickness of the oil layer has to be specified by the user in terms of the depth of the oil pools, with 2 cm as a recommended value. For the subsequent weathering in broken ice, the user is asked to specify the ice coverage, which is presumed constant in time. In this compartment, (as in the third and last - open sea), the model calculations also include spreading, emulsification and dispersion of the oil. The presence of ice is taken into account by introduction of some ice dependent factors or "multipliers" in the general weathering equations.

For dispersion (entrainment) of oil spills in a broken ice field, a constant factor of 10 is introduced in the OCS model for the total entrainment rate to "describe the increase of (initial) dispersion in broken ice". This increase was justified on the basis of wave tank experiments (Payne et al, 1987, 1990). However, it should be observed that since the entrainment rate is computed from the wind speed — independent of the presence of sea ice — the effect of wave damping in the ice field is obviously not taken into account in the model. The postulated increase in the entrainment rate by a factor of 10 will for this reason cause a severe overestimation of the rate of natural dispersion in broken ice fields (Singsaas et al., 1994), except possibly directly at the ice edge.

For emulsification in broken ice, a factor of 10 has been introduced to account for observations from wave tank experiments that "indicate that the emulsification rate in broken ice is increased by an order of magnitude" (Payne et al, 1987). Such an increase may be observed in experiments with and without broken ice under similar wave conditions. As mentioned above, sea-state is expressed in terms of the wind speed in the model, with no account for wave damping in the presence of sea ice. Due to this, the postulated net increase in the emulsification rate seems to be doubtful, and is strongly counter-indicated by actual field data (Singsaas et al., 1994).

The spreading rate is reduced in broken ice by introduction of a factor depending on the ice coverage. This is obviously an over-simplification, perhaps justified by lack of experimental data in ice-infested waters.

3.7 Oil properties

The OCS model keeps track of the changes in the composition of the oil due to loss of volatile fractions. Changes in the oil density are computed on this basis. An attempt to compute the viscosity of the oil in terms of the viscosity of the remaining fractions was also made, but this procedure was found to produce unrealistic values (Payne et al, 1987). Instead, the OCS model computes the viscosity of the weathered oil from the viscosity of the fresh oil at a standard reference temperature (25°C) and the fraction lost by evaporation. This viscosity is scaled with temperature according to the Andrade equation. The increase in viscosity due to emulsification was computed from the viscosity of the weathered oil and the water content by a formula proposed by Mackay et al. (op cit.).

Density and viscosity are the only physical-chemical oil properties computed in the model besides the oil composition. However, in conjunction with assessments of the potential efficiency of different oil spill combat methods, other properties, such as the pour point and the flash point of the oil, may also be of interest. These additional properties will also change as weathering, but predictions of these changes, like those for viscosity, are best made based on empirical data for each individual oil or petroleum product.

3.8 Environmental parameters

The OCS weathering model uses wind speed and air temperature to relate oil weathering to environmental conditions. Wind speed affects directly the processes of evaporation, emulsification, and natural dispersion in the model. Temperature is used in the calculation of the viscosity, as well as in the evaporation process.

The Alaska version of the model uses a constant wind speed, whereas the GOM version also allows the user to read from a wind file, thus feeding the model time-variable wind speeds. The wind file is unusual in our experience, in that each wind speed is given a duration, rather than a time stamp, as is the usual case with meteorological data files. The procedures for running the GOM version of the model are awkward, requiring the user to enter and leave both the GWBasic compiler and the DOS mode of PC operation. On the other hand, the inclusion of time-variable winds does represent an improvement over the limitations of the original version.

Implementation of a graphical user interface would facilitate wind time series input by the user. Simple translators to allow the model to read directly from standard meteorological files should also be implemented.

3.9 Summary of weaknesses in the OCS OWM

The OCS model incorporates the following weathering processes:
- Spreading in open water
- Evaporation
- Natural dispersion
- Emulsification

The algorithms used to describe these processes are mainly chosen from a report presented by Mackay et al. (1980a), with some minimal modifications included to account for effects of oil-ice interactions in broken ice. Here we will summarize the major shortcomings of these algorithms. Potential improvements are discussed in Sections 4 and 6.

3.9.1 Spreading

The spreading formula from Mackay et al. (op cit.) represents a simplified version of Fay's gravity-viscous spreading formula, where the influence of the density difference between water and oil has been included in an empirical spreading constant. The rate of spreading computed by the model is insensitive to variations in oil density, and to changes in the oil density due to loss of volatile fractions and emulsification. Thus emulsified Prudhoe Bay Crude and marine diesel fuel spread at the same rate in the model.

3.9.2 Evaporation

The pseudo-component concept used in the evaporation model is based on well-established theories. The vapor pressure for each cut is computed from the average boiling point of the cut and the temperature of the oil. Different empirical or semi-empirical formulas have been developed for this purpose, and the one used in the OCS model has recently been questioned.

The mass-transfer coefficient used in the evaporation model is based on a correlation function proposed by Mackay and Matsugu (1973). This formula is used in many evaporation models, but deviates from formulas commonly used for calculation of surface fluxes of momentum, heat and moisture in open sea.

3.9.3 Natural dispersion

In the OCS model, only the thick portion of the slick is considered, whilst Mackay et al. (op cit.) applied the dispersion equations for both the thick and the thin portions of the slick. By neglecting transfer of oil from the thick to the thin portion of the slick — where the fraction of permanently dispersed oil will be enhanced — the OCS model may be expected to underestimate the overall dispersion rate.

The water content in the emulsion is not included in the slick thickness applied in the dispersion equations in the OCS model. Due to the inverse thickness dependency postulated by Mackay et al. (op cit.), this is likely to cause an overestimation of the fraction permanently dispersed from emulsified oils.

3.9.4 Emulsification

A review of the original study by Mackay et al. (op cit.) has shown that the authors finally recommended a simpler equation than the one chosen for the OCS model. Both equations were found to be equally able to reproduce the same set of observations. The authors preferred the differential form of the explicit formulation. The emulsification parameters in both equations must be derived from experimental studies of the actual oil, and these parameters have been found to vary considerably between different oils. More recent studies also indicate that the emulsification rate also depends on the degree of weathering of the oil. This also implies that the differential form of the emulsification equation is preferred.

3.9.5 Oil-Ice Interactions

For oil spills in broken ice, a constant factor of 10 is introduced in the OCS model for the total entrainment rate. This increase was justified on the basis of wave tank experiments, but does not agree with field observations. The same factor of 10 is used in the model to increase the emulsification rate. However, the sea-state dependence is expressed in terms of wind speed, with no account for wave damping in the presence of sea ice. The postulated net increase in the dispersion and emulsification rates in broken ice therefore seem extremely doubtful, and run counter to field observations.

3.9.6 Oil properties

The OCS model computes oil density and, in addition to changes in the oil composition due to evaporation. Other properties, such as the pour point and the flash point of the oil, may also be of interest in conjunction with assessments of the potential efficiency of different oil spill combat methods. Predictions of changes in these properties are probably best made based on empirical data for each individual oil (Daling et al, 1990).

3.9.7 Conclusions

This review of the model concepts applied in the OCS model may explain some of the reasons for the most frequent problems reported by the users of the model:

- *Slick thickness does not increase with water content:*
  - The film thickness is computed from the oil volume, with no account for the increase in volume due to emulsification.

- *Persistence (lifetime) seems to be too high, particularly for light oils (diesel):*
  - Diesel oils in general contain relatively small fractions of volatile oil components. Hence, the evaporative loss from such oils will be limited, and the short lifetime reported for such products must be due to large dispersion rates.
  - The high persistence of diesel and other non-emulsifying oils predicted by the model may be explained by the fact that all oils spread at the same rate in the model, and that rate is calibrated for emulsified Prudhoe Bay Crude. For this reason, the model will not reflect the increased area and rate of natural dispersion associated with more rapid spreading of non-emulsifying oils.

- *The model appears to behave questionably outside the narrow range of oils and conditions for which it was developed:*
  - The above comment on spreading applies here as well. In addition, some of the parameters required to specify additional oils in the model are based on non-standard procedures, and relevant oil-specific parameters may thus be difficult to obtain. This applies particularly to the emulsion-viscosity constant and the viscosity-fraction evaporated coefficient. Judging from the variations within the set of values used for the six "library oils" in the Alaska version of the model, these parameters may be expected to vary significantly among different oils.

Recommendations for correcting these technical shortcomings of the model, and others identified in the teleconference, are discussed in Chapter 6 of this report.

4. Progress in modeling of oil weathering

In this chapter, we will present a brief description of the different approaches applied in other oil weathering models and summarize the findings from a review of recent advances in modeling of oil weathering processes. This review focuses primarily on developments more recent than about 1990, relying on existing published state-of-the-art reviews (Spaulding, 1988; ASCE, 1996) to summarize earlier work.

A large number of oil spill models are in use in the world today. Many of these are trajectory and fates models, in which a weathering model is one component. Some of the more widely published and recognized models are listed in Table 4.1, along with an indication of the weathering algorithms used.

It is important to note that two models purporting to contain the same algorithms may in general give quite different results. The fact is that implementation is critical to algorithm performance. This is especially true with complex concepts, such as Delvigne entrainment, in which the performance of the model will be strongly affected by the computed droplet size distribution, itself a function of the breaking wave energy dissipation function and the viscosity. The numerical strategy for transferring oil from the surface slick into the water column, and the eventual re-surfacing of oil droplets, is too complex to model in its entirety; each modeler takes shortcuts here. Which shortcuts are chosen can strongly alter model behavior. Furthermore, performance of an algorithm will be affected by performance of other algorithms in the model, a clear example being the relationships among spreading, evaporation, emulsification and dispersion.

Table 4.1 Some widely recognized oil spill weathering models. All but the first two models also incorporate transport capabilities.

Spill Model Name	Organization	Spreading	Evaporation	Entrainment / Dispersion	Emulsifi - cation	Oil-Ice Interaction
MMS OWM	MMS, USA	Mackay-adjusted Fay	TBP, Mackay	Mackay	Mackay	ad hoc
ADIOS	NOAA, USA	Lehr - adjusted Fay	Distillation Curve Fit, Mackay	Modified Delvigne	Mackay	no
OSIS	BMT, UK	modified Fay	TBP, Mackay	unknown "rule of thumb"	Mackay	no
OILMAP	ASA, USA	Mackay-adjusted Fay	Distillation Curve Fit, Mackay	Modified Delvigne	Mackay	ad hoc
SINTEF OWM *	SINTEF, Norway	half-life (Mackay-adjusted Fay)	lab data (TBP, Mackay or Smith mass transfer)	Modified Delvigne	lab data (Mackay)	ad hoc
OSCAR	SINTEF, Norway	uses SINTEF OWM				
COZOIL	MMS, Alaska, USA	uses MMS OWM, with Stiver and Mackay evaporation				
Oil Spill	Oceanor, Norway	uses SINTEF OWM, with Audunson Dispersion				

* Processes listed in parenthesis are invoked for oils for which no laboratory weathering data is available.

It is well known that the weathering processes being discussed here are closely inter-related. Much of the advance in our understanding of weathering over the past decade or two is reflected in an increased awareness of these interactions, as outlined in Figure 4.1. The nature of these interactions comprises a significant portion of the following discussions.

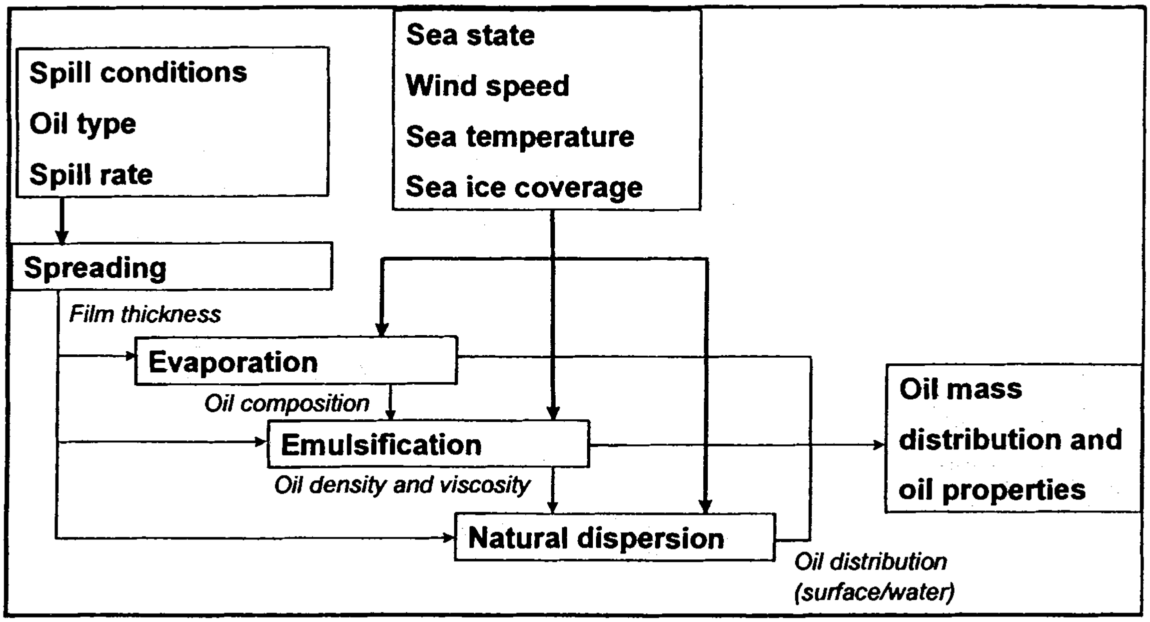

Figure 4.1 General layout of oil weathering models. This scheme indicates that the weathering processes are more or less closely inter-linked, such that the output from one process algorithm will influence the output of another.

The chapter is organized in sections according to the major processes included in the OCS-model:

- Spreading
- Evaporation
- Dispersion (oil into water)
- Emulsification (water into oil)
- Oil-ice interactions.

Other processes, such as stranding, are also important near-shore, but require linkage to a trajectory model. In each section below, the model concepts used in the OCS model will be compared with corresponding concepts applied in more recent oil weathering models, with the aim of identifying potentials for modifications or improvements.

4.1 Spreading

In the context of oil weathering models, estimates of slick thickness and area serve at least three purposes:

- Oil film thickness (or area) is used in the predictions of changes in oil composition (loss of volatile fractions), which will determine changes in oil properties with time.
- Oil film thickness is used in the predictions of the rate of natural dispersion, which will determine the persistence (lifetime) of the oil.
- Estimates of film thickness and slick area will be required for evaluation of the potential efficiency of different oil spill combat methods and for assessments of environmental impacts.

The potentials for modification or replacement of the algorithm for prediction of slick area and thickness must be judged on this basis.

Lehr (1995) presents a review of recent progress in oil spreading modeling, pointing out that the relevance of the classical Fay spreading equations has been questioned for a long time, based on the following observations:

- Oil spills are observed to form elongated slicks, with a thin film trailing behind a thicker part in the front of the slick.
- Viscous oil spreads more slowly than less viscous oil.
- Oil slicks tends to break up in patches and small fragments due to wave action, and these patches or fragments are dispersed horizontally due to oceanic turbulence.

Because of such observations, modifications have been suggested to the Fay model. Such modifications will be discussed in the following sections.

4.1.1 Wind-induced spreading

Lehr et al. (1984b) proposed a revised model to account for the observed non-symmetrical spreading of oil slicks. The extension of the slick in the wind direction was presumed to increase with time in proportion to the wind speed, while the lateral spreading of the slick was represented by the original Fay equation for gravity spreading. On this basis, the slick was represented in terms of an elongated ellipse, rather than the circular disk predicted by the Fay equation. The spreading rate in the direction of the wind was represented by an empirical wind factor obtained from observations. In other studies, this spreading behavior was explained more correctly as a result of shear spreading, caused by natural dispersion due to wave action and subsequent resurfacing of oil droplets (Johansen, 1984; Elliot et al. 1986).

NOAA (1994) has incorporated a corresponding spreading model in the ADIOS model, where the slick is represented as an ellipse, elongated in the direction of the wind. The initial area of the slick is computed according to the area at the time of transition between Fay's gravity-inertial spreading and gravity-viscous spreading regime. Fay's surface tension regime is not used in the model, but, instead, the slick is presumed to stop spreading when it reaches a terminal thickness of e.g. 0.1 millimeters. This approach produces a slick with homogeneous thickness, contrary to the observations from full-scale experiments and accidental spills.

Strictly, this concept applies only to instantaneous spills, but the ADIOS model also accepts continuous spills, defined by a spill rate and a duration. In that case, the spreading rate is adjusted at each time step to "incorporate new oil discharged and any loss of oil due to evaporation". As discussed in more detail in Section 4.14, this is a doubtful extension of the model. The application of Thiessen polygons to estimate local thickness from Langrangian elements (Galt, 1995 and personal communication) may prove useful in resolving spatial variations in average thickness.

4.1.2 Effects of viscosity

Experimental studies have indicated that viscous oils spread more slowly than less viscous oils. This effect is not accounted for in the original Fay equations, but several attempts have been made to include this parameter in Fay-type spreading models. Based on experiments within a limited viscosity range, Buist and Twardus (1984) proposed to reduce the spreading rate predicted by the Fay equations by a factor depending on the viscosity ratio between oil and water. In a subsequent paper, Buist et al., (1989) performed a series of tests with waxy crude oils, and proposed a terminal thickness function incorporating the difference between the pour point of the oil and the ambient water temperature. Later, based on experiments in cold water (-1.5 to 1.3°C), Venkatesh et al. (1990) proposed to replace the viscosity of water by the viscosity of the oil in the original Fay equations. El-Tahan and Venkatesh (1994) approach the problem on a theoretical basis, and tried to include an extra viscosity term in the force balance equation for oil spreading, representing the shear resistance in the oil. The authors compared the extended model with experimental data, and found substantial improvements compared to the original Fay equation. However, the limited range of experiments makes it questionable to extrapolate these results to other oils. This applies particularly to emulsion forming oils, where the viscosity may be order of magnitudes larger than the viscosity range covered in the experiments.

Studies of oil spreading on cold water have also indicated that spreading tends to stop as the slick approaches a terminal thickness on the order of 1 to 8 mm, apparently depending on the viscosity of the oil (Venkatesh et al. op cit.). An empirical relation was proposed to account for the increase in terminal thickness with viscosity, but this correlation was not confirmed by later supplementary experiments (El-Tahan and Venkatesh, op cit.). This implies that one has to look for others factor that could be responsible for the termination of spreading. Solidification of the oil due to crystallization of the wax content at temperatures below the pour point of the oil might be one candidate.

4.1.3 Termination of spreading

Under natural conditions, oil spreading will not stop when the terminal thickness is reached. At this point, the oil slick will tend to break up in patches and small fragments due to wave action and current shears, and these patches or fragments will be spread due to oceanic turbulence. This is one of the reasons for Lehr's somewhat pessimistic attitude towards attempts to improve Fay type spreading models. Lehr (1995) states that "it is doubtful that any of these approaches will accurately predict the slick area over any extended time period because of the neglect of outside environmental factors." The factors neglected in these approaches are mainly wave action and spreading induced by shear currents and oceanic turbulence, which are presumed to be the dominant long term spreading processes.

4.1.4 *Continuous spills*

Lehr (op cit.) also points out that "most spreading algorithms assume instantaneous release of oil in open water conditions, while real spill incidents may cause leaks which continue at a varying rate for hours or days –." As mentioned previously, methods used to predict spreading of instantaneous spills are questionable for cases with continuous spills. This is mainly due to the fact that as oil leaks from continuous spills, the oil will be moved away from the source with wind and currents. In such cases, at some distance from the source, lateral spreading forces will dominate, while spreading forces along the slick axis will be negligible. As pointed out early by Waldman et al. (1972), this implies that the oil will spread more in the manner of spreading in a channel (i.e., one-dimensional spreading, symmetric about the slick axis). In such cases, the slick can not be considered as a homogenous entity (as in the Fay (1969, 1971), Mackay et al., (1980a,b), and Lehr et al., (1984a,b) models). Obviously, with a continuous release, the thickness and the properties of the oil in the slick will vary not only with time, but also with the distance from the source.

A sub-sea blowout from offshore exploration or production is one of the more serious situations leading to a continuous leak at a varying rate for hours or days. In such a case, the surface spreading of the oil will be governed by other mechanisms than gravity spreading. Sub-sea blowouts will generate buoyant plumes where the buoyancy flux is mainly related to the flow of gas released together with the oil. The oil will be transported to the surface together with the seawater entrained by the plume, and the surface spreading of the oil will be governed by the radial outflow of this entrained water. In general, the oil film generated in such cases will be in the order of one magnitude thinner than slicks formed by surface leaks.

Theoretical and experimental studies of oil spreading from sub-sea blowouts were initiated in the early eighties (Fanneløp and Sjøen 1980, Milgram 1983, Milgram and Burgess 1984), and refinements of these models have continued up to present (Swan and Moros 1993, Zheng and Yapa 1997, Rye and Brandvik 1997). This recent work implies that predictions of the surface spreading may be made with acceptable accuracy for sub-sea blowouts from moderate water depths. However, for releases from greater depths (e.g. 500 to more than 1000 m), modifications of the present models will be necessary, particularly due to the expected formation of gas hydrates.

4.1.5 *Conclusions*

From the point of view of weathering models, we may conclude this review of the state of the art of spreading modeling as follows:

- Instantaneous spills:
  - Fay-type spreading models may provide at least during the early stages of a release, adequate predictions of the film thickness in the thick part of the slick, where the major fraction of oil volume will be found.
  - Modifications of the Fay model for effects of oil viscosity and termination of spreading should be considered.
  - Linking spreading to dispersion probably will best retain the recognized physics of the spreading process.

- Continuous spills:
  - For continuous surface leaks in open sea conditions, where lateral spreading will be dominant some distance downstream from the source, one-dimensional Fay spreading models seem to be more relevant than the radial spreading models used for instantaneous spills.
  - Modifications for effects of oil viscosity and termination of spreading should also be considered in this case.
  - For sub-sea blowouts, where the Fay equations are inadequate, surface spreading may be predicted by use of model concepts based on buoyant plume theory, allowing for significant differences in behavior as a function of oil composition.

4.2 Evaporation

Estimates of evaporative losses are required in order to assess the persistence (lifetime) of the spill, and are also the basis for estimates of changes in oil properties with time. In the OCS model, the algorithms for evaporation are based on a pseudo-component evaporation method. Simpler and less computer intensive methods have been widely used, mainly based on an analytical model proposed by Stiver and Mackay (1984). A model of this type is used by NOAA (1988) in the ADIOS model. More recently, Fingas (1997, 1998) has proposed a simple empirical method derived from small-scale pan evaporation experiments. Jones (1997) has recently compared predictions made with the different evaporation models, and discussed data requirements and characteristics of the models. The results from these studies will be discussed in the following sections.

4.2.1 Pseudo-component methods

In these methods, the fraction evaporated is computed as a function of time, temperature, and wind speed. In such models, the oil is divided into a number of "cuts" specified in terms of intervals in boiling point temperature. The volume fraction in each of these cuts is obtained from true boiling point (TBP) data obtained by a standard ASTM-method. These volume fractions are converted into mole fractions on the basis of the average specific gravity and molecular weight of each cut. The vapor pressure of each cut is computed from the average boiling point and the oil temperature by means of empirical or semi-empirical formulas. On the condition that the partial pressures of these components are negligible in the ambient air, the evaporation rate for each cut is presumed to be proportional to the partial vapor pressure of each component. The modeled rate of evaporation depends also on a mass transfer coefficient, which in general is related to the surface wind.

Jones (1997) has modified this method by introducing an empirical relation between molar volumes and boiling point, based on data for n-alkanes. In this way, the pseudo-component method may be used in spite of the common lack of data on specific gravity of the boiling point cuts. The same author has also introduced an empirical equation for determination of the vapor pressure as a function of boiling point and oil temperature. This equation is said to produce more realistic pressure values, particularly at high boiling points, than the Clausius-Clapeyron equation and the Trouton's rule used in the OCS model. However, the formulation for the mass transfer coefficient is the same as recommended in the OCS model, and based on an early paper by Mackay and Matsugu (1973).

A similar pseudo-component concept is used in the SINTEF weathering model (Daling et al. 1997). However, the mass transfer coefficient in this model is based on formulations commonly used for computations of surface of fluxes of momentum, heat and moisture in open sea (Smith 1988). This implies that the mass transfer coefficient is proportional to the wind speed, with the air-sea drag coefficient used as the factor of proportionality. However, as shown by Amorocho and DeVries (1980) and Blake (1991), the drag coefficient depends on the wind speed due to changes in the surface roughness of the sea with the sea-state. Amorocho and DeVries (1980) have shown that the drag coefficient for near-neutral conditions is observed to increase from a constant value of about 1×10^{-3} at wind speeds above 7 m/s, where white caps start to form. At wind speeds of about 20 m/s, the drag coefficient attains a constant value about twice the value at small to moderate wind speeds.

Note that with this approach, the mass transfer rate does not depend on the spatial extent of the oil slick, as postulated by Mackay and Matsuga (1973). Moreover, the same mass transfer coefficient will apply to all components, independent of differences in the molecular properties of the cuts. This may be justified by the common assumption in turbulent heat and mass transfer, that passive contaminants are transported by turbulent motion in much the same way as momentum (Tennekes and Lumley 1990).

4.2.2 Analytical and empirical methods

Due to the data requirements and computational complexity of the pseudo-component concept, simpler methods have been proposed, such as the so-called analytical method developed by Stiver and Mackay (1984). This method is used presently in many oil drift models, as well as by NOAA (1994) in the ADIOS model. The method is based on several simplifications, including the questionable assumption of a linear relationship between the boiling point of the liquid phase and the fraction lost by evaporation. This linear relation is specified in terms of an initial liquid phase boiling point temperature and the gradient of this boiling point temperature versus the fraction evaporated.

It should be noted that the liquid phase boiling point data required in the analytical method are different from the data that are provided by the standard True Boiling Point curve. For this reason, a subroutine for calculation of the initial boiling point based on the TBP curve is included in the ADIOS model (NOAA *op cit.*). This subroutine calculates by trial and error the temperature where the vapor pressure above the fresh oil is equal to the atmospheric pressure, and contains essentially the same algorithms as required for calculations of the vapor pressure of the remaining oil fractions in a pseudo-component concept.

When Jones (1997) made his comparisons between the analytical model and the pseudo-component method, he found that the analytical method in general predicted significantly larger evaporative losses than his own pseudo-component model. He presumed that the difference could be explained by the use of different algorithms for calculating vapor pressures in the two methods. The high evaporative losses predicted by the analytical method may also in part be explained by the postulated linear approximation of the boiling point curve.

In the derivation of the analytical method, Stiver and Mackay (1984) also introduced the evaporative exposure parameter θ. They showed that the relation between the evaporative loss and this parameter is thermodynamic in nature and does not depend on how the exposure is achieved. Hence, the relation is only a function of the initial oil composition and the oil temperature. For constant wind speed, the evaporative exposure parameter may be expressed as $\theta = Kt / h$, where K is the surface mass transfer coefficient, h is the initial film thickness and t is the exposure time. This implies that if the evaporative loss is computed as a function of time for one combination of wind speed and initial film thickness, the results may be used for any another combinations of wind speed and film thickness by a simple time scaling. The same applies to cases with variable wind, where the exposure is obtained from the integral $\theta = \int (K / h)\, dt$.

Johansen and Skognes (1988) applied this concept in a statistical trajectory model in order to reduce the computational requirements of the evaporation calculations. In this model, the evaporative loss is computed as a function of time for a selection of crude oils at a chosen reference condition, defined in terms of a fixed initial oil film thickness and a constant wind speed. These results are tabulated in a file, which is later read during the start-up of the trajectory model. During the trajectory simulations, the evaporative loss is determined by simple interpolation, on the basis of the integrated evaporative exposure along each trajectory.

It should be noted that this concept also might be based on empirical evaporation data from laboratory scale evaporation experiments, provided that the resulting evaporative losses are related to relevant evaporative exposures. Fingas (1997) has conducted such experiments for a variety of crude oils and oil products, and derived some simple empirical relations for prediction of the evaporative loss as a function of time, based on commonly available distillation data for oils (i.e., percent by weight distilled at 180°C). However, Fingas (1998) also concluded from these experiments that wind speed and exposed surface area do not significantly influence the evaporation rate. For this reason, he advocated that his correlations should be used with no corrections for film thickness on wind speed, but with a minor correction for temperature. These conclusions are not at present generally accepted in the field of oil spill modeling, and run counter to most prior work in this area.

Jones (1997) compared predictions with his pseudo-component model at different wind speeds and oil film thicknesses with the predictions based on the empirical equations proposed by Fingas, and concluded that the empirical correlations in general produced significantly smaller evaporative losses than the pseudo-component method. However, as Jones (*op cit.*) points out, Fingas used low wind speeds and relatively thick oil to establish the parameters in his model. When examining the results under such conditions, Jones found that the models were in good agreement. This may imply that the evaporative exposure relevant for the laboratory conditions could be established, such that adjustments of the empirical predictions for other conditions (wind speed, film thickness) would be possible. However, further tests at other wind speeds and comparisons with calculations based on the pseudo-component concept should be made before such adjustments can be recommended for general use.

4.2.3 Conclusions

Different methods for computation of evaporation have been discussed in this section, including the pseudo-component method, the analytical method and the more recent empirical method. The discussion may be concluded as follows:

- The analytical method developed by Stiver and Mackay is based on liquid phase boiling point data not readily available. Introduction of methods to derive the required data from standard distillation data will obviously reduce the primary advantage of the analytical method – i.e., its simplicity. The analytical method is also based on questionable assumptions, which tend to produce overestimation of the evaporative losses.

- The surface mass transfer coefficient formula originally proposed by Mackay, which is used in many models to date, should be examined critically together with alternative formulations based on sea surface exchanges of momentum, heat and moisture.

- The pseudo-component method seems to be the most reliable and flexible of the discussed methods. However, for use in trajectory and fates models, the computational intensity of the method may still justify a search for simpler methods (empirical correlations) or "shortcuts" (i.e., application of the evaporative exposure concept).

4.3 Natural dispersion

Computation of natural dispersion is required for assessment of the lifetime of an oil spill. The rate of natural dispersion depends on environmental parameters (i.e., the sea-state), and is also influenced by oil-related parameters, such as oil film thickness and oil properties (viscosity, density, and surface tension). Emulsification (Section 4.4) will contribute significantly to the persistence of oil spills, mainly due to the increase in viscosity and slick thickness with water content, factors retarding spreading, increasing volume, and reducing natural dispersion.

4.3.1 Alternative approaches

In the OCS model, an algorithm based on an early work of Mackay et al. (1980a) is used to estimate the rate of natural dispersion. More recently, a dispersion model based on the experimental work of Delvigne and Sweeney (1988) has gained more attention, and this model has been implemented by NOAA (1994) in the ADIOS model, as well as in the SINTEF weathering model (Daling et al. 1997).

Delvigne and Sweeney (*op cit.*) conducted investigations of natural dispersion of surface oil due to breaking waves in a small laboratory flume, and in a larger test basin. On this basis, an empirical relation was derived for the entrainment rate (dispersed mass per unit time) as a function of oil type and breaking wave energy. The authors also determined relations for predicting the droplet size distribution of the entrained oil as a function of the same parameters. The experiments revealed a common feature of the droplet size distribution of the entrained oil for all the experiments. The number of droplets in a certain diameter class could be related to the droplet size with a common power law relationship, independent of the type of oil and the wave conditions. From this general observation, an expression was derived for the droplet size distribution of the oil mass entrained by each breaking wave: $Q_{d \le D} = CD^p$.

In this equation, $Q_{d \le D}$ is the entrained oil mass per unit area included in droplets up to a certain diameter D. The exponent $p = 1.7$ was derived from the power law distribution of the droplet size determined from the experiments. The factor of proportionality C was found to depend on the oil type and the height of the breaking wave H, i.e., $C = a\,H^q$, where the dispersion coefficient a could be related to the oil type in terms of the oil viscosity. The exponent q was found to be 1.14 from the wave flume experiments, while a slightly larger value ($q = 1.4$) was found in later small scale experiments (Delvigne and Hulsen, 1994).

Based on the limited viscosity range in the wave flume experiments, the authors postulated that the dispersion coefficient a was inversely proportional to the viscosity of the oil. However, in the subsequent small scale experiments in an extended viscosity range, this postulated relationship was not confirmed. Instead, the authors concluded that the coefficients were very similar for all low-viscous oil types and weathering states with viscosity less than 100 cSt. For viscosities above this range, the coefficients decreased considerable with increasing viscosity. Thus for an increase in viscosity from 100 to 1000 cSt, the dispersion coefficient was found to be reduced by about two orders of magnitude (Delvigne and Hulsen, 1994). This agrees with observations that the dispersion rates of emulsified oils will be significantly reduced compared to non-emulsified oils (e.g. Reed et al., 1994, 1995).

The above equation applies to the mass entrained by each breaking wave. In order to obtain an expression for the entrainment rate, the equation must be multiplied by a rate factor F_w. This factor is obtained from the white cap coverage, which is divided by the mean wave period to obtain the fraction F_w of the sea surface hit by breaking waves per unit time.

The authors suggest that the oil droplet dispersion may be assumed to follow this empirical relationship for the range from the smallest size classes to the size where the entrained mass equals the local surface concentration of oil (oil mass per unit area). This implies that the predicted maximum droplet size will depend on the oil film thickness, as well as the sea-state and the type and weathered state of oil.

In the ADIOS model, as in the SINTEF weathering model, this equation is used to estimate the entrained oil mass per unit area and unit time included in droplets below a certain threshold diameter, below which the droplets are presumed to be permanently dispersed. In ADIOS, this threshold diameter has been assigned a value of 70 μm, with reference to recent field measurements of the size distribution of dispersed oil droplets (Lunel, 1993). However, the use of a specific threshold diameter is questionable for several reasons:

Entrained oil droplets tend to be dispersed permanently in the water masses when the magnitude of the vertical turbulent motions is high compared to the rise velocity of the droplets.
When the turbulent motion dominates, dispersed oil droplets tend to be mixed down into the water column, and as a result, the rise time to the surface will increase.

This implies that the limit for permanent dispersion should be related to droplet rise velocities and sea state, rather than the droplet size alone.

Moreover, dispersed oil droplets tend to lag behind the surface slick due to the wind-induced current shear in the upper part of the water column. The gradual resurfacing of droplets within a certain size range will then contribute to the observed elongation of the slick, where a tail of thin oil film will be formed behind a thicker portion of the slick. This process may be quantitatively important in determining mass balance since the thin portion is easily dispersed naturally, and represents a sink for oil from the thick slick. These processes have been included in oil drift models based on the particle concept (Johansen 1987, Elliot 1991, Reed et al., 1984, 1998). However, since predictions of the transport of oil due to wind and currents are normally not requested in weathering models, simplified concepts for estimates of the permanently dispersed fraction may be acceptable. The SINTEF OWM contains these processes, and uses a threshold diameter of 150 µm as the cutoff between resurfacing and permanently dispersed oil droplets. This value was selected from theoretical and empirical considerations. In any case, the consequences of the choice of a certain threshold diameter (or rise velocity) for permanent dispersion should be investigated further by sensitivity analysis.

4.3.2 Conclusions

In recent oil weathering models, dispersion calculations based on the work of Mackay and collaborators in the early eighties have been replaced by an empirical method derived by Delvigne and Sweeney (1988). This new method, which is based on experimental studies in wave flumes and small-scale laboratory apparatus, may be used to predict the droplet size distribution of the entrained oil as a function of oil type and sea-state.

In oil weathering models, the method is used to estimate the fraction of the oil that will be permanently dispersed in various sea states. However, this approach rests on the selection of a certain threshold droplet size. This may be a questionable approach, mainly due to the fact that permanent dispersion is a result of the balance between vertical turbulent motions in the water masses and the rise velocity of the droplets. This implies that the threshold for permanent dispersion should be expressed in terms of rise velocity and sea state, rather than droplet size alone.

The method of Delvigne and Sweeney is the best available technology for upgrading of the dispersion algorithms in the OCS model, but the threshold droplet size assumption should be evaluated through sensitivity analysis before the method can be used with confidence.

4.4 Emulsification

Emulsification contributes significantly to the persistence of oil spills, due to the resultant increase in viscosity and the increase in slick thickness with water content, factors retarding spreading, increasing volume, and reducing natural dispersion.

4.4.1 Alternative approaches

In the OCS model, emulsification is computed with an implicit algorithm originally proposed by Mackay et al. (1980a). The same authors in fact advocated the use of a simpler explicit algorithm, which could be expressed in differential form (Mackay et al, 1980b). This algorithm is used by NOAA in the ADIOS model, and also in a slightly modified form in the SINTEF weathering model. The simplified algorithm contains two parameters, defining the water uptake rate and the maximum water content. Both parameters may be derived from laboratory experiments, but the parameter for the water uptake rate must in some way be scaled to field conditions and different sea-states (Johansen, 1991).

Experimental studies of emulsification for different crude oils have revealed that both the water uptake rate and the maximum water content vary significantly from one crude to another, and that these parameters also are influenced by the state of weathering of the oils (Daling and Brandvik, 1988). Often, but not always, the maximum water content tends to decrease with the viscosity of the parent oil. The differences in the water uptake rate might be related to the chemical make-up of the oil (i.e., the content of resins, waxes and asphaltenes), but the results from a limited range of crude oils were not conclusive. Due to the significant differences in emulsification between different oils, Daling et al (1990) recommended that the emulsification parameters be determined on the basis of experimental data for specific oils.

Fingas et al. (1997, 1998) have recently presented a literature review of emulsification and related model concepts. They conclude that past emulsification modeling was based on first-order rate equations that were developed before extensive work on emulsion physics took place. They suggest that empirical data should be used as a basis for further developments of emulsification models, and that such models also should take into account the stability of emulsions formed by different oils (stable, meso-stable, unstable). The stability is a measure of the decrease in the water content of an emulsion when kept in stagnant conditions. Meso-stable emulsions will lose some water when kept at rest for e.g. 24 hours, while unstable emulsions will lose practically all water when kept at rest for the same period.

Emulsions exhibit non-Newtonian rheological characteristics, in that the measured viscosity is strongly dependent on the shear rate (e.g. McDonagh et al. 1995). Emulsions are therefore often described by using an apparent viscosity at a specific shear rate. While the apparent viscosity of a stable emulsion may be two to three orders of magnitudes greater than the viscosity of the parent oil, the apparent viscosity of unstable emulsions are no more than an order of magnitude greater than that of the parent oil. The apparent viscosity of meso-stable emulsions generally falls between these ranges and depends on the degree of stability. These observations should be taken into account in the prediction of the viscosity of emulsions, which normally are based solely on water content, independent of specific emulsion characteristics such as water droplet size distribution.

4.4.2 Conclusions

An explicit first order rate model, also recommended by Mackay et al. (1980b), should replace the present implicit algorithm for prediction of emulsification used in the OCS model. The first order rate equation may be expressed in a convenient differential form to account for subsequent changes in emulsification rate due to changes in the oil composition (due to evaporation) and variable sea-state.

It should be noted that the emulsification parameters that are required in this model (emulsification rate and maximum water content) might be different for each specific crude or oil product. Consequently, efforts should made to determine empirical correlations for these parameters based on the extensive data presently available from experimental studies of emulsification. Meanwhile, these parameters must be based on laboratory studies conducted for each crude or oil product. To the extent that the OCS model is applied to a limited number of oils, this should not represent a problem.

As recently pointed out by Fingas et al, (1997, 1998) water-in-oil emulsions formed by some crude oils have been found to be unstable or meso-stable. Unstable and meso-stable water-in-oil emulsions will in general have lower apparent viscosity than stable emulsions, and may for this reason be less persistent than stable emulsions. The stability of emulsions typically changes from unstable to meso-stable to stable as the oil weathers. Efforts should be made to take this behavior into account in emulsification predictions, and also in predictions of the viscosity of the emulsion as a function of water content.

4.5 Oil-ice Interactions

The behavior of oil in ice is complex, and difficulties in modeling the physics of ice movement and formation on scales of meters are magnified when the uncertainties of oil behavior are added. A very significant literature exists describing oil-ice interaction studies over the past 25 years. Fingas (1992) and Dickens and Fleet (1992) give extensive overviews of the subject up to the beginning of this decade.

More recent work has focussed largely on spreading of oil in and under ice (Yapa and Weerasuriya, 1997; Yapa and Belaskas, 1993; El-Tahan and Venkatesh, 1994), but calibrations rely largely on small scale, short-term laboratory studies, in which edge effects rapidly limit applicability to real situations. After the first hour or so, spreading in the field will be governed by ice lead dynamics, which tend not to be included in these solutions.

The most realistic data on the weathering of oil in the presence of sea ice is probably the field data reported by Singsaas et al., 1994. This data show that the processes of evaporation, dispersion, and emulsification are all significantly retarded in ice leads, completely contrary to the conclusions drawn by Payne et al (1987) from meso-scale laboratory experiments. Wave-damping, the limitations on spreading dictated by the presence of sea ice, and temperature appear to be the primary factors governing the observed weathering rates.

A key problem in achieving any improvement in modeling these processes lies in our very limited ability to model the behavior of the ice itself at the necessary spatial scales, which are on the order of meters. The real time forecasting attempt reported by Reed and Aamo (1994) and the model development and hindcasting work by Johansen and Skognes (1995) exemplify the problems encountered when oil-ice interaction models are put into active use in the field. Our limited ability to model ice behavior at the 1-10 m scale also seriously limits the extent to which we can make good use of the advances in modeling of oil spreading cited above. Ice coverage is a dynamic variable, and can change from 50% to 99% overnight, with extreme consequences for oil weathering due to changes in thickness.

The pessimistic view is that the modeling of oil weathering in the presence of sea ice remains at an ad hoc level, limited largely by the state-of-the-art in modeling sea ice physics at the appropriate scale. A more optimistic summary would take account of the advances that have been made in our understanding of oil weathering processes in the presence of sea ice. This new understanding has come primarily through fieldwork, the results of which have corrected misconceptions introduced through prior laboratory weathering studies. The optimistic conclusion, then, is that the next generation of oil-in-ice weathering models will be more nearly correct than earlier models, but will remain highly parameterized, still lacking dynamic reliability at the appropriate time and space scales.

5. Literature review of available data sets from experimental oil releases suitable for calibration/verification of Oil Weathering Models

The objective with this section is to obtain an overview of data sets from experimental oil releases at sea suitable for calibration/verification of Oil Weathering Models. Several persons have contributed background data concerning field trials in different countries:

USA: Bob Fiocco, Exxon
Canada: Don Mackay Trent University and Merv Fingas Environment Canada
France: Francois Merlin, cedre
Norway: Per Johan Brandvik, SINTEF
UK: Alun Lewis, AEA

This information has been collected, reviewed and summarized at SINTEF by Per Johan Brandvik.

5.1 The "ideal data set"

The ideal data set for calibration/verification of Oil Weathering Models from experimental field trials should satisfy the following criteria:

5.1.1 Environmental background data

Relevant meteorological and oceanographic data should be available. The following variables should be included in the data set:

- air/water temperature,
- wind (direction/strength),
- waves (significant height, frequency),
- currents (at relevant depths)

Vertical TCD (temperature, salinity/conductivity, and density) profiles should also be included if modeling of sub-sea releases is an issue.

5.1.2 Oil characterization

The ideal data set should contain sufficient data to establish a mass balance (surface oil, evaporated, dispersed, soluble, biodegraded, stranded) for the oil slick as a function of time for a longer period (several days).

The original oil properties listed below should be documented, and the same variables should be followed through time in the data set:

- Evaporative loss,
- water content of w/o emulsion,
- viscosity of w/o-emulsion,
- emulsion stability,
- pour point,
- flash point,

- density,
- chemical dispersability,
- surface oil film thickness (in-situ measurements),
- surface distribution of oil (remote sensing),
- oil concentration (dispersed/soluble) in water column,
- droplet size distribution of dispersed oil.

5.1.3 Documentation - Standardized methods

The methods used for sampling and analysis should be in accordance to internationally accepted standards (ASTM/ISO/IP). However, no such standards exist for several of these analyses. The Marine Spill Response Corporation (MSRC) in the USA took an initiative in 1994 to develop standard protocols for handling and characterization of oil samples during field operations. Unfortunately this project was terminated in 1995 due to lack of funding. From the work performed during this project there are several "informal standards" describing procedures for sampling, handling and analysis of oil samples worked out by relevant organizations in the USA, Canada, France, UK and Norway (e.g. Daling et al, 1990 , Strøm-Kristiansen et al. 1997, 1996, and Lewis et al. 1998).

5.1.4 Sampling frequency

The sampling frequency for the oil weathering variables listed in Section 5.1.2 should be 15 min, 30 min, 1 hour, 2, 4, 8, 12, 24 and then twice every succeeding day.

5.1.5 Replicate samples

To describe the inhomogeneity within a surface oil slick, replicate samples should be taken at different locations for some of the sampling times in Section 5.1.4.

5.2 Relevant field Trials – historical summary

These sections summarize the most relevant field trials from England, US, France, Canada and Norway. A brief description of each field trial is given in Appendix A "Standardized field data sheets". An evaluation of the data sets for calibration/verification of Oil Weathering Models is given in the next section, literature references are given in Section 5.5.

5.2.1 England

Year date	Ref Id	Responsible organization	Weathering time	Oil type	Oil volume	Main purpose of experiment	literature reference
Sep-97	AEA-97	AEA Technology	days	Cr./bunker	100 m^3	Weathering studies and dispersant treatment	9
Sep-95	AEA-95	AEA Technology	days	Cr./MFO	20 m^3	Weathering studies and dispersant treatment	8
Aug-94	AEA-94	AEA Technology	1 day	Forties	2x15 m^3	Weathering studies and dispersants treatment	1
Sep-93	AEA-93	AEA Technology	days	MFO	2x20 m^3	Weathering studies and dispersants treatment	2
Jun-92	AEA-92a	AEA Technology	days	MFO	38 m^3	Weathering studies and Demulsifier treatment	3
Jun-92	AEA-92b	AEA Technology	6 h	Crude	4 m^3	Weathering studies – emulsification/evaporation	4
Jun-92	AEA-92c	AEA Technology	2 days	Crude	15 m^3	Weathering studies – emulsification	4
Apr-92	AEA-92d	AEA Technology	32 h	Forties	18 m^3	Weathering studies – emulsification/evaporation	4
May-92	AEA-92e	AEA Technology	2 h	Crude	2.6 m^3	Weathering studies – emulsification/evaporation	4
Aug-88	WSL-88	Warren Spring Lab.	hours	Flotta	??	Weathering studies	5
Aug-87	WSL-87	Warren Spring Lab.	hours	Forties	??	Weathering studies	6

Main Source of information: Alun Lewis, AEA

5.2.2 *France*

Year date	Ref Id	Responsible organisation	Weathering time	Oil type	Oil volume	Main purpose of experiment	literature reference
May-79	Protechmar I	CEDRE/IFP	hours	Fuel oil	3 m^3	Effectiveness of dispersants and application equipment	25, 35,36
Sep-80	Protechmar II	CEDRE/IFP	hours	Fuel oil	1-5.5 m^3	Effectiveness of dispersants and application equipment	35, 36
Sep-81	Protechmar III	CEDRE/IFP	hours	Fuel oil	6.5 m^3	Effectiveness of dispersants and application equipment	35, 37
Sep-82	Protechmar IV	CEDRE/IFP	hours	Fuel oil	3-5 m^3	Effectiveness of dispersants and application equipment	35
Sep-82	Protechmar IV	CEDRE/IFP	hours	Fuel oil	3-5 m^3	Effectiveness of dispersants and application equipment	35
Oct-83	Protechmar V	CEDRE/IFP	hours	Crude	22 m^3	Weathering - application of dispersants by helicopter bucket	35
Sep-85	Protechmar VI	CEDRE/IFP	hours	Fuel oil	28 m^3	Weathering - application of dispersants from boat	35
Jul-89	Polutmar I	CEDRE/IFP	hours	Chemicals	1-2 m^3	Dispersion/spreading of chemicals	26
Oct-89	Polutmar II	CEDRE/IFP	hours	Chemicals	1-2 m^3	Dispersion/spreading of chemicals	26
1990	Polutmar III	CEDRE/IFP	hours	Oil/Chem.	1-2 m^3	Dispersion/spreading of chemicals and oil	27

The Ecumare program (started in 1984 and still ongoing!) has tested and verified the performance of equipment for mechanical recovery of oil spills at sea.

Main source of information: Francois Merlin, CEDRE

5.2.3 US

Year date	Ref Id	Responsible organisation	Weathering time	Oil type	Oil volume	Main purpose of experiment	literature reference
Oct-75	API-75	JBF Scientific corp.	7 hours	Crude	4x1.7 m^3	Fate of dispersed oil and studies of evaporative loss	11, 12
1976	UNIV-76	Univ. of WA.		Cr/bunk	Litres	Spreading of oil in ice – tank experiments	39a-c
Nov-78	API-78a	JBF Scientific corp.	Several hours	Crude	4x1.7 m^3	Fate of dispersed oil	10
Sep-78	API-78b	API/SC-PCO	5 hours	Crude	0.8-3.2 m^3	Testing equip. for dispersant application and mech. recovery	13
Sep-79	SC-PCO-79	SC-PCO	3 hours	Crude	1.6-3.2 m^3	Dispersant application/fate of dispersed oil	14
1980-84	NOAA-84	Science Appl. Int.	Several months	Crude	Liters	Oil weathering in open outdoor wave tank in Alaska	9

Main source of information: Bob Fiocco, Exxon

5.2.4 Canada

Year date	Ref Id	Responsible organisation	Weathering time	Oil type	Oil volume	Main purpose of experiment	literature reference
1974	NORCOR	NORCOR	Months	crude	60 m^3	Oil released under first year ice	29
1978	Gripper bay	Arctec Canada ltd	Months-years	crude	1.8 m^3	Oil released under multiyear ice	30, 33
1980?	DOME	Dome petroleum	Months			Oil/gas released under Sea ice	31, 32
1986	ICE-86	Ross/Dickins	Hours	crude	3x1 m^3	Oil weathering in broken ice, terminated with burning	28
1984	Beaufort-84	uncertain	Minutes	crude	litres	Dispersant effectiveness studies	34

Main Source of information: Don Mackay, Trent University

Norway

Year date	Ref Id	Responsible organisation	Weathering time	Oil type	Oil volume	Main purpose of experiment	literature reference
Sep-78	SINTEF-78	SINTEF	5 days	Crude	25 m^3	Study oil weathering, oil trackers and spill trajectories	15
Jul-82	SINTEF-82	SINTEF	6 days	crude	100 m^3	Verify/develop models for oil drift and spreading	16
1982	PFO-82	SINTEF and others	Hours	Crude	7x2 m^3	Dispersant treatment – water diluted dispersants	17
Jun-84	PFO-84	SINTEF and others	Hours	Crude	6x10 m^3	Dispersant application – concentrated dispersants	17
Jun-85	DOOS-85	SINTEF	hours to 1 day	Crude	6x10 m^3	Drifting and spreading of dispersed oil versus surface oil	18
Jul-89	Haltenb-89	Oceanor/MMS	4 days	Crude	30 m^3	Oil weathering, Oil trackers, remote sensing	19, 20
Aug-91	Haltenb-91	Oceanor/MMS	hours to 1.5 day	Crude	3x 20 m^3	Oil Trackers, oil weathering	21
Apr-93	MIZ-93	SINTEF	7 days	Crude	26 m^3	Weathering of oil in the Marginal Ice Zone	22
Jun-94	NOFO-94	SINTEF	1 day	Crude	2x 20 m^3	Dispersant application by helicopters	23
Sep-95	NOFO-95	SINTEF	1 day	Crude	Tot 85 m^3	Underwater release and dispersant application by helicopters	24
Jun-96	NOFO-96	SINTEF	hours – 1 day	Crude	Tot 75 m^3	Underwater release and dispersant application by helicopters	25

In addition to these field trials annual releases of oil have been carried out to develop and verify the performance of equipment for mechanical recovery of oil at sea.

Main source of information: Per Johan Brandvik at SINTEF

5.2.5 *Others*

Year date	Ref Id	Responsible organisation	Weathering time	Oil type	Oil volume	Main purpose of experiment	literature reference
Aug-82	DELFT-82	Delft hydraulics lab.	Hours	Crude/fuel	9x2 m3	Dispersant effectiveness vs. sea state	38

5.3 Evaluation of field data for model calibration/verification

None of the field trials listed in Section 5.2 fully satisfy the strict demands for an "ideal data set" described in Section 5.1. None of these data sets gives a complete documentation of oil mass balance as a function of time for a longer period. However, this lack of the "ideal data set" should not prevent us from using the best of these data sets for calibration/verification of oil weathering models.

There are several trends in the available data, which will be discussed and evaluated for each country below. The information used for this evaluation is described in Section 5.2 "Relevant field trials – a historical summary" and Appendix A "Standardized field data sheets".

5.3.1 England

England has an extensive experience from field trials with oil releases in the North Sea. These field trials have been performed by AEA Technology and have mainly been funded by MPCU and to some degree by UK and foreign oil companies.

Studying oil weathering and effectiveness of dispersants and emulsion breakers have been the main objectives for these sea trials the last years. Data from last years sea trials (from 1992) contains extensive data sets describing environmental conditions oil weathering (evaporation, viscosity, surface oil distribution, natural dispersion etc.).

5.3.2 France

This section gives an evaluation of relevant data from French sea trials.

PROTECMAR

The French Protechmar program was carried out in the period 1979-85. The main objectives were to correlate dispersant effectiveness from laboratory and field experiments and to study different application techniques for dispersants. Different oil types were used; including different mixtures of fuel oils and Arabian Light crude. The weathering of the oil slicks at sea was relatively short (approximate 1 hour) before application of different types of dispersants.

Since metocean data (wind/waves) and data describing natural and chemical dispersion (UV fluorescence and turbidity measurements) are available, these data sets could be used for testing of algorithms describing short term dispersion (natural/chemical) of oil slicks.

POLUTMAR

The Polutmar program was carried out in the period 1989-90. The main objectives were to compare or verify the predicted spreading of chemicals at sea with field measurements. Examples of chemical used were; ethyl-2 hexanol, gas tracers, ethylene glycol and diesel fuel.

Spreading of the chemicals was monitored both at the surface, in the air and in the water column for a period of 30 to 60 minutes. The main findings were that the spreading in the air, at the surface and in the water column were slower than predicted by the models.

These data sets have very little potential for calibration/verification of oil weathering models, since they mainly describe spreading of water-soluble components and gases.

ECUMARE
This program is mainly focused on R&D concerning mechanical recovery equipment the data from these sea trials are of little relevance for our purpose.

5.3.3 USA

This section gives an evaluation of relevant data from sea trials performed in the US.

API-78a, API-78b and SC-PCO-79
Three of the sea trials in Section 5.2.3 "Field trials in USA" are mainly focused on the effect of dispersant application and spraying equipment; API-78a, API-78b and SC-PCO-79. Weathering of the oil slicks is given little attention and the data collected from the surface oil slicks are very limited. Water samples were analyzed to determine the content of water-soluble components. The data from these field trials have little potential for calibration/verification of oil spill weathering models.

API-75
This field trial focused on the changes in surface spreading, evaporation and water-soluble hydrocarbons for the first hours (up to 7 hours) at sea. The data indicates that the slick drifts with 3% of the wind and 2-60 ppb of hydrocarbons were measured under the slick for the first 30 minutes. These findings were of great importance 25 years ago, but are more general knowledge today. The data from these field trials have limited potential for calibration/verification of oil spill weathering models. The data could be used for calibration of the release rates of water-soluble components from the oil slick.

UNIV-76
Very little information exists concerning this field trial because we have not received the report from University of Washington.

NOAA-84
These experiments were performed in a wave tank under summer and winter conditions (with and without ice). The weathering of Prudhoe Bay crude and other oils are well documented with respect to evaporative loss, dissolution, dispersion and emulsification. These data sets provided the primary basis for calibration of the OCS oil spill weathering model.

However, significant problems are apparent when compared data from basin studies with field observations (Singsaas, 1994). Evaporation may be representative of field conditions, but emulsification and dispersion rates are not representative of those observed in the field, and are generally difficult to scale to field conditions. These basin experiments are for this reason not regarded as a field experiment producing data suitable for calibrating/verifying models.

5.3.4 Canada

This section gives an evaluation of relevant data from the Canadian field trials.

We do not have the full documentation from all the Canadian field trials, but Don Mackay's evaluation is that the Canadian field experiments have not yielded suitable data for model validation.

5.3.5 Norway

In Norwegian sea trials, ranging from work prior to the Bravo blow-out in 1977 to the simulated underwater blow-outs in 1995 and 1996, the focus has been on different topics. A brief evaluation of the different types of sea trial performed is given below. As in other countries the Norwegian field trial were designed to generate data for several purposes and the same field trial may be discussed in several categories below.

Development of oil spill trajectory models (SINTEF-78, SINTEF-82, DOOS-85)
These three field trials focused on testing and development of oil trajectory models. Models were refined from describing surface oil drift only as a function of wind and currents towards modern particle based models. These data sets were valuable for the development of our present models, but better data sets exist for verifying/testing the existing models today (see below).

Development of Oil Weathering Models (Haltenbanken-89, MIZ-93 and NOFO-94/95/96)
These five sea trials have a large span concerning both environmental conditions; North Sea versus Arctic conditions (Haltenbanken-89 and MIZ-93) and different sea states (NOFO 94/95/96). The three first are performed with the same oil type (Oseberg/Sture Blend), while a comparison can be made between Sture blend and Troll crude among the three last trials. The weathering of the oils are extensively documented from these trials with a weathering time varying from 1 day to 1 week. These data sets should have a high potential for calibration/verification of existing Oil Weathering Models.

Other sea trials performed in Norway have mainly focused on operational aspects like development/testing of equipment for mechanical recovery (NOFO's annual trials in the period 1978-96)), burning (field trials at Spitsbergen 1989-94) or use of dispersant (PFO-82, PFO-84 and NOFO-94/95/96) and are not further evaluated here.

5.3.6 Others

Other than those studies mentioned above the Delft Hydraulics Laboratory in the Netherlands has carried out field trials focused on use of dispersants and the effectiveness versus different wind and wave conditions. The weathering time of the oil is only 1 hour. This data have a potential to validate the dispersant algorithms as a function of Sea State.

5.4 Conclusions

Many of the older data sets reviewed in this study have limited potential for calibration-/verification of oil weathering models. This is caused by varying quality of the data due to lack of consistent procedures for sampling and analysis of the weathering parameters.

The more recent field trials have, however, use well-documented and suitable procedures for field sampling and further analysis. Our preliminary conclusion is that data from the following field trials have a high potential for calibration/verification of oil weathering models.

UK: Field trials in the North Sea from the period 1992-97

These experiments have been conducted on a yearly basis with different objectives. The more recent experiments (from 1992) have well documented and suitable procedures for sampling and further analysis. These field trials cover several crude oil (Forties, Alaska North slope) and different bunker fuels. The weathering time ranges from only hours to several days and the weathering parameters include (emulsification, evaporation, natural dispersion, water soluble components, emulsion viscosity, emulsion stability, water droplets distribution in emulsion and others). Some of these UK sea trials also include extensive monitoring of dispersed oil concentrations versus time and also measurements of droplet sizes of the dispersed oil droplets. Data are available from AEA Technology as reports and publications.

Norway: Field trials in the North Sea and in the marginal ice zone of the Barents Sea from the period (1989-96)

These experiments have been conducted on an almost yearly basis, but only some of the trials are relevant for our purpose. The SINTEF-89 and MIZ-93 trials gives data sets which can be used to compare weathering of the same oil type at a North Sea and an Arctic environment. These trials and the later NOFO trials (1994/95/96) have used well-documented and suitable procedures for sampling and further analysis. The weathering time ranges from one day up to seven days, and the weathering parameters include emulsification, evaporation, natural dispersion, water-soluble components, emulsion viscosity, and emulsion stability, among others. Data are available from SINTEF as reports and publications.

5.5 Literature list

The numbers in this list refers to the numbers used in the "literature" column in section 3 "Relevant field trials".

5.5.1 *UK field trials*

1 Amop 1995, p.471, Walker, Lewis and Brandvik
2 AMOP 1994, p. 951
3 Kananaskis Proceedings, "Formation and Breaking of w/o-emulsions, MSRC Technical report; 93-018, Walker et al.
4 OSC 93, p. 391. Walker et al.
5 WSL report no: LR725, 1988 by Hurford
6 WSL report no: LR671, 1977 By Buchanan and Hurford
7 Amop, 1996, p. 1355-1393, Lunel and dawis
8 Amop, 1998, p. 319344, Lewis et al.

5.5.2 *French field Trials*

25 OSC 85, p 445-452, "Recent advances in dispersant effectiveness evaluation: experimental and field aspects. Desmarquest et al.
26 7th Technical seminar on chemical spills, 1990, pp. 47-54. "Experimental study of chemical behavior at sea: Pollutmar I and II trials". Kantin et al.
27 8th Technical seminar on chemical spills, 1991, pp. 79-90. "Experimental study of chemical behavior at sea: Pollutmar II sea trials", Merlin.
35 OSC 87, pp. 225, "PROTECHMAR: The French experience from seven year dispersant offshore trials program". Bocard et al.
36 Bocard et al., 1981, "Operation PROTECHMAR", Spill technology Newsletter, v6, n2, pp. 54-85.
37 ASTM STP 840, 1984. pp. 125-142, Bocard et al., "Chemical oil dispersion in trials at sea and in laboratory test: the key role of dilution processes"

5.5.3 *US field trials*

9 Polar Research vol.10. No: 2, 1991. Oil Weathering behavior in Arcic Environment., J.R. Payne et al.
10 Response of crude oil slicks to dispersant treatment at sea: 1978. JBF Scientific Corporation, under EPA contract no: R806056
11 API Report, Physical and chemical behavior of crude oil slicks on the ocean. Publication 4290, April 1979.
12 ASTM STP 659 p.141, 1978: Physical and chemical behavior of small crude oil slicks on the ocean.
13 OSC 1979 Smith and Holliday, API/SC-PCO Southern California 1978 oil spill test
14 OSC 1981 McAuliffe et al., API/SC-PCO Southern California 1979 oil spill test
39a University of Washington report no: 69, Seattle WA, 1976, Martin, S.

39b Journal of Glaciology 22, p. 473-502 A field study of brine drainage and oil entrainment in first-year ice., Martin, S.
39c Proc. 27th Alaska Science Conference, 1976, Fairbanks, AK, US. Martin et al.

5.5.4 Canadian field trials

28 Environmental Studies Revolving Funds report no: 062, 1987. S.L.Ross and D.F. Dickins
29 Beaufort Sea Project report no: 27, 1975, NORCOR Engineering Research ltd
30 6th AMOP 1983, p14-19, Comfort et al.
31 OSC-81, p.183-189, Dickins et al.
32 Final report. "Oil and Gas under Sea Ice", Dome Petroleum, Vol. 1.
33 Env. Canada report EE-42, 1983, ARCTEC Canada Ltd,
34 Env. Canada report EE-58, 1985, Beaufort sea small scale dispersant trial

5.5.5 Norwegian field trials

7 IKU-SINTEF report no: p146/p195, 1980, "Experimental oil release at Trømsøflaket", Sørstrøm et al. (in Norwegian)
8 IKU-SINTEF publication no: 112, 1984, "The experimental Oil Spill on Haltenbanken 1982", Sørstrøm et al.
9 Oil Pollution Controll Research and Development Program (PFO) Final report (1985) and sub-reports
10 SINTEF report 02.0763, "Dispersion of oil on Sea (DOOS) report", Sørstrøm and Johansen
11 SINTEF report 22.1934, "Weathering of surface oil – experimental oil spill at Haltenbanken, 1989 – data report", Daling, Brandvik and Almås
12 Oceanor report OCN89054, 1990 "The Haltenbank 1989 experiment" Sørstrøm
13 SINTEF report 22.2054, "Weathering of surface oil – Experimental oil spill at Haltenbanken 1991", Hokstad
14 SINTEF Report no: 22.2120.00/02/94, "Experimental oil release in the marginal ice zone outside Spitsbergen, final summary report", Sørstrøm et al, 1994.
15 SINTEF report 22.2050.00/14/95, "Dispersant trials, NOFO exercise June 1994 – Main report", Lewis et al.
16 SINTEF report 415141.00/01/95, "Summary report from the 1995 NOFO exercise", Brandvik et al.
17 SINTEF report STF66 f97050, "NOFO 1996 oil on water exercise – Analysis of sample material", Strøm-Kristiansen et al.

5.5.6 Other field Trials

38 Delft Hydraulics Laboratory, report no: m 1933-1, 1983, "Sea measurements on natural and chemical dispersion of oil".

6. Summary and recommendations

In this chapter, the major findings from the review are summarized, and recommendations are given for modifications to or replacements of existing algorithms in the OCS model.

6.1 Review of the OCS model

The presentations and discussions at the teleconference clearly demonstrated the extent to which the present OCS model has fallen behind both the needs of its users, the state-of-the-art in terms of computational hardware and software, and also the scientific developments in oil spill weathering. These shortcomings were in general validated by the review of the documentation of OCS oil weathering model presented in Chapter 3 of this report. In this review, the reasons for the most frequent problems reported by the users of the model are also explained:

- *The model behaves questionably outside the narrow range of oils and conditions for which it was developed:*
- Some of the parameters required to specify additional oils in the model are based on non-standard procedures, and relevant oil-specific parameters may thus be difficult to obtain.
- The three parameters defining the emulsification process (i.e., the 'viscosity constant' the water uptake rate and maximum water content), and the 'viscosity-fraction-evaporated coefficient' are especially difficult to identify. Judging from the variations within the set of values used for the six "library oils", these parameters may be expected to vary significantly between different oils, and no standard procedures are established to identify their values.
- The model was built and calibrated around Prudhoe Bay Crude, and behaves reasonably well for that oil. Problems arise because model assumptions relevant for that oil are not relevant for other oils or petroleum products, marine diesel being a clear example.

- *Persistence (lifetime) seems to be too high, particularly for light oils (diesel):*
- Diesel oils in general contain relatively small fractions of volatile components. Hence, the evaporative loss from such oils will be limited, and the short lifetime reported for such products must be due to large dispersion rates.
- The high persistence of e.g. diesel oils produced by the MMS OCS model may thus be explained by the fact that the effect of variable oil density and subsequent changes in this parameter due to emulsification are not accounted for in the computations of the spreading rate. For this reason, the model will not reflect the increased rate of natural dispersion due to more rapid spreading of non-emulsifying oils.

- *Slick thickness does not increase with water content:*
- The film thickness is computed from the oil volume, with no account for the increase in volume due to emulsification.

6.2 Summary of recommended improvements by algorithm

A review of recent advances in various aspects of oil weathering modeling was presented in Chapter 4. The review was organized in sections according to the major weathering processes, spreading, evaporation, natural dispersion, and emulsification. Recommendations arising from this review are summarized below.

6.2.1 Spreading

The spreading algorithm in the OCS OWM is outdated. For instantaneous spills, Fay-type spreading models, modified for effects of oil viscosity and termination of spreading, will provide better predictions of the film thickness in the thick part of the slick, where the major fraction of oil volume will be found. The eventual inclusion of shear spreading will allow the flow of mass from the thick to the thin portion of the slick, where dispersion occurs most rapidly.

For continuous surface leaks or blowouts in open sea conditions, where lateral spreading will be dominant some distance downstream from the source, one-dimensional Fay spreading models seem to be more relevant than the radial spreading models used for instantaneous spills. For sub-sea blowouts, where the Fay equations are inadequate, surface spreading may be predicted by use of model concepts based on buoyant plume theory, allowing the characteristics of the oil to determine the form of the resulting surface slick. Spreading due to entrainment and current shear should also be incorporated.

We note that there exists at present no widely accepted "best" methodology for computation of oil spreading.

6.2.2 Evaporation

The pseudo-component method seems to be the most reliable and flexible of the discussed methods. Although the implementation used in the OCS model appears overly complicated, it should perform acceptably given proper input data.

6.2.3 Natural dispersion

In recent oil weathering models, the method derived by Delvigne and Sweeney (1998) is used to estimate the fraction of the oil that will be permanently dispersed in various sea states. However, this approach rests on the existence of a certain threshold droplet size. This may be a questionable assumption, since permanent dispersion results from the balance between vertical turbulent motions in the water masses and the rise velocity of the droplets. This implies that the threshold for permanent dispersion should be expressed in terms of rise velocity and time-varying sea state, rather than a single droplet size alone. In our view, this method is the best candidate for an upgrade of the dispersion algorithms in the OCS model, but the threshold droplet size assumption should be investigated further before the new method can be used with confidence.

6.2.4 *Emulsification*

An explicit first order rate model, also recommended by Mackay et al. (1980b), should replace the present implicit algorithm for prediction of emulsification used in the OCS model. The first order rate equation may be expressed in a convenient differential form to account for subsequent changes in emulsification rate due to changes in the oil composition (due to evaporation) and variable sea-state.

The emulsification parameters required in this model (emulsification rate and maximum water content) will in general be different for each specific crude or oil product. Consequently, efforts should made to determine empirical correlations for these parameters based on the extensive data presently available from experimental studies of emulsification. Meanwhile, these parameters must be based on laboratory studies conducted for each crude or oil product. The stability of such emulsions should also be included as a result of such studies, and incorporated into the model, since emulsion stability pays a key role in slick lifetime.

6.2.5 *Oil-in-Ice*

Recent work on initial spreading of oil in and under ice should replace the older algorithms in the existing OCS model. The multiplication factors in the model for emulsion and dispersion rates are clearly wrong, except possibly for oil directly at the ice edge, and should be replaced using field observations (e.g. Singsaas et al, 1994; Ross and Dickens, 1987; MacNeill and Goodman, 1987).

6.3 Recommendations for updating the OCS model

Some of the problems discussed in Sections 6.1 and 6.2 might be addressed by changes in the existing code, but no significant improvement in reliability will be achieved in this way.

Viscosity is the single most important oil characteristic controlling spill lifetime. Emulsification, to the extent that it affects viscosity, will have significant influence on the windows-of-opportunity for alternative oil spill response actions. At this time there is no reliable methodology for predicting emulsion formation and stability based solely on fresh oil properties. Oil-specific parameters must be supplied to the emulsification algorithm. These parameters can be determined by standard published methods (e.g. Daling et al, 1987, 1990, and 1997). In the near future it may be possible to establish general empirical relations between the model parameters and standard oil parameters. A key element in upgrading or replacing the existing OCS model is therefore creating a coupling to a standardized oil weathering database.

Other necessary model improvements that will require major changes in the model are:

- creation of a graphical user interface, coupling to standard word processors and spreadsheets;
- realistic simulations of scenarios with variable winds and temperatures, preferably using standard meteorological data file formats;

- more realistic ice scenarios, with more realistic oil-ice interaction algorithms;
- simulation of different discharge conditions, including continuous surface and subsurface leaks (pipeline rupture, blowouts);
- updating spreading and natural dispersion algorithms.

The potentials for easier model use are obvious, and may be demonstrated by comparison with more recent oil weathering models, such as the ADIOS model (NOAA 1994) and the SINTEF Oil Weathering Model (Daling et al. 1997), both based on graphical user interfaces. To establish a user-friendly interface, as well as the other requested improvements, a complete revision of the model code is probably required.

In summary, the MMS OCS model consists of a mixture of
- outdated or incorrect algorithms (spreading, natural dispersion, emulsification, oil-ice interactions) and algorithms which remain in current use (evaporation).
- outdated technology (software) that doesn't take advantage of modern software and hardware (graphical input/output capabilities).

The result is a model that is difficult to use and unreliable when applied. Possible alternatives to be addressed are
(a) a complete re-write of the OCS model,
(b) acquisition of an existing model containing the required improvements, or
(c) improvement of an existing model to meet MMS needs.

The ADIOS model is undergoing a major re-write at the present time (Lehr, personal communication), such that some shortcomings of the previous version are being addressed. Specific planned changes include

- evaporation by pseudo-components,
- entrainment to include wind fetch in the wave calculation,
- spreading by turbulent diffusion and areal averaging,
- sedimentation of oil.

MMS could presumably acquire ADIOS at no cost. Disadvantages may be the lack of user support (Hudon, 1998), and the fact that ADIOS is designed for short term spill response issues, whereas MMS's applications are focussed on longer term, spill life-time predictions for environmental assessment and contingency planning. None of the above changes address the major weakness of ADIOS and the OCS model, the lack of an empirical oil weathering database to guard against unrealistic predictions. The ADIOS model, for example, predicts an emulsion viscosity for Prudhoe Bay Crude of 125,000 cSt after 24 hours, whereas reported values lie in the range 10,000 to 30,000 cSt even after 30 hours (Payne et al, 1987, 1990).

A second option is the SINTEF OWM, which already meets most of the above specifications. The addition of a module for underwater pipeline leaks and blowouts is also underway. This model is available to governmental organizations for a minimal price to cover user support and model maintenance. The model is designed for contingency planning purposes, with linkage to an oil database built up from standardized laboratory studies of oil weathering. This model has been verified against numerous field experiments (e.g. Daling et al, 1997).

Any of these acquisition options will probably be more cost-effective than re-writing the OCS model, an effort we estimate at a minimum of 1000 hours by a development team experienced with oil spill modeling and graphical user interface development. Again, this solution would not automatically include an oil weathering database.

6.4 Recommendations for testing of algorithms

As discussed in Chapter 4, two models purporting to contain the same algorithm may produce quite different results. The fact is that implementation is critical to algorithm performance. It is therefore insufficient to implement alternate algorithms or concepts within a single model, and then test them one against the other, since it is not only the algorithm that needs to be tested, but also the implementation. Furthermore, performance of an algorithm will be affected by performance of other algorithms in the model, a clear example being the relationships among spreading, evaporation, emulsification and dispersion.

We therefore recommend the idea of establishing a series of relatively complete observational data sets, which include the best available mass balance information over time. One can "drive" an algorithm to be tested using the observational values for the other processes. In this way different algorithms can be compared in a robust, controlled environment, de-coupled from others. Ultimately, of course, each model must be tested in its entirety against several such data sets, to evaluate the couplings among algorithms, and the overall implementation.

We suggest beginning with two of the data sets recommended in Section 5.4, for example the 1989 Norwegian Haltenbanken experiment, and the 1992a-c UK field trials carried out by AEA Technology. Each data set should be compiled and prepared following a standard format, as specified below. Not all the data from these field trials, for example remote sensing data, are direct available in existing reports or publications and require some effort to be found and compiled.

6.5 Specifications for standardized reporting of field trial data for testing of oil weathering models

Wind speed: ASCII file with descriptive header, 10 minute averages for speed and direction, corrected to 10m height, start at least 12 hr before first release of oil.
Current speed: ASCII file with descriptive header, 10 minute averages for speed and direction, 1m depth, start at least 12 hr before first release of oil.
Wave data: spectral information, wave height and period as available.
Oil time series data: as per Table 6.1.

Table 6.1 Recommended format for standard reporting of surface oil field data for testing of oil weathering models. We note that dispersed oil mass in the mass balance column will generally be estimated by subtracting the surface and evaporated mass from the total mass released. Numbers of data points for surface oil (estimated from remote sensing data) may also be limited and have relatively high uncertainty.

Standard Reporting Data Sheet for Experimental Oil Spills	
Release Name or ID	
Oil Type	
Amount Released	
Duration of Release	
Location	
Special Conditions	

Date, Time	**Surface Oil Information**					**Mass Balance Estimate**			**Comments**
year: month: dy:hr:min	**Sheen Area (km^2)**	**Black Area (km^2)**	**Emulsion Area (km^2)**	**Water Content (%)**	**Viscosity (cP)**	**Surface (% total mass)**	**Evaporated (% total mass)**	**Dispersed (% total mass)**	

Report Completed by		**day month year**
printed name:	**signature:**	**date: / /**

7. References

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Appendix I: Publications and presentations resulting from this contract

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Workshop on Calibration and Verification of Oil Spill Weathering Models. Minutes of the Meeting. (See Appendix III).

Appendix II: Standardized field data sheets

Standardized field data sheets
From field trials in UK

Field data review form - MMS project

Administrative information: **ID:** AEA-97

Date:	September 1997
Performed by:	AEA Technology
Contact person:	Dr Tim Lunel
Address:	NETCEN (National Environment Technology Centre) AEA Technology plc
	Culham, Abingdon,
	Oxfordshire, OX14 3DB, UK
Funders:	MPCU

Main objectives:

Oil weathering and dispersant treament

Processes studied:

[x] Drifting/spreading	[x] Emulsification	[X] evaporation	[x] nat.dispersion	[ ] WSF
[ ] mec.recovery	[ ] Burning	[X] dispersants	[ ] stranding	[ ] sedimentation

Comments:

Environmental data available:

[x] sea temp. [x] air temp. [x] wind [X] waves [ ] currents

Comments:

Report for MPCU on data from Met-buoy

Oil type: Crude and Bunker fuel

Amount: 2 x 50 tonnes Forties, 30 tonnes Alaske North Slope and 20 tonnes of IF-180 Bunker fuel

Release conditions: 5 – 15 knots

Duration of experiment: 48-55 hours, Slicks sprayed with dispersants (Corexit 9500 and Dasic NS)

Surface oil sampling: # oil samples during first two hours: 8 total # of samples: many

Comments:

Heavely weathered slicks sprayed with dispersant to determine upper limit for dispersability

Short description of surface oil sampling (keywords):

WSL bucket.

Analysis performed at spill site (on fresh samples):

[x] water content [ ] emul. stability [x] Viscosity [x] surf. oil thickness [ ] chem disp.
[ ] emulsion breaker [ ] disp.oil conc. [x] disp. oil droplets [ ] em. water droplets

Comments: UVF used extensively

"Post-trial" analysis performed in the laboratory:

[x] bulk oil prop [x] water content [ ] emul. Stability [x] evap. Loss [x] viscosity
[ ] Pourpoint [ ] flash point [ ] Density [ ] surf. Tension [ ] chem disp.
[x] em. water droplets

Comments: Remote sensing image analysis was an important part of this trial.

Reports/papers :

AMOP 98, p. 319-344, Lewis et al.

Reports availability: [ ] Confidential [ ] Internal [x] limited availability [ ] open/available
Data format [x] paper (reports) [ ] Digital (diskettes/tapes etc.)

Comments: Both Amop paper and AEA reports for MPCU and Exxon

Overall usefulness of this data for model evaluation (according to project objectives):
[ ] Excellent [x] good [ ] poor [ ] not suitable

General comments:

Field data review form - MMS project

Administrative information:	**ID:** AEA-95
Date:	July 1995
Performed by:	AEA Technology
Contact person:	Dr Tim Lunel
Address:	NETCEN (National Environment Technology Centre) AEA Technology plc
	Culham, Abingdon,
	Oxfordshire, OX14 3DB, UK
Funders:	MPCU

Main objectives:

Oil weathering

Processes studied:

[x] Drifting/spreading	[x] emulsification	[X] evaporation	[x] nat.dispersion	[ ] WSF
[ ] mec.recovery	[ ] burning	[ ] dispersants	[ ] stranding	[ ] sedimentation

Comments:

Environmental data available:

[x] sea temp. [x] air temp. [x] wind [X] waves [ ] currents

Comments:

Confidential report for MSRC/MPCU on data from Met-buoy

Oil type: Forties blend

Amount: 2 x 20 tonnes

Release conditions: Baufort force 2 up to 8 and down again to 5-6 m/s

Duration of experiment: 48 hours

Surface oil sampling: # oil samples during first two hours: 8 total # of samples: many

Comments:

Short description of surface oil sampling (keywords):

WSL bucket.

Analysis performed at spill site (on fresh samples):

[x] water content [ ] emul. stability [x] viscosity [x] surf. oil thickness [ ] chem disp.
[ ] emulsion breaker [ ] disp.oil conc. [x] disp. oil droplets [ ] em. water droplets

Comments: UVF used extensively

"Post-trial" analysis performed in the laboratory:

[x] bulk oil prop [x] water content [ ] emul. stability [x] evap. Loss [x] viscosity
[ ] pourpoint [ ] flash point [ ] density [ ] surf. Tension [ ] chem disp.
[x] em. water droplets

Comments: Remote sensing image analysis was an important part of this trial.

Reports/papers :

AMOP 96, p. 1355-1393, Lunel and Davis.

Reports availability: [ ] Confidential [ ] internal [x] limited availability [ ] open/available
Data format [x] paper (reports) [ ] digital (diskettes/tapes etc.)

Comments: Both Amop papers and AEA reports for MPCU and MSRC

Overall usefulness of this data for model evaluation (according to project objectives):
[ ] excellent [x] good [ ] poor [ ] not suitable

General comments:

Field data review form - MMS project

Administrative information:	ID: AEA-94
Date:	20th August 1994
Performed by:	AEA Technology
Contact person:	Dr Tim Lunel
Address:	NETCEN (National Environment Technology Centre) AEA Technology plc
	Culham, Abingdon,
	Oxfordshire, OX14 3DB, UK
Funders:	MPCU/MSRC

Main objectives:

1. Continuous releases for dispersant test calibration
2. Instantaneous release for dispersant application testing
3. Instantaneous release for oil weathering

Processes studied:

- [ ] Drifting/spreading
- [x] emulsification
- [x] evaporation
- [ ] nat.dispersion
- [ ] WSF
- [ ] mec.recovery
- [ ] burning
- [ ] dispersants
- [ ] stranding
- [ ] sedimentation

Comments: Full environmental data only in internal reports.

Environmental data available:

- [x] sea temp.
- [ ] air temp.
- [x] wind
- [ ] waves
- [ ] currents

Comments:

Oil type: FORTIES BLEND CRUDE OIL

Amount: 2 x 15 m^3

Release conditions: 4-6 m/s average 5 m/s

Duration of experiment: 25 hours

Surface oil sampling: # oil samples during first two hours: 9 total # of samples 29 (slick A)

Comments: 8 28 (slick B)

WSL bucket method / IKU polypropylene net

Short description of surface oil sampling (keywords):

Analysis performed at spill site (on fresh samples):

[x] water content [x] emul. stability [x] viscosity [x] surf. oil thickness [ ] chem disp.
[ ] Emulsion breaker [ ] disp.oil conc. [ ] disp. oil droplets [ ] em. water droplets

Comments: AEA and IKU measurements available

"Post-trial" analysis performed in the laboratory:

[ ] bulk oil prop [x] water content [ ] emul. stability [x] evap. loss [ ] viscosity
[ ] Pourpoint [ ] flash point [ ] density [ ] surf. tension [ ] chem disp.
[ ] em. Water droplets

Comments: Results in AMOP '95 p. 471 Wlaker, Lunel, Brandvik & Lewis.

Reports/papers : AMPO'95 p. 471 Walker, Lunel, Brandvik & Lewis.

Reports availability: [x] confidential [x] internal [ ] limited availability [ ] open/available
Data format [x] paper (reports) [ ] digital (diskettes/tapes etc.)

Comments: AMOP '95 gives details.

Overall usefulness of this data for model evaluation (according to project objectives):
[x] excellent [ ] good [ ] poor [ ] not suitable

General comments:
Limited met data available from AMOP '95 paper.

Field data review form - MMS project

Administrative information: **ID: AEA-93**

Date:	5th September 1993
Performed by:	AEA Technology
Contact person:	Dr Tim Lunel
Address:	NETCEN (National Environment Technology Centre) AEA Technology plc Culham, Abingdon, Oxfordshire, OX14 3DB, UK
Funders:	MPCU

Main objectives:

Demulsifier and dispersant testing

Processes studied:

[x] Drifting/spreading	[x] emulsification	[ ] evaporation	[ ] nat.dispersion	[ ] WSF
[ ] mec.recovery	[ ] burning	[x] dispersants	[ ] stranding	[ ] sedimentation

Comments:

Environmental data available:

[x] sea temp. [x] air temp. [x] wind [ ] waves [ ] currents

Comments:

Oil type: FUEL OIL / GAS OIL MIX (50:50)

Amount: 2 x 20 tonnes

Release conditions: 5-10 m/s

Duration of experiment: 16 hours

Surface oil sampling: # oil samples during first two hours: 1 total # of samples 4 (slick A)

Comments: 3 7 (slick B)

Short description of surface oil sampling (keywords):

WSL bucket.

Analysis performed at spill site (on fresh samples):

$10s^{-1}$

- [x] water content
- [ ] emulsion breaker
- [ ] emul. stability
- [ ] disp.oil conc.
- [x] viscosity
- [x] disp. oil droplets
- [x] surf. oil thickness
- [ ] em. water droplets
- [ ] chem disp.

Comments: UVF used extensively

"Post-trial" analysis performed in the laboratory:

- [x] bulk oil prop
- [ ] pourpoint
- [x] em. water droplets
- [x] water content
- [ ] flash point
- [ ] emul. stability
- [ ] density
- [x] evap. loss
- [ ] surf. tension
- [x] viscosity
- [ ] chem disp.

Comments: Remote sensing image analysis was an important part of this trial.

Reports/papers :

AMOP 94 p 955 Lunel and Lewis.

Reports availability: [x] confidential [ ] internal [ ] limited availability [ ] open/available

Data format [x] paper (reports) [ ] digital (diskettes/tapes etc.)

Comments: AMOP '94 has limited environmental data

Overall usefulness of this data for model evaluation (according to project objectives):

[ ] excellent [ ] good [x] poor [ ] not suitable

General comments:

Not suitable for this project because MFO/GO does not behave like a crude oil.

Field data review form - MMS project

Administrative information: **ID: AEA-92a**

Date: June 1992

Performed by: AEA Technology

Contact person: T. Lunel

Address: NETCEN
(National Environment Technology Centre) AEA Technology plc
Culham, Abingdon,
Oxfordshire, OX14 3DB, UK

Funders: MPCU/MSRC

Main objectives:

Application of aerially applied dispersant and demulsifier testing

Processes studied:

[x] Drifting/spreading [x] emulsification [x] evaporation [ ] nat.dispersion [ ] WSF
[ ] mec.recovery [ ] burning [ ] dispersants [ ] stranding [ ] sedimentation

Comments:

Environmental data available:

[ ] sea temp. [ ] air temp. [ ] wind [ ] waves [ ] currents

Comments:

Oil type: 50% MF0/ 50% GAS OIL

Amount: 37,650 litre (37.65 m^3) as 3 slicks

Release conditions: Instantaneous

Duration of experiment: 12 hours

Surface oil sampling: # oil samples during first two hours:____ total # of samples____
Comments: unknown

Short description of surface oil sampling (keywords):

WSL bucket method

Analysis performed at spill site (on fresh samples):

- [x] water content
- [x] emulsion breaker
- [ ] emul. stability
- [ ] disp.oil conc.
- [x] viscosity
- [ ] disp. oil droplets
- [ ] surf. oil thickness
- [ ] em. water droplets
- [ ] chem disp.

Comments: Haake VT500 viscometer

"Post-trial" analysis performed in the laboratory:

- [x] bulk oil prop
- [ ] pourpoint
- [ ] em. water droplets
- [x] water content
- [ ] flash point
- [ ] emul. stability
- [x] density
- [ ] evap. loss
- [ ] surf. tension
- [x] viscosity
- [ ] chem disp.

Comments:

Reports/papers : Aerial Application of demulsifier solution to experimental oil slicks
Lewis, A., M. Walker & K. Colcomb-Heliger
Formation and Breaking of Water-in-oil Emulsions, (Kananaskis Village, Canada)
Workshop Proceedings MSRC Report 93-018
Internal AEA Report

Reports availability: [x] confidential [ ] internal [ ] limited availability [ ] open/available
Data format [x] paper (reports) [ ] digital (diskettes/tapes etc.)

Comments:
Not relevant to this project as MFO/GO weathering does not correctly simulate crude oil.

Overall usefulness of this data for model evaluation (according to project objectives):

[ ] excellent [ ] good [x] poor [ ] not suitable

General comments:
MFO/GO weathering not relevant to this project

Field data review form - MMS project

Administrative information: **ID: AEA-92b**

Date: 27th May 1992

Performed by: AEA Technology

Contact person: Dr Tim Lunel

Address: NETCEN
(National Environment Technology Centre) AEA Technology plc
Culham, Abingdon,
Oxfordshire, OX14 3DB, UK

Funders: MPCU + 14 BRITISH OIL COMPANIES

Main objectives: Improvement of Eurospill / OSIS

Processes studied:

- [x] Drifting/spreading
- [ ] mec.recovery
- [x] emulsification
- [ ] burning
- [x] evaporation
- [x] dispersants
- [x] nat.dispersion
- [ ] stranding
- [ ] WSF
- [ ] sedimentation

Environmental data available:

- [x] sea temp.
- [x] air temp.
- [x] wind
- [x] waves
- [x] currents

Comments: Wind speed 12 m/s at release / 5 m/s overnight / 7-9 m/s
Sea temperature of 11 deg C

Oil type: FORTIES Crude Oil

Amount: 18 m^2

Release conditions: 12 m/5 / 5 m/s overnight / 7-9 m/s next day

Duration of experiment: 32 hours

Surface oil sampling: # oil samples during first two hours: 4 total # of samples 15

Comments:
High frequency sampling at first; 40 min. 1:20 hr.min, 2:50 hr.min

Short description of surface oil sampling (keywords):
Samples collected from windrows close to downwind edge of slick

Analysis performed at spill site (on fresh samples):

[x] water content | [ ] emul. stability | [x] viscosity @ 10^{s-1} | [ ] surf. oil thickness | [ ] chem disp.
[ ] emulsion breaker | [ ] disp.oil conc. | [ ] disp. oil droplets | [ ] em. water droplets

Comments: Haake VT500/NV/SV viscometry

"Post-trial" analysis performed in the laboratory:

[ ] bulk oil prop | [x] water content | [ ] emul. stability | [x] evap. loss | [x] viscosity
[ ] pourpoint | [ ] flash point | [x] density | [ ] surf. tension | [x] chem disp.
[ ] em. water droplets

Comments:
Water by Dean and Stark, dispersibility by WSL method

Reports/papers :
OSC'93 Walker M^c Donagh et al pp 389 – 393

Reports availability: [x] confidential [ ] internal [ ] limited availability [ ] open/available
Data format [x] paper (reports) [ ] digital (diskettes/tapes etc.)

Comments: Full environmental data only available from "Commercially in Confidence" reports

Overall usefulness of this data for model evaluation (according to project objectives):

[x] excellent [ ] good [ ] poor [ ] not suitable

General comments:

Field data review form - MMS project

Administrative information: **ID: AEA-92c**

Date: 29th May 1992

Performed by: AEA Technology

Contact person: Dr Tim Lunel

Address: NETCEN
(National Environment Technology Centre) AEA Technology plc
Culham, Abingdon,
Oxfordshire, OX14 3DB, UK

Funders: MPCU

Main objectives: Improvement of Eurospill / OSIS

Processes studied:

- [x] Drifting/spreading
- [x] emulsification
- [x] evaporation
- [x] nat.dispersion
- [ ] WSF
- [ ] mec.recovery
- [ ] burning
- [x] dispersants
- [ ] stranding
- [ ] sedimentation

Comments:

Environmental data available:

- [ ] sea temp.
- [ ] air temp.
- [x] wind
- [ ] waves
- [ ] currents

Comments: 5 m/s

Oil type: Crude Oil

Amount: 2.6 m^3

Release conditions: 5 m/s

Duration of experiment: 1.5 hours

Surface oil sampling: # oil samples during first two hours: 4 total # of samples 4

Comments: Initial evaporation was main "target process"
Insufficient sample after 2.5 hours

Short description of surface oil sampling (keywords):

WSL bucket method

Analysis performed at spill site (on fresh samples):

[x] water content	[ ] emul. stability	[x] viscosity ($10s^{-1}$)	[ ] surf. oil thickness	[ ] chem disp.
[ ] emulsion breaker	[ ] disp.oil conc.	[ ] disp. oil droplets	[ ] em. water droplets	

Comments:

"Post-trial" analysis performed in the laboratory:

[ ] bulk oil prop	[x] water content	[ ] emul. stability	[x] evap. loss	[x] viscosity
[ ] pourpoint	[ ] flash point	[ ] density	[ ] surf. tension	[ ] chem disp.
[ ] em. water droplets				

Comments:

Reports/papers :

Comparison of Observed and Predicted changes to Oil after Spills

Walker, M. M. McDonagh, D. Albone, S. Grigson, A. Wilkinson and G. Baron

International Oil Spill Conference '93 pp. 389- 393

Plus Internal AEA Report

Reports availability: [x] confidential [ ] internal [ ] limited availability [ ] open/available

Data format [x] paper (reports) [ ] digital (diskettes/tapes etc.)

Comments:

Environmental data given only in internal reports.

Overall usefulness of this data for model evaluation (according to project objectives):

[x] excellent [ ] good [ ] poor [ ] not suitable

General comments:

Field data review form - MMS project

Administrative information: **ID: AEA-92d**

Date: 1st June 1992

Performed by: AEA Technology

Contact person: Dr Tim Lunel

Address: NETCEN
(National Environment Technology Centre) AEA Technology plc
Culham, Abingdon,
Oxfordshire, OX14 3DB, UK

Funders: MPCU

Main objectives: Improvement of Eurospill / OSIS

Processes studied:

[ ] Drifting/spreadin	[x] emulsification	[ ] evaporation	[ ] nat.dispersion	[ ] WSF
[ ] mec.recovery	[ ] burning	[ ] dispersants	[ ] stranding	[ ] sedimentation

Comments:

Environmental data available:

[x] sea temp. [ ] air temp. [x] wind [ ] waves [ ] currents

Comments: 11 deg C sea temperature

Oil type: Crude Oil

Amount: 4 m^3

Release conditions: 4 – 5 m/s

Duration of experiment: 5 ½ hours

Surface oil sampling: # oil samples during first two hours: 4 total # of samples 9

Comments:

Short description of surface oil sampling (keywords):

WSL bucket method

Analysis performed at spill site (on fresh samples):

[x] water content [ ] emul. stability [x] viscosity [x] surf. oil thickness [ ] chem disp.
[ ] emulsion breaker [ ] disp.oil conc. [ ] disp. oil droplets [ ] em. water droplets

Comments:

"Post-trial" analysis performed in the laboratory:

[ ] bulk oil prop [x] water content [ ] emul. stability [x] evap. loss [x] viscosity
[ ] pourpoint [ ] flash point [ ] density [ ] surf. tension [ ] chem disp.
[ ] em. water droplets

Comments:

Reports/papers :

Comparison of Observed and Predicted changes to Oil after Spills
Walker, M. M. McDonagh, D. Albone, S. Grigson, A. Wilkinson and G. Baron
International Oil Spill Conference '93 pp. 389- 393
Plus Internal AEA Report

Reports availability: [x] confidential [ ] internal [ ] limited availability [ ] open/available
Data format [x] paper (reports) [ ] digital (diskettes/tapes etc.)

Comments:

Overall usefulness of this data for model evaluation (according to project objectives):

[x] excellent [ ] good [ ] poor [ ] not suitable

General comments:

Field data review form - MMS project

Administrative information:	**ID: AEA-92e**
Date:	1st June 1992
Performed by:	AEA Technology
Contact person:	Dr Tim Lunel
Address:	NETCEN (National Environment Technology Centre) AEA Technology plc
	Culham, Abingdon,
	Oxfordshire, OX14 3DB, UK
Funders: MPCU	

Main objectives: Study weathering of crude oil to develop OSIS

Processes studied:

- [x] Drifting/spreading
- [x] emulsification
- [x] evaporation
- [ ] nat.dispersion
- [ ] WSF
- [ ] mec.recovery
- [ ] burning
- [ ] dispersants
- [ ] stranding
- [ ] sedimentation

Comments:

Environmental data available:

- [x] sea temp.
- [ ] air temp.
- [x] wind
- [ ] waves
- [ ] currents

Comments: Sea Temperature 11 deg C

Oil type: Crude Oil

Amount: 15m^3

Release conditions: 4-5 m/s / 6-9 m/s for next two days

Duration of experiment: 51 hours

Surface oil sampling: # oil samples during first two hours: 4 total # of samples 19

Comments:.

Short description of surface oil sampling (keywords):

WSL bucket method

Analysis performed at spill site (on fresh samples):

[x] water content [ ] emul. stability [x] viscosity [ ] surf. oil thickness [ ] chem disp.
[ ] emulsion breaker [ ] disp.oil conc. [ ] disp. oil droplets [ ] em. water droplets

Comments: Dean & Stark water content. Haake VT500 viscsometer

"Post-trial" analysis performed in the laboratory:

[x] bulk oil prop [x] water content [ ] emul. stability [ ] evap. loss [ ] viscosity
[ ] pourpoint [ ] flash point [ ] density [ ] surf. tension [ ] chem disp.
[ ] em. water droplets

Comments:

Reports/papers :

Comparison of Observed and Predicted changes to Oil after Spills
Walker, M. M. McDonagh, D. Albone, S. Grigson, A. Wilkinson and G. Baron
International Oil Spill Conference '93 pp. 389- 393
Plus Internal AEA Report

Reports availability: [x] confidential [ ] internal [ ] limited availability [ ] open/available
Data format [x] paper (reports) [ ] digital (diskettes/tapes etc.)

Comments:

Overall usefulness of this data for model evaluation (according to project objectives):

[x] excellent [ ] good [ ] poor [ ] not suitable

General comments:

Field data review form - MMS project

Administrative information: **ID: WSL-88**

Date: August 1988

Performed by: WSL

Contact person: Tim Lunel

Address: NETCEN
(National Environment Technology Centre) AEA Technology plc
Culham, Abingdon,
Oxfordshire, OX14 3DB, UK

Funders: MPCU

Main objectives:

Weathering of Flotta crude oil

Processes studied:

- [x] Drifting/spreading
- [ ] mec.recovery
- [x] emulsification
- [ ] burning
- [x] evaporation
- [ ] dispersants
- [ ] nat.dispersion
- [ ] stranding
- [ ] WSF
- [ ] sedimentation

Comments:

Environmental data available:

- [x] sea temp.
- [x] air temp.
- [x] wind
- [ ] waves
- [ ] currents

Comments:

Only available in internal reports.

Oil type: FLOTTA CRUDE OIL

Amount:

Release conditions:

Duration of experiment:

Surface oil sampling: # oil samples during first two hours:____ total # of samples____

Comments: unknown

Short description of surface oil sampling (keywords):

Analysis performed at spill site (on fresh samples):

☐ water content ☐ emul. stability ☐ viscosity ☐ surf. oil thickness ☐ chem disp.
☐ emulsion breaker ☐ disp.oil conc. ☐ disp. oil droplets ☐ em. water droplets

Comments:

"Post-trial" analysis performed in the laboratory:

☐ bulk oil prop ☐ water content ☐ emul. stability ☐ evap. loss ☐ viscosity
☐ pourpoint ☐ flash point ☐ density ☐ surf. tension ☐ chem disp.
☐ em. water droplets

Comments:

Reports/papers :

Hurford, N., (1990) Report of the Flotta Fate Trial, August 1988. WSL Report Nº. LR 725 (MPBM)

Reports availability: [x] confidential [x] internal ☐ limited availability ☐ open/available
Data format ☐ paper (reports) ☐ digital (diskettes/tapes etc.)

Comments: No open reports available

Overall usefulness of this data for model evaluation (according to project objectives):

☐ excellent ☐ good ☐ poor ☐ not suitable

General comments:
Not possible to use as data is confidential

Field data review form - MMS project

Administrative information: **ID: WSL-87**

Date: July 1987

Performed by: WSL

Contact person: Tim Lunel

Address: NETCEN
(National Environment Technology Centre) AEA Technology plc
Culham, Abingdon,
Oxfordshire, OX14 3DB, UK

Funders: MPCU

Main objectives: Weathering study on Forties crude oil

Processes studied:

[x] Drifting/spreading [x] emulsification [x] evaporation [ ] nat.dispersion [ ] WSF
[ ] mec.recovery [ ] burning [ ] dispersants [ ] Stranding [ ] sedimentation

Comments:

Environmental data available:

[x] sea temp. [x] air temp. [x] wind [x] waves [x] currents

Comments: Data only available in internal report.

Oil type: FORTIES

Amount: 20 m^3

Release conditions: Seaspring gently cercling

Duration of experiment: 75 hours

Surface oil sampling: # oil samples during first two hours:__2__total # of samples_12__

Comments:

Short description of surface oil sampling (keywords):
WSL bucket

Analysis performed at spill site (on fresh samples):

[x] water content [ ] emul. stability [x] viscosity [x] surf. oil thickness [ ] chem disp.
[ ] emulsion breaker [ ] disp.oil conc. [ ] disp. oil droplets [ ] em. water droplets

Comments:

"Post-trial" analysis performed in the laboratory:

[x] bulk oil prop [x] water content [ ] emul. stability [x] evap. loss [x] viscosity
[x] pourpoint [x] flash point [x] density [ ] surf. tension [x] chem disp.
[ ] em. water droplets

Comments: Comprehensive study

Reports/papers :

Buchanan, i and Hurford, N. Report of the Forties Fate Trial, July 1987. WSL Report Nº (OP)

Reports availability: [x] confidential [x] internal [ ] limited availability [ ] open/available
Data format [ ] paper (reports) [ ] digital (diskettes/tapes etc.)

Comments: Data only available in internal report.

Overall usefulness of this data for model evaluation (according to project objectives):

[ ] excellent [x] good [ ] poor [ ] not suitable

General comments:

IF data were openly available

Standardized field data sheets
From field trials in France

Field data review form - MMS project

Administrative information: **ID: Protechmar I-VI**

Date: 1979 until 1985

Performed by: CEDRE and IFP

Contact person: Francois Merlin, CEDRE

Address:

Funders: IFP, CEDRE and The European Community

Main objectives: Comparing dispersant effectiveness measured in lab and in field with different Oil types and weather conditions. Testing different equipment for dispersant application.

Processes studied:

- [ ] Drifting/spreading
- [ ] emulsification
- [ ] evaporation
- [x] nat.dispersion
- [ ] WSF
- [ ] mec.recovery
- [ ] burning
- [x] dispersants
- [ ] stranding
- [ ] sedimentation

Comments:

Oil slicks dispersed after very litle weathering (minutes to hours)

Environmental data available:

- [x] sea temp.
- [x] air temp.
- [x] wind
- [x] Waves
- [x] currents

Comments:

Oil type: Fuel oil mixture

Amount: 1-28 m3

Release conditions:

Duration of experiment: minutes to a few hours

Surface oil sampling: # oil samples during first two hours:____ total # of samples____

Comments:

Very litle surface sampling

Short description of surface oil sampling (keywords):

Analysis performed at spill site (on fresh samples):

- [ ] water content
- [ ] emulsion breaker
- [ ] Emul. stability
- [x] Disp.oil conc.
- [ ] viscosity
- [ ] disp. oil droplets
- [ ] surf. oil thickness
- [ ] em. water droplets
- [ ] chem disp.

Comments:

"Post-trial" analysis performed in the laboratory:

- [ ] bulk oil prop
- [ ] pourpoint
- [ ] em. water droplets
- [ ] water content
- [ ] flash point
- [ ] emul. stability
- [ ] density
- [ ] evap. loss
- [ ] surf. tension
- [ ] viscosity
- [ ] chem disp.

Comments:

Reports/papers :

See reference list no: 25, 35, 36, 37

Reports availability: [ ] Confidential [ ] internal [ ] limited availability [X] open/available

Data format [ ] paper (reports) [ ] digital (diskettes/tapes etc.)

Comments:

Overall usefulness of this data for model evaluation (according to project objectives):

[ ] excellent [ ] good [x] poor [ ] not suitable

General comments:

Some of the data may be used for testing of algorithms for short term natural/chemical Dispersion of surface oil slicks

Field data review form - MMS project

Administrative information: **ID: Polutmar I-III**

Date: 1989 until 1990

Performed by: CEDRE and IFP

Contact person: Francois Merlin, CEDRE

Address:

Funders: IFP, CEDRE and The European Community

Main objectives:

Dispersion, evaporation and surface spreading of chemicals (gases, chemicals and diesel oil)

Processes studied:

- [x] Drifting/spreading
- [ ] emulsification
- [x] evaporation
- [x] nat.dispersion
- [ ] WSF
- [ ] mec.recovery
- [ ] burning
- [ ] dispersants
- [ ] stranding
- [ ] Sedimentation

Comments:

Environmental data available:

- [x] sea temp.
- [x] air temp.
- [x] wind
- [x] Waves
- [x] Currents

Comments:

Oil type: Chemicals e.g. ethyl-2 hexanol, butyl metacrylate, acetone, gas tracer (SF_6) , marine diesel

Amount: 1-2 m^3

Release conditions:

Duration of experiment: a few hours

Surface oil sampling: # oil samples during first two hours:____ total # of samples____

Comments:

Litle surface sampling

Short description of surface oil sampling (keywords):

Analysis performed at spill site (on fresh samples):

[ ] Water content [ ] Emul. stability [ ] viscosity [ ] surf. oil thickness [ ] chem disp.
[ ] Emulsion breaker [x] Disp.oil conc. [ ] disp. oil droplets [ ] em. water droplets

Comments:

Monitoring of chemical vapors, concentrations in the water column and at the surface

"Post-trial" analysis performed in the laboratory:

[ ] Bulk oil prop [ ] water content [ ] emul. stability [X] evap. Loss [ ] viscosity
[ ] Pourpoint [ ] flash point [ ] density [ ] surf. Tension [ ] chem disp.
[ ] Em. water droplets

Comments:

Reports/papers :

See reference list no: 26 and 27

Reports availability: [ ] Confidential [ ] internal [ ] limited availability [X] open/available
Data format [ ] Paper (reports) [ ] digital (diskettes/tapes etc.)

Comments:

Overall usefulness of this data for model evaluation (according to project objectives):

[ ] Excellent [ ] Good [ ] poor [x] not suitable

General comments:

Data is not suitable for calibration/verification of Oil Spill Models since the data mostly
Describes spreading of water soluble components and gases

Standardized field data sheets
From field trials in USA

Field data review form - MMS project

Administrative information: **ID: API-78a**

Date: 2-9 November 1978

Performed by: JBF Scientific Corporation

Contact person: Leo T. McCarthy or J.C.Johnsen@JBFScientific

Address: U.S. Environmental Protection Agency, Cinncinnati, Ohio 45268, USA

Funders: USEPA and API

Main objectives: Determine the physical and chemical behaviour of crude oil slicks on the sea after treatment with a dispersant

Processes studied:

[X] Drifting/spreading [ ] emulsification [ ] Evaporation [ ] nat.dispersion [ ] WSF
[ ] Mec.recovery [ ] burning [X] Dispersants [ ] stranding [ ] sedimentation

Comments:

Environmental data available:

[X] sea temp. [x] air temp. [x] wind [x] waves [X] currents

Comments:

Oil type: LaRosa and Murban crude oil

Amount: Four 1.7 m3 (440 gal)

Release conditions: with two 9.6 cm hoses into floats over a period 3-6 minutes

Duration of experiment: Several hours

Surface oil sampling: # oil samples during first two hours: 0 total # of samples 0

Comments: No surface sampling

Short description of surface oil sampling (keywords):

Analysis performed at spill site (on fresh samples):

☐ water content ☐ emul. Stability ☐ viscosity ☐ surf. oil thickness ☐ chem disp.
☐ emulsion breaker ☐ disp.oil conc. ☐ disp. oil droplets ☐ em. water droplets

Comments: Samples of fresh crude were used in laboratory tests to determin equilibrium concentrations of dissolved hydrocarbons in sea water

"Post-trial" analysis performed in the laboratory:

☐ bulk oil prop ☐ Water content ☐ emul. Stability ☐ evap. loss ☐ viscosity
☐ Pourpoint ☐ flash point ☐ Density ☐ surf. tension ☐ chem disp.
☐ em. Water droplets

Comments:
Measured total extractable organic mater in water samples collected at various depths and locations

Reports/papers :
"Response of crude oil slicks to dispersant treatment at sea: 1978", by JFB Scientific Corporation, Wilington MA, USA under APA grant no: R806056

Reports availability: ☐ confidential ☐ Internal ☐ limited availability ☒ open/available
Data format ☒ paper (reports) ☐ Digital (diskettes/tapes etc.)
Comments:

Overall usefulness of this data for model evaluation (according to project objectives):

☐ Excellent ☐ good ☒ poor ☐ not suitable

General comments:
Spills were sprayed immedeatelly or after 2 hours , only oil concentrations and composition in sea water samples at various depths. Less effective dispersion on 2 hour old La Rosa crude.

Field data review form - MMS project

Administrative information: **ID: API-75**

Date: 24-25 October 1975 and 10-12 November 1975

Performed by: JBF Scientific Corporation

Contact person: J.C.Johnsen@JBFScientific,

Address: 2 Jewel drive, Wilmington, MA 01887, USA

Funders: API

Main objectives: Determine the physical and chemical behaviour of crude oil slicks on the sea in the early minutes and hours after release.

Processes studied:

[x] Drifting/spreading [ ] Emulsification [X] Evaporation [ ] nat.dispersion [x] WSF
[ ] Mec.recovery [ ] Burning [ ] Dispersants [ ] Stranding [ ] sedimentation

Comments:

Environmental data available:

[x] Sea temp. [x] air temp. [x] Wind [x] Waves [X] currents

Comments:

Oil type: LaRosa and Murban crude oil

Amount: Four 1.7 m3 (440 gal)

Release conditions: with two 9.6 cm hoses into floats during 3-6 minutes

Duration of experiment: Seven hours

Surface oil sampling: # oil samples during first two hours: Many total # of samples_many___

Comments:

Slicks contained one or more thick patches (several mm thick) containing maybe 90% of the total oil, surrounded by thin oil film

Short description of surface oil sampling (keywords):

Spesial skimmer in galvanized steel bucket and 2000 ml separatory funnel as backup system

Analysis performed at spill site (on fresh samples):

☐ water content ☐ emul. Stability ☐ viscosity ☐ surf. Oil thickness ☐ chem disp.
☐ Emulsion breaker ☐ disp.oil conc. ☐ disp. oil droplets ☐ em. Water droplets

Comments:
Measured slick area as a function of time

"Post-trial" analysis performed in the laboratory:

☐ bulk oil prop ☐ Water content ☐ emul. Stability ☒ evap. Loss ☐ viscosity
☐ Pourpoint ☐ flash point ☐ Density ☐ surf. Tension ☐ chem disp.
☐ em. Water droplets

Comments:
Measured total extractable organic mater in water samples collected at various depths and locations

Reports/papers :
API Report, "Physical and chemical behaviour of crude oil slicks on the sea" Publication 4290, April 30. 1976

"Physical and chemical behaviour of crude oil slicks on the ocean" in Chemical Dispersion for the control of oil spills, ASTM STP 659, pp. 141-158, 1978

Reports availability: ☐ confidential ☐ Internal ☐ limited availability ☒ open/available
Data format ☒ paper (reports) ☐ Digital (diskettes/tapes etc.)
Comments:

Overall usefulness of this data for model evaluation (according to project objectives):

☐ Excellent ☒ good ☒ Poor ☐ not suitable

General comments:
The findings in this report were of large importance 25 years ago, but are today more general knowledge. The dataset are of limited importance for calibration of oil spill weathering models, could be used for calibration of release rate of water soluble components.

Field data review form - MMS project

Administrative information: **ID: API-78b**

Date: 26-27 September 1978

Performed by: Southern California Petroleum Contingency Organisation (SC-PCO)

Contact person: C.D. Barker, General Manager

Address: 2 Jewel drive, Wilmington, MA 01887, USA

Funders: API and SC-PCO

Main objectives:

To test dispersant application methods and mechanical cleanup equipment

Processes studied:

☐	Drifting/spreading	☐	Emulsification	☐	Evaporation	☐	nat.dispersion	x	WSF
X	Mec.recovery	☐	Burning	X	Dispersants	☐	Stranding	☐	sedimentation

Comments: 2 dispersants used at 3 to 10 gallons pr acre, application systems were problematic

Environmental data available:

☐ sea temp. ☐ air temp. ☐ wind ☐ Waves ☐ Currents

Comments:

Oil type: Alaskan North Slope Crude (27.2 ° API)

Amount: Seven 5 to 20 barrel slicks

Release conditions: Gravity discharge from tank on vessel

Duration of experiment: 5 hours

Surface oil sampling: # oil samples during first two hours: 0 total # of samples 0

Comments:

Short description of surface oil sampling (keywords):

No surface oil sampling

Analysis performed at spill site (on fresh samples):

[ ] water content [ ] emul. Stability [ ] viscosity [ ] surf. oil thickness [ ] chem disp.
[ ] Emulsion breaker [ ] disp.oil conc. [ ] disp. oil droplets [ ] em. Water droplets

Comments:
Only oil content and biological analysis of water samples

"Post-trial" analysis performed in the laboratory:

[ ] bulk oil prop [ ] Water content [ ] emul. Stability [X] evap. Loss [ ] viscosity
[ ] Pourpoint [ ] flash point [ ] Density [ ] surf. Tension [ ] chem disp.
[ ] em. Water droplets

Comments:
No data reported

Reports/papers :
"API/SC-PCO Southern California 1978 oil spill test program" 1979 Oil Spill Conference, D. D. Smith and G.H. Holliday

Reports availability: [ ] confidential [ ] Internal [ ] limited availability [X] open/available
Data format [X] paper (reports) [ ] Digital (diskettes/tapes etc.)
Comments:

Overall usefulness of this data for model evaluation (according to project objectives):

[ ] Excellent [ ] good [X] Poor [ ] not suitable

General comments:
Appears to be unsuccessful due to poor dispersant application technique

Field data review form - MMS project

Administrative information: **ID: SC-PCO-79**

Date: 26-27 September 1979

Performed by: Southern California Petroleum Contingency Organisation (SC-PCO)

Contact person: C.D. Barker, General Manager

Address: 2 Jewel drive, Wilmington, MA 01887, USA

Funders: SC-PCO

Main objectives:

1. Evaluate different techniques for dispersant application
2. Measure oil concentration and dilution in water
3. Measure weathering of dispersed oil under treated and untreated slicks

Processes studied:

[ ] Drifting/spreading	[ ] Emulsification	[ ] Evaporation	[ ] nat.dispersion	[x] WSF
[ ] Mec.recovery	[ ] Burning	[X] Dispersants	[ ] Stranding	[ ] sedimentation

Comments: Aerial and boat application of dispersant on fresh and 2 hours old slicks

Environmental data available:

[ ] sea temp. [ ] air temp. [x] wind [x] Waves [ ] Currents

Comments:

Oil type: Prudhoe Bay crude

Amount: seven 10 barrel slicks and two 20 barrel slicks

Release conditions: Gravity discharge from tank on vessel with a 13 cm hose into a plywood float

Duration of experiment: up to 2 hours

Surface oil sampling: # oil samples during first two hours: 0 total # of samples 0

Comments:
Only water samples for oil content analysis

Short description of surface oil sampling (keywords):
No surface oil sampling

Analysis performed at spill site (on fresh samples):

[ ] water content [ ] emul. Stability [ ] viscosity [ ] surf. oil thickness [ ] chem disp.
[ ] Emulsion breaker [ ] disp.oil conc. [ ] disp. oil droplets [ ] em. water droplets

Comments:
No onsite analysis

"Post-trial" analysis performed in the laboratory:

[ ] bulk oil prop [ ] Water content [ ] emul. Stability [X] evap. Loss [ ] viscosity
[ ] Pourpoint [ ] flash point [ ] Density [ ] surf. Tension [ ] chem disp.
[ ] em. Water droplets

Comments:
Only oil content in water samples using GC

Reports/papers :
"The 1979 Southern California Dispersant Treatment Research Oil Spills", C.D. McAuliffe et al., 1981 Oil Spill Conference

Reports availability: [ ] confidential [ ] Internal [ ] limited availability [X] open/available
Data format [X] paper (reports) [ ] Digital (diskettes/tapes etc.)
Comments:

Overall usefulness of this data for model evaluation (according to project objectives):

[ ] Excellent [ ] good [X] Poor [ ] not suitable

General comments:
Focus was not on oil weathering

Field data review form - MMS project

Administrative information: **ID: NOAA-84**

Date: 1980 – 1984

Performed by: Science Applications International Corporation

Contact person: J.R. Payne

Address: Science Applications International Corporation, San Diego, California

Funders: U.S. MMS and NOAA

Main objectives:

Characterize physical and chemical changes that occur to oil released in open ocean and ice infested waters

Processes studied:

- [x] Drifting/spreading
- [ ] Mec.recovery
- [x] Emulsification
- [ ] Burning
- [x] Evaporation
- [ ] Dispersants
- [x] nat.dispersion
- [ ] Stranding
- [X] WSF
- [X] Sedimentation

Comments: Experiments were conducted in an outdoor wave tank at the NOAA field lab at Kasitsna Bay (Homer), Alaska

Environmental data available:

- [x] sea temp.
- [X] Air temp.
- [x] wind
- [x] waves
- [ ] Currents

Comments:

Oil type: Prudhoe Bay crude

Amount:

Release conditions:

Duration of experiment: Months

Surface oil sampling: # oil samples during first two hours: many total # of samples many

Comments:

Extensive surface oil sampling

Short description of surface oil sampling (keywords):

Analysis performed at spill site (on fresh samples):

[x] Water content [ ] emul. Stability [x] viscosity [X] surf. oil thickness [ ] Chem disp.
[ ] Emulsion breaker [X] disp.oil conc. [ ] disp. oil droplets [ ] em. water droplets

Comments:

"Post-trial" analysis performed in the laboratory:

[ ] bulk oil prop [x] Water content [ ] emul. Stability [x] evap. loss [x] Viscosity
[ ] Pourpoint [ ] flash point [x] Density [x] surf. tension [ ] chem disp.
[ ] em. Water droplets

Comments:

Reports/papers :

"Oil Weathering Behaviour in Arctic Environment" J.R. Payne et al., Polar Research vol. 10, no:2 December 1991, Oslo, Norway.

Many other paper and reports are also available from these experiments.

Reports availability: [ ] Confidential [ ] Internal [ ] limited availability [X] open/available
Data format [X] paper (reports) [ ] Digital (diskettes/tapes etc.)
Comments:

Overall usefulness of this data for model evaluation (according to project objectives):

[ ] Excellent [ ] good [x] Poor [ ] not suitable

General comments:
This work focused on weathering of crude, controlled experiments in wave tank, performed under summer conditions, winter/open water and winter with ice conditions. However, this basin data is not very suitable for verifying/calibrating models due to differences in the data from tank and open water experiments.

Standardized field data sheets
From field trials in Norway

Field data review form - MMS project

Administrative information: **ID: Haltenb-89**

Date: 1-4 July 1989

Performed by: Oceanor and SINTEF, Trondheim, Norway

Contact person: Per Johan Brandvik, Sintef (per.j.brandvik@chem.sintef.no)

Address: 7034 Trondheim, Norway

Funders: US-MMS, Norwegian oil companies and authorities

Main objectives:

1. Evaluate different oil spill trackers
2. Seabird – oil spill interaction
3. Measure weathering of surface oil – verification of SINTEF Oil Weathering Model

Processes studied:

[x] Drifting/spreading	[x] Emulsification	[x] Evaporation	[x] nat.dispersion	[ ] WSF
[ ] Mec.recovery	[ ] Burning	[ ] Dispersants	[ ] Stranding	[ ] Sedimentation

Comments:

Environmental data available:

[x] sea temp. [x] air temp. [x] wind [x] Waves [X] Currents

Comments:

Oil type: Oseberg crude

Amount: 30 m3

Release conditions: Discharge from tank on vessel with a 15 cm hose into the water

Duration of experiment: sampling for 3.5 days

Surface oil sampling: # oil samples during first two hours: 7 total # of samples many

Comments:

Short description of surface oil sampling (keywords):

Oil sampled with plastic net, surplus/free water drained off in separation funnel

Analysis performed at spill site (on fresh samples):

[x] water content [x] emul. Stability [x] viscosity [x] surf. oil thickness [x] chem disp.
[X] Emulsion breaker [ ] disp.oil conc. [ ] disp. oil droplets [ ] em. water droplets

Comments:
Analysis performed in onboard laboratory

"Post-trial" analysis performed in the laboratory:

[x] bulk oil prop [X] Water content [ ] emul. Stability [x] evap. Loss [ ] viscosity
[x] Pourpoint [X] flash point [x] Density [x] surf. Tension [ ] chem disp.
[ ] em. Water droplets

Comments:

Reports/papers :
See reference no: 19 and 20

Reports availability: [ ] confidential [ ] Internal [ ] limited availability [X] open/available
Data format [X] paper (reports) [ ] Digital (diskettes/tapes etc.)
Comments:

Overall usefulness of this data for model evaluation (according to project objectives):

[x] Excellent [ ] good [ ] Poor [ ] not suitable

General comments:

Field data review form - MMS project

Administrative information: **ID: MIZ-93**

Date: April 1993

Performed by: SINTEF, Trondheim, Norway

Contact person: Per Johan Brandvik, Sintef (per.j.brandvik@chem.sintef.no)

Address: 7034 Trondheim, Norway

Funders: NOFO, Norwegian Clean Seas Accosiation

Main objectives:

1. Emulsification of oil in ice
2. Drift and spreading of oil in ice
3. Measure weathering of oil in ice – verification of SINTEF Oil Weathering Model

Processes studied:

[x] Drifting/spreading [x] Emulsification [x] Evaporation [x] nat.dispersion [ ] WSF
[ ] Mec.recovery [ ] Burning [ ] Dispersants [ ] Stranding [ ] Sedimentation

Comments:

Environmental data available:

[x] sea temp. [x] air temp. [x] wind [x] Waves [X] Currents

Comments:

Oil type: Oseberg crude
Amount: 26 m3
Release conditions: Discharge from tank on vessel with a 10 cm into a release create on an ice flo
Duration of experiment: sampling for 10 days
Surface oil sampling:# oil samples during first two hours: 7 total # of samples many

Comments:

Short description of surface oil sampling (keywords):
Oil sampled with plastic net, surplus/free water drained off in separation funnel

Analysis performed at spill site (on fresh samples):

[x] water content [x] emul. Stability [x] Viscosity [x] surf. oil thickness [x] chem disp.
[X] Emulsion breaker [ ] disp.oil conc. [ ] disp. oil droplets [ ] em. water droplets

Comments:
Analysis performed in onboard laboratory

"Post-trial" analysis performed in the laboratory:

[x] bulk oil prop [X] Water content [ ] emul. Stability [x] evap. Loss [ ] viscosity
[x] Pourpoint [X] flash point [x] Density [x] surf. Tension [ ] chem disp.
[ ] em. Water droplets

Comments:

Reports/papers :
See reference no: 22

Reports availability: [ ] confidential [ ] Internal [ ] limited availability [X] open/available
Data format [X] paper (reports) [ ] Digital (diskettes/tapes etc.)
Comments:

Overall usefulness of this data for model evaluation (according to project objectives):

[x] Excellent [ ] good [ ] Poor [ ] not suitable

General comments:

Field data review form - MMS project

Administrative information: **ID: NOFO-94**

Date: June 1994

Performed by: NOFO and SINTEF, Trondheim, Norway

Contact person: Per Johan Brandvik, Sintef (per.j.brandvik@chem.sintef.no)

Address: 7034 Trondheim, Norway

Funders: NOFO and Esso Norge

Main objectives:

1. Testing of a small bucket for dispersant application (UK system Rotortech TC-3)
2. Use of FLIR camara onboard application helicopter to locate thick area of the oil slick
3. Measure weathering of surface oil – verification of SINTEF Oil Weathering Model

Processes studied:

[x] Drifting/spreading [x] Emulsification [x] Evaporation [x] nat.dispersion [x] WSF
[ ] Mec.recovery [ ] Burning [X] Dispersants [ ] Stranding [ ] Sedimentation

Comments:

Environmental data available:

[x] sea temp. [x] air temp. [x] Wind [x] Waves [X] Currents

Comments:

Oil type: Sture blend (Oseberg crude)
Amount: 2 x 20 m3
Release conditions: Discharge from tank on vessel through floating skimmer head
Duration of experiment: sampling for 1.5 days
Surface oil sampling:# oil samples during first two hours: 7 total # of samples many

Comments:

Short description of surface oil sampling (keywords):
Oil sampled with plastic net, surplus/free water drained off in separation funnel

Analysis performed at spill site (on fresh samples):

[x] water content	[x] emul. Stability	[x] Viscosity	[x] surf. oil thickness	[x] chem disp.
[X] Emulsion breaker	[x] disp.oil conc.	[ ] Disp. oil droplets	[X] em. water droplets	
[ ]	[ ]		[ ]	

Comments:

Analysis performed in onboard laboratory

"Post-trial" analysis performed in the laboratory:

[x] bulk oil prop	[X] Water content	[ ] Emul. Stability	[X] evap. Loss	[ ] viscosity
[x] Pourpoint	[X] flash point	[x] Density	[X] surf. Tension	[x] chem disp.
[X] em. Water droplets				

Comments:

Reports/papers :
See reference no: 23

Reports availability: [ ] confidential [ ] Internal [ ] limited availability [X] open/available
Data format [X] paper (reports) [ ] Digital (diskettes/tapes etc.)
Comments:

Overall usefulness of this data for model evaluation (according to project objectives):

[x] Excellent [ ] good [ ] Poor [ ] not suitable

General comments:

Field data review form - MMS project

Administrative information: **ID: NOFO-95**

Date: Sep 1995

Performed by: NOFO and SINTEF, Trondheim, Norway

Contact person: Per Johan Brandvik, Sintef (per.j.brandvik@chem.sintef.no)

Address: 7034 Trondheim, Norway

Funders: NOFO

Main objectives:

1. Testing of a large bucket for dispersant application (French system – SOKAF 3000)
2. Simulate a pipeline leakage – release oil (no gas) from 100 meters depth
3. Monitor subsurface and surface oil – verification of SINTEF Blow-out Model and OWM

Processes studied:

[x] Drifting/spreading [x] Emulsification [x] Evaporation [X] nat.dispersion [x] WSF

[ ] Mec.recovery [ ] Burning [X] Dispersants [ ] Stranding [ ] Sedimentation

Comments:

Environmental data available:

[x] sea temp. [x] air temp. [x] Wind [x] Waves [X] Currents

Comments:

Oil type: Sture blend (Oseberg crude)

Amount: 3 x 15 m^3 (dispersant testing) and 2 x 25 m^3 (underwater experiment)

Release conditions: Through floating skimmer head and from release frame at 100 m depth

Duration of experiment: sampling upto 1.5 days

Surface oil sampling:# oil samples during first two hours: 7 total # of samples many

Comments:

Short description of surface oil sampling (keywords):

Oil sampled with plastic net, surplus/free water drained off in separation funnel

Analysis performed at spill site (on fresh samples):

- [x] water content
- [x] Emulsion breaker
- [x] emul. Stability
- [x] disp.oil conc.
- [x] Viscosity
- [ ] Disp. oil droplets
- [x] surf. oil thickness
- [x] em. water droplets
- [x] chem disp.

Comments:

Analysis performed in onboard laboratory

"Post-trial" analysis performed in the laboratory:

- [x] bulk oil prop
- [x] Pourpoint
- [x] em. Water droplets
- [x] Water content
- [x] flash point
- [ ] Emul. Stability
- [x] Density
- [x] evap. Loss
- [x] surf. Tension
- [ ] viscosity
- [x] chem disp.

Comments:

Reports/papers :

See reference no: 24

Reports availability: [ ] confidential [ ] Internal [ ] limited availability [x] open/available

Data format [x] paper (reports) [ ] Digital (diskettes/tapes etc.)

Comments:

Overall usefulness of this data for model evaluation (according to project objectives):

[x] Excellent [ ] good [ ] Poor [ ] not suitable

General comments:

Field data review form - MMS project

Administrative information: **ID: NOFO-96**

Date: June 1996

Performed by: NOFO and SINTEF, Trondheim, Norway

Contact person: Per Johan Brandvik, Sintef (per.j.brandvik@chem.sintef.no)

Address: 7034 Trondheim, Norway

Funders: NOFO and Norsk Hydro Norge

Main objectives:

1. Testing of a new Norwegian bucket for dispersant application (Response 3000)
2. Simulate a blow out at 100 meters depth releasing oil and gas (GOR 67)
3. Monitor oil subsurface and surface oil – verification of SINTEF blow-out and OWM

Processes studied:

[x] Drifting/spreading	[x] Emulsification	[x] Evaporation	[x] nat.dispersion	[x] WSF
[ ] Mec.recovery	[ ] Burning	[X] Dispersants	[ ] Stranding	[ ] Sedimentation

Comments:

Environmental data available:

[x] sea temp. [x] air temp. [x] Wind [x] Waves [X] Currents

Comments:

Oil type: Troll crude

Amount: 2 x 15 m3 (dispersant testing) and 45 m^3 (blow-out simulation)

Release conditions: Through floating skimmer head and from release frame at 100 m depth

Duration of experiment: sampling upto 1.5 days

Surface oil sampling: # oil samples during first two hours: 7 total # of samples many

Comments:

Short description of surface oil sampling (keywords):

Oil sampled with plastic net, surplus/free water drained off in separation funnel

Analysis performed at spill site (on fresh samples):

- [x] water content
- [X] Emulsion breaker
- [ ]
- [x] emul. Stability
- [x] disp.oil conc.
- [ ]
- [x] Viscosity
- [ ] Disp. oil droplets
- [x] surf. oil thickness
- [X] em. water droplets
- [ ]
- [x] chem disp.

Comments:

Analysis performed in onboard laboratory

"Post-trial" analysis performed in the laboratory:

- [x] bulk oil prop
- [ ]
- [x] Pourpoint
- [X] em. Water droplets
- [X] Water content
- [ ]
- [X] flash point
- [ ] Emul. Stability
- [x] Density
- [X] evap. Loss
- [ ]
- [X] surf. Tension
- [ ] viscosity
- [ ]
- [x] chem disp.

Comments:

Reports/papers :

See reference no: 25

Reports availability: [ ] confidential [ ] Internal [ ] limited availability [X] open/available

Data format [X] paper (reports) [ ] Digital (diskettes/tapes etc.)

Comments:

Overall usefulness of this data for model evaluation (according to project objectives):

[x] Excellent [ ] good [ ] Poor [ ] not suitable

General comments:

Appendix III: Summary Proceedings Oil Spill Modelling Workshop: Methodology for Evaluating Weathering Models

Lillehammer, Norway
March 6, 1998

List of attendees

Name	Organization	E-mail addresses
Alun Lewis	AEA Technology	alun.lewis@aeat.co.uk
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Agenda

09:00	Overview and Goals	Mark Reed/SINTEF
09:15	Use of weathering models	MPCU, SFT, MMS
10:00	Suggested test methodology	Øistein Johansen/SINTEF
10:30	Coffee	
10:45	Discussion and refinement	Jerry Galt, US NOAA, moderator
12:00	Lunch	
13:00	Description of available field data sets	Alun Lewis/AEA
13:30	Discussion and refinement	David Bedborough, moderator
14:00	Criteria for good field data sets	Per S. Daling/SINTEF
14:20	Discussion and refinement	David Bedborough, moderator
15:00	Summary and Recommendations	Mak Reed, Jerry Galt, moderators
16:00	Closure	
17:00	Dinner	

Summary of Workshop, Presentations and Discussions

1. Background and goals

- oil weathering model (OWM) uses include contingency planning, oil spill exercises, environmental impact assessment and decision making for response

- OWM errors can result in significant unnecessary costs in dimensioning oils spill response, or in unnecessary environmental impacts due to poor guidance for decision-making

- goals:
  1. establishment of a methodology for testing OWM's, and comparison of alternative weathering algorithms
  2. method should reflect both differences between algorithms and differences between alternative implementations

I. Uses

David Bedborough described MPCU uses of weathering models. Jerry Galt summarized some NOAA experiences with OWM applications in response, stressing that models and algorithms should be evaluated relative to their intended uses and sensitivities. Geir Lenes of gave an overview of SFT's reliance on OWM applications, including the need for laboratory evaluation of specific oils to strengthen the foundation for model use.

II. Proposed testing methodology

Øistein Johansen presented a suggested methodology for testing of alternate algorithms. The basic idea was to supply time-series input data for all processes except that being tested, where the input data would come from field experiments. This methodology isolates a single algorithm, such that interrelationships with other algorithms are eliminated in the evaluation.

III. Available data sets

Alun Lewis summarized available data sets, including those from the UK, Canada, US, France and Norway. Some of the newer, more complete data sets from the UK and Norway appear useful for model testing.

IV. Criteria for ideal data sets

Per Daling summarized criteria for improved future data sets, including

- good documentation of wind, waves, currents, air and water temperature;
- frequent sampling during the early stages of an experimental release;
- replicate samples in time and space to reflect variability and patchiness;
- standardized sampling and handling procedures

V. Conclusions from discussions

- There was general agreement on the potential usefulness of the proposed methodology.
- All agreed that, with the exception of evaporation, existing algorithms are relatively weak. Emulsification is especially problematic, given its importance in oil spill behavior.
- There exist data sets that can be used to evaluate the proposed testing methodology. The more recent data from the UK and Norway appear to be most complete, and of the most consistent quality.
- Direct measurement of dispersion rates/amounts remains difficult except in the case of a continuos release under constant environmental conditions
- Evaluation should reflect algorithm sensitivity
- Field data sets should reflect observed variability
- Some data sets from spills of opportunity (for example the Sea Empress, and the Exxon Valdez) may also prove useful for algorithm evaluation
- The availability of data sets was discussed. It was agreed that some sharing of data sets within a limited set of research organizations would be possible

VI. Action plan

SINTEF, in collaboration with AEA and CEDRE, will submit a proposal to MMS, MPCU, SFT, NOAA, the French Pollution Authorities, and Environment Canada to address

- model sensitivity testing
- preparation and archival of specified data sets
- testing of model algorithms

Manuscript submitted for publication in Spill Science and Technology Bulletin. Expected publication date is October, 1998.

Appendix IV: Oil Spill Modeling towards the Close of the 20th Century: Overview of the State of the Art

MARK REED*, ØISTEIN JOHANSEN*, PER JOHAN BRANDVIK*, PER DALING*, ALUN LEWIS**, ROBERT FIOCCO***, DON MACKAY¤, RICHARD PRENTKI¤¤

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¤ Environmental Modeling Centre, Trent University, Peterborough, Ontario KI9J0 7B8, Canada
¤¤ Minerals Management Service, Alaska Region, Anchorage, USA

The state-of-the-art in oil spill modeling is summarized, focusing primarily on the years 1990 to the present. All models seek to describe the key physical and chemical processes that transport and weather the oil on and in the sea. Current insights into the mechanisms of these processes, and the availability of algorithms for describing and predicting process rates are discussed. Advances are noted in the areas of advection, spreading, evaporation, dispersion, emulsification, and interactions with ice and shorelines. Knowledge of the relationship between oil properties, and oil weathering and fate, and the development of models for the evaluation of oil spill response strategies are summarized. Specific models are used as examples where appropriate. Future directions in these and other areas are indicated.

Keywords: **oil spill models, numerical models, review, simulation, oil weathering**

Introduction

The purpose of this paper is to present an overview of the different approaches applied in numerical models of the behavior and fate of oil spilled in the marine environment. This review focuses primarily on developments since 1990, relying on existing published state-of-the-art reviews (Spaulding, 1988; ASCE, 1996) to summarize earlier work.

A large number of oil spill models is in use in the world today. These range in capability from simple trajectory, or particle-tracking models, to three-dimensional trajectory and fate models that include simulation of response actions and estimation of biological effects. Many of these models are mentioned here; a set of one-page summaries is included elsewhere in this volume.

Two models purporting to contain the same algorithms may give quite different results from the same input data. Implementation is critical to algorithm performance. Furthermore, performance of one algorithm will be affected by performance of other algorithms in the model, a clear example being the relationships among spreading, evaporation, emulsification and natural dispersion.

The close inter-dependence of oil spill weathering processes is well known. Many of the advances in our understanding of weathering over the past decade or two are reflected in an increased awareness of these interactions. The nature of these interactions therefor comprises a significant portion of the following discussions.

Transport and Weathering Processes

Advection

Oil moves horizontally in the marine environment under forcing from wind, waves, and currents. Being itself a fluid with a density only slightly less than that of water, oil is also transported vertically in the water column in the form of droplets of various sizes. Both vertical and horizontal current shears are therefore important factors in the net motion of oil at sea.

Early oil spill models were typically two-dimensional surface models, using constant or variable parameters to link wind and current velocities to the velocity of the surface oil slick. Recent work by Reed et al (1994a) suggests that, in light winds without breaking waves, that 3.5% of the wind speed in the direction of the wind gives a good simulation of oil slick drift in offshore areas. As wind speed increases, oil will be dispersed into the water column, and current shears become more important. Field, laboratory, and modelling studies (Johansen ,1985; Elliott et al. , 1986; Delvigne & Sweeney, 1988; Singsaas and Daling, 1992; Reed et al ,1994a) have clearly demonstrated the importance of the vertical dimension in oil movement. These studies have demonstrated that natural entrainment of oil can play an important role not only in mass balance calculations, but also in determining the spatial and temporal distribution of oil on the sea surface.

Studies of the Braer oil spill off the Shetland Islands (Brandvik et al. 1993; Ritchie and O'Sullivan, 1994) further underscore the importance of entrainment in both mass balance and transport of spilled oil. The Braer went aground within 100 m of the Shetland Islands Coastline, and released over 80,000 tonnes of crude oil into the surf zone. The released oil was mixed into the water column, and appears to have been largely transported southwards, almost directly against the wind (Ritchie and O'Sullivan, 1994; Spaulding et al, 1994; Proctor et al, 1994). Observations of experimental oil spills described in Reed et al (1994a) further demonstrate the importance of subsurface transport to simulate oil slick trajectories realistically over a range of oil types and environmental conditions. Youssef and Spaulding (1993) derive a wind and wave current model that successfully reproduces the above observations, assuming a mean transport depth of 2.5 to 5 times the wave height.

Advective currents in oil spill simulations may be derived from current atlases or other static approximations. Direct or indirect linkages to hydrodynamic models are becoming much more common, as the latter have become more widely used and easily applied (e.g. Hodgins et al, 1995; Morita et al, 1995; Elliott et al, 1992; Howlett et al, 1993). Direct coupling between oil spill and hydrodynamic forecast models is common in operational oil spill response systems (Galt et al, 1995; Martinsen et al, 1994). Input of surface currents from real-time radar measurements is also possible (e.g. Hodgins et al, 1994; Howlett et al, 1993), but set-up times for such systems tend to limit their usefulness. Surface drifting buoys represent yet another source of real-time surface current data (Howlett et al, 1993).

Transport on scales of 10 to 100 m is important in determining the spreading of oil. Langmuir, or windrow circulation is a key surface and near-surface process at these scales. Li (1996), Fallet and Auer (1988), and Leibovich(1997) have developed methods for representing the effects of such convergence zones in oil spill models. Although their importance is recognized, these methods are not yet in general use.

Summary

Advection of oil is recognised as a three dimensional process, with key mechanisms occurring over a wide range of scales. Increasing computational power will combine with this increased insight to produce rapid improvements in this area over the next decade.

Spreading

Slick thickness and area are key variables in oil weathering and transport models. Oil slick area (or film thickness) is used in the computation of evaporation, which determines changes in oil composition and properties with time. Oil film thickness is used by many models in the computation of the rate of natural dispersion, which determines the persistence (lifetime) of the oil on the sea surface. In addition, estimates of film thickness and slick area are required for evaluation of the potential efficiency of different oil spill combat methods, and for assessments of environmental impacts.

The now classical spreading equations developed by Fay (1969, 1971) and Hoult (1972) form the basis for most spreading algorithms in use today, even though it is widely recognized that oil spreading cannot be fully explained by these equations. Major observed factors not reflected in these equations are:

formation of elongated slicks, with a thin film trailing behind the thick slick;
reduced spreading rate of viscous oils ;
break-up of oil slicks into small patches;
dependence of spreading rate on discharge conditions (surface versus subsurface, and instantaneous versus continuous releases).

Mackay et al., (1980) proposed a "thick-thin" variant of the gravity-viscous equation developed by Fay and Hoult, with the thick portion feeding oil to the thin layer. However, the term representing the effect of the density difference between water and oil in the original Fay equation was included in a general spreading constant. The resulting spreading rate is therefore independent of the initial oil density and insensitive to subsequent changes in density caused by evaporation and emulsification. The recognition of a link between the thick and thin portions of an oil slick represented an advance, but the model lacked any physics-based relationship between the two phases of the slick.

Lehr et al. (1984b) proposed a revised model to account for the observed non-symmetrical spreading of oil slicks. The extension of the slick in the wind direction was presumed to increase with time in proportion to the wind speed, while the lateral spreading of the slick was represented by the original Fay equation for gravity spreading. On this basis, the slick was represented in terms of an elongated ellipse, rather than the circular disk predicted by the Fay equation. The spreading rate in the direction of the wind was represented by an empirical wind factor obtained from observations. This model did not account for variability in thickness within the slick.

NOAA (1994) has incorporated a corresponding spreading model in the ADIOS model, with the slick represented as an ellipse, elongated in the direction of the wind. The initial area of the slick is computed according to the area at the time of transition between Fay's gravity-inertial spreading and gravity-viscous spreading regime. Fay's surface tension regime is not used in the model, but, instead, the slick is presumed to stop spreading when it reaches a terminal thickness of e.g. 0.1 millimeters. This approach produces a slick with homogeneous thickness, contrary to the observations from full-scale experiments and accidental spills.

Johansen (1984) and Elliot et al. (1986) developed the concept of shear spreading, caused by natural dispersion and subsequent resurfacing of oil droplets. More recent experimental work in the lab (Delvigne and Sweeney, 1988), and in the field (Reed et al, 1994a) strongly supports this approach, which is generally accepted as the correct explanation of the physics behind the spreading phenomenon, once gravity spreading has ceased.

Experimental studies have demonstrated that viscous oils spread more slowly than less viscous oils. This effect is not accounted for in the original Fay equations, but several attempts have been made to include this parameter in Fay-type spreading models. Based on experiments within a limited viscosity range, Buist and Twardus (1984) proposed to reduce the spreading rate predicted by the Fay equations by a factor depending on the viscosity ratio between oil and water. In a subsequent paper, Buist et al., (1989) performed a series of tests with waxy crude oils, and proposed a terminal thickness function incorporating the difference between the pour point of the oil and the ambient water temperature. Later, based on experiments in cold water (-1.5 to 1.3°C), Venkatesh et al. (1990) proposed to replace the viscosity of water by the viscosity of the oil in the original Fay equations. El-Tahan and Venkatesh (1994) approach the problem on a theoretical basis, and tried to include an extra viscosity term in the force balance equation for oil spreading, representing the shear resistance in the oil. The authors compared the extended model with experimental data, and found substantial improvements compared to the original Fay equation. However, the limited range of experiments makes it questionable to extrapolate these results to other oils. This applies particularly to emulsion forming oils, where the viscosity may be order of magnitudes larger than the viscosity range covered in the experiments.

Studies of oil spreading on cold water have also indicated that spreading tends to stop as the slick approaches a terminal thickness on the order of 1 to 8 mm, apparently depending on the viscosity of the oil (Venkatesh et al. op cit.). An empirical relation was proposed to account for the increase in terminal thickness with viscosity, but this correlation was not confirmed by later supplementary experiments (El-Tahan and Venkatesh, op cit.). This implies that other factors could be responsible for the termination of spreading, such as solidification of the oil due to crystallization of the wax content at temperatures below the pour point of the oil.

Under natural conditions, oil spreading will not stop when the terminal thickness is reached. At this point, the oil slick will tend to break up into patches and small fragments due to wave action and current shears, and these patches or fragments will be spread due to oceanic turbulence. This is one of the reasons for the somewhat pessimistic attitude expressed by Lehr (1995) towards attempts to improve Fay type spreading models: "it is doubtful that any of these approaches will accurately predict the slick area over any extended time period because of the neglect of outside environmental factors." The factors neglected in these approaches are mainly wave action and spreading induced by shear currents and oceanic turbulence, which are presumed to be the dominant long term spreading processes.

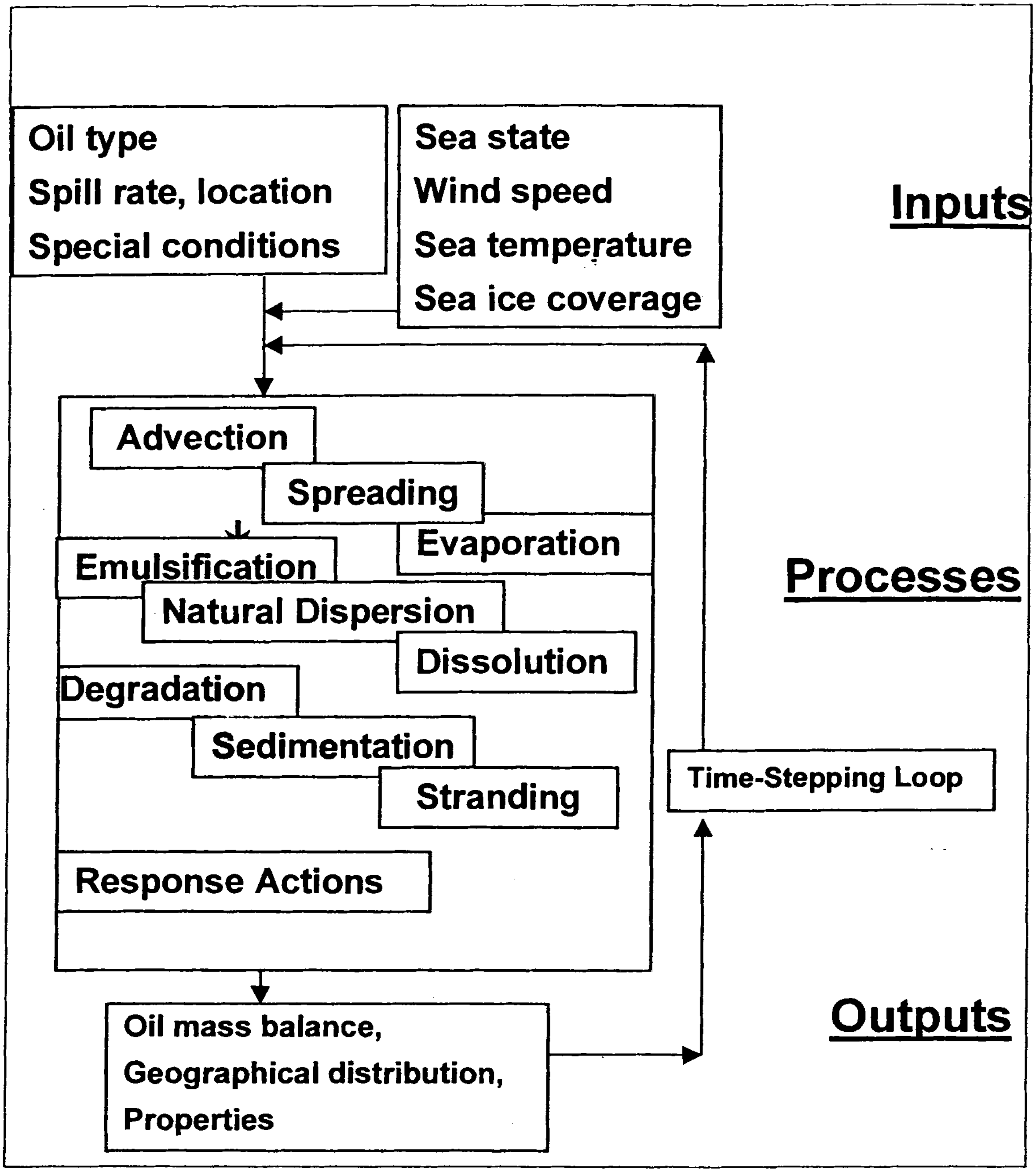

Figure 1 General layout of oil weathering models. This schematic indicates that the weathering processes are closely inter-linked; the output from one process algorithm will influence the behavior of others.

Lehr (op cit.) also points out that most spreading algorithms assume instantaneous release of oil in open water conditions, while real spill incidents may involve leaks which continue at a varying rate for hours or days. Methods used to predict spreading of instantaneous spills are questionable for cases with continuous spills. This is mainly due to the fact that as oil leaks from continuous spills, the oil will be moved away from the source with wind and currents. In such cases, at some distance from the source, lateral spreading forces will dominate, while spreading forces along the slick axis will be negligible. As pointed out early by Waldman et al. (1972), this implies that the oil will spread more in the manner of spreading in a channel (i.e. one-dimensional spreading, symmetric about the slick axis). In such cases, the slick can not be considered as a homogenous entity (as in the Fay (1969, 1971), Mackay et al., (1980), and Lehr et al., (1984a,b) models). Obviously, with a continuous release, the thickness and the properties of the oil in the slick will vary not only with time, but also with the distance from the source.

A sub-sea blowout from offshore exploration or production is one of the more serious situations leading to a continuous leak at a varying rate for hours or days. In such a case, the surface spreading of the oil will be governed by mechanisms other than gravity spreading. Sub-sea blowouts will generate buoyant plumes where the buoyancy flux is mainly related to the flow of gas released together with the oil. The oil will be transported to the surface together with the seawater entrained by the plume, and the surface spreading of the oil will be governed by the radial outflow of this entrained water. The oil film generated in such cases will be thinner than slicks formed by surface leaks, perhaps by a factor of ten or more.

Theoretical and experimental studies of oil spreading from sub-sea blowouts were initiated in the early eighties (Fanneløp and Sjøen 1980, Milgram 1983, Milgram and Burgess 1984), and refinements of these models have continued up to present (Swan and Moros 1993, Zheng and Yapa 1997, Rye and Brandvik 1997). This recent work implies that predictions of the surface spreading may be made with acceptable accuracy for sub-sea blowouts from moderate water depths. However, for releases from greater depths (e.g. 500 to more than 1000 m), modifications of the present models will be necessary, particularly due to the expected formation of gas hydrates.

Summary

In summary, for instantaneous spills, Fay-type spreading models may provide adequate predictions of the film thickness in the thick part of the slick, where the major fraction of oil volume will be found. Such models are appropriate at least during the early stages of a release. Modifications of the Fay model for effects of oil viscosity and termination of spreading should be considered for future development. Linking spreading to dispersion probably best represents the recognized physics of the spreading process after initial gravity-viscous spreading is complete.

For continuous spills in open sea conditions, where lateral spreading will be dominant some distance downstream from the source, one-dimensional Fay spreading models seem to be more relevant than the radial spreading models used for instantaneous spills. Modifications for effects of oil viscosity and termination of spreading should also be considered in this case. For sub-sea blowouts, where the Fay equations are inadequate, surface spreading may be predicted by use of model concepts based on buoyant plume theory, allowing for significant differences in behavior (for example, hydrate formation) as a function of oil composition, temperature, and depth.

Evaporation

Estimates of evaporative losses are required in order to assess the persistence (lifetime) of the spill, and are also the basis for estimates of changes in oil properties with time. Simple methods have been widely used, mainly based on an analytical model proposed by Stiver and Mackay (1984). A model of this type is used by NOAA (1988) in the ADIOS model. More recently, Fingas (1997, 1998) has proposed a simple empirical method derived from small-scale pan evaporation experiments. Jones (1997) has recently compared predictions made with the different evaporation models, and discussed data requirements and characteristics of the models.

We distinguish here between pseudo-component and analytic methods. In the pseudo-component approach, the fraction evaporated is computed as a function of time and temperature alone. In such models, the oil is divided into a number of "cuts" or "fractions" specified in terms of intervals in boiling point temperature. The volume fraction in each of these cuts is obtained from true boiling point (TBP) data obtained by a standard ASTM-method. These volume fractions are converted into mole fractions on the basis of the average specific gravity and molecular weight of each cut. The vapor pressure of each cut is computed from the average boiling point and the oil temperature by means of empirical or semi-empirical formulas. On the condition that the partial pressures of these components are negligible in the ambient air, the evaporation rate for each cut is presumed to be proportional to the partial vapor pressure of each component. The actual rate of evaporation depends also on a mass transfer coefficient, which is related to the temperature and the surface wind speed. Fingas (1997, 1998) argues that the wind speed is not a relevant parameter.

Jones (1997) has modified this method by introducing an empirical relation between molar volumes and boiling point, based on data for n-alkanes. In this way, the pseudo-component model may be used in spite of the common lack of data on specific gravity of the boiling point cuts. The same author has also introduced an empirical equation for determination of the vapor pressure as a function of boiling point and oil temperature. This equation is said to produce more realistic pressure values, particularly at high boiling points, than the Clausius-Clapeyron equation and the Trouton's rule used in Payne et al (1987).

A similar pseudo-component concept is used in the SINTEF weathering model (Daling et al. 1997). However, the mass transfer coefficient in this model is based on formulations commonly used for computations of surface of fluxes of momentum, heat and moisture in open sea (Smith 1988). This implies that the mass transfer coefficient is proportional to the wind speed, with the air-sea drag coefficient used as the factor of proportionality. However, as shown by Amorocho and DeVries (1980) and Blake (1991), the drag coefficient depends on the wind speed due to changes in the surface roughness of the sea with the sea-state. The drag coefficient for near-neutral conditions appears to increase from a constant value of about 1×10^{-3} at wind speeds under 6 or 7 m/s, where white caps start to form, to about twice that value at 20 m/s (Amorocho and DeVries, 1980).

Due to the large data requirements and computational complexity of the pseudo-component concept, simpler methods have been proposed, such as the so-called analytical method developed by Stiver and Mackay (1984). This method is used presently in many oil drift models, as well as by NOAA (1994) in the ADIOS model. The method is based on several simplifications, including the questionable assumption of a linear relationship between the boiling point of the liquid phase and the fraction lost by evaporation. This linear relation is specified in terms of an initial liquid phase boiling point temperature and the gradient of this boiling point temperature versus the fraction evaporated.

It should be noted that the liquid phase boiling point data required in the analytical method are different from the data that are provided by the standard True Boiling Point curve. For this reason, a subroutine for calculation of the initial boiling point based on the TBP curve is included in the ADIOS model (NOAA *op cit.*). This subroutine calculates by trial and error the temperature at which the vapor pressure above the fresh oil is equal to the atmospheric pressure, and contains essentially the same algorithms as required for calculations of the vapor pressure of the remaining oil fractions in a pseudo-component concept.

When Jones (1997) made his comparisons between the extended analytical model and the pseudo-component method, he found that the extended analytical method in general predicted significantly larger evaporative losses than his own pseudo-component model. He presumed that the difference could be explained by the use of different algorithms for calculating vapor pressures in the two models. The high evaporative losses predicted by the analytical model may also in part be explained by the postulated linear approximation of the boiling point curve.

In the derivation of the analytical method, Stiver and Mackay (1984) also introduce the evaporative exposure parameter θ. They show that the relation between the evaporative loss and this parameter is thermodynamic in nature and does not depend on how the exposure is achieved. Hence, the relation is only a function of the initial oil composition and the oil temperature. For constant wind speed, the evaporative exposure parameter may be expressed as $\theta = Kt / h$, where K is the surface mass transfer coefficient, h is the initial film thickness and t is the exposure time. This implies that if the evaporative loss is computed as a function of time for one combination of wind speed and initial film thickness, the results may be used for any another combinations of wind speed and film thickness by a simple time scaling. The same applies to cases with variable wind, where the exposure is obtained from the integral $\theta = \int (K / h)\, dt$.

Johansen and Skognes (1988) applied this concept in a statistical trajectory model in order to reduce the computational requirements of the evaporation calculations. In this model, the evaporative loss is computed as a function of time for a selection of crude oils at a chosen reference condition (defined in terms of a fixed initial oil film thickness and a constant wind speed). These results are tabulated in a file, which is later read during the start-up of the trajectory model. During the trajectory simulations, the evaporative loss is determined by simple interpolation, on the basis of the integrated evaporative exposure along each trajectory.

This approach could also be based on empirical evaporation data from laboratory scale evaporation experiments, provided that the resulting evaporative losses are related to relevant evaporative exposures. Fingas (1997) has conducted such experiments for a variety of crude oils and oil products, and derived simple empirical relations for prediction of the evaporative loss as a function of time, based on commonly available distillation data for oils (i.e. percent by weight distilled at 180°C). However, Fingas (1998) also concluded from these experiments that wind speed and exposed surface area do not significantly influence the evaporation rate. For this reason, he advocated that his correlations should be used with no corrections for film thickness on wind speed, but with a minor correction for temperature. These conclusions are not at present generally accepted in the field of oil spill modeling, and run counter to most prior work in this area.

Jones (1997) compared predictions with his pseudo-component model at different wind speeds and oil film thicknesses with the predictions based on the empirical equations proposed by Fingas, and concluded that the empirical correlations in general produced significantly smaller evaporative losses than the pseudo-component method. However, as Jones (*op cit.*) points out, Fingas used low wind speeds and relatively thick oil to establish the parameters in his model. When examining the results under such conditions, Jones found that the models were in good agreement. If the evaporative exposure relevant for the laboratory conditions could be established, adjustments of the empirical predictions for other conditions (wind speed, film thickness) could be made. However, further tests at other wind speeds and comparisons with calculations based on the pseudo-component concept should be made before such adjustments can be recommended for general use.

Summary

In summary, different methods for computation of evaporation have been discussed in this section, including the pseudo-component method, the analytical method and the more recent empirical method. The discussion may be concluded as follows:

The popular analytical method developed by Stiver and Mackay is based on distillation data not readily available. Introduction of methods to derive the required data from standard distillation data will obviously reduce the primary advantage of the analytical method – i.e. its simplicity. The analytical method is also based on questionable assumptions, which tend to produce overestimation of the evaporative losses.

The surface mass transfer coefficient formula originally proposed by Mackay, which is used in many models to date, should be examined critically together with alternative formulations based on sea surface exchanges of momentum, heat and moisture.

The pseudo-component method seems to be the most reliable and flexible of the discussed methods. However, the computational intensity and the high data requirements of the method may still justify a search for simpler methods (empirical correlations) or "shortcuts" (i.e. application of the evaporative exposure concept).

Natural dispersion

Computation of natural dispersion is required for assessment of the lifetime of an oil spill. The rate of natural dispersion depends on environmental parameters (i.e. the sea-state), but is also influenced by oil-related parameters, such as oil film thickness and oil properties (density, surface tension and viscosity). Emulsification will contribute significantly to the persistence of oil spills, mainly due to the sharp increase in viscosity and the increase in slick thickness with water content (retarded spreading, increasing volume, reducing natural dispersion).

Loss of oil from the surface slick due to natural dispersion can be computed by equations originally proposed by Mackay et al. (1980). This concept is based on an estimate of the fraction F of the sea surface subjected to dispersion per unit time, supplemented by an estimate of the fraction F_B of the entrained oil containing droplets with a size small enough to be permanently dispersed in the water column. The total rate of entrainment (m^3/m^2 s) is obtained by multiplying F by the oil film thickness. The rate of permanent dispersion is then found by multiplication this product with F_B.

Mackay et al. postulate that the fraction F depends on the sea-state, with an increase proportional to the square of the wind speed. The fraction permanently dispersed is, on the other hand, supposed to be independent of the sea state, and influenced mainly by the oil film thickness and the properties of the oil (i.e. the viscosity and the oil/water surface tension). Thin oil films with low viscosity and low surface tension are thus postulated to disperse more rapidly than thick oil films with high viscosity and surface tension.

In some models (e.g. Payne et al, 1987; Reed et al, 1989c), only the thick portion of the slick is considered, whilst Mackay et al. applied the dispersion equations for both the thick and the thin portions of the slick. By neglecting transfer of oil from the thick to the thin portion of the slick — where the fraction of permanently dispersed oil will be enhanced — these models may underestimate the overall dispersion rate.

Dispersion models based on the experimental work of Delvigne and Sweeney (1988) have now become more standard. Delvigne and Sweeney conducted investigations of natural dispersion of surface oil due to breaking waves in a small laboratory flume, and in a larger test basin. On this basis, an empirical relation was derived for the entrainment rate (dispersed mass per unit time) as a function of oil type and breaking wave energy. The authors also determined relations for predicting the droplet size distribution of the entrained oil as a function of the same parameters. The experiments revealed a common feature of the droplet size distribution of the entrained oil for all the experiments. The number of droplets in a certain diameter class could be related to the droplet size with a common power law relationship, independent of the type of oil and the wave conditions. From this general observation, an expression was derived for the droplet size distribution of the oil mass entrained by each breaking wave: $Q_{d \le D} = CD^p$.

In this equation, $Q_{d \le D}$ is the entrained oil mass per unit area included in droplets up to a certain diameter D. The exponent $p = 1.7$ was derived from the observed power law distribution of the droplet size determined from the experiments. The factor of proportionality C was found to depend on the oil type and the height of the breaking wave H, i.e. $C = a\, H^q$, where the dispersion coefficient a could be related to the oil type in terms of the oil viscosity. The exponent q was found to be 1.14 from the wave flume experiments, while a slightly larger value ($q = 1.4$) was found in later small scale experiments (Delvigne and Hulsen, 1994).

Based on the limited viscosity range in the wave flume experiments, the authors postulated that the dispersion coefficient a was inversely proportional to the viscosity of the oil. However, in the subsequent small scale experiments in an extended viscosity range, this postulated relationship was not confirmed. Instead, the authors concluded that the coefficients were very similar for all low-viscous oil types and weathering states with viscosity less than 100 cSt. For viscosities above this range, the coefficients decreased considerable with increasing viscosity. Thus for an increase in viscosity from 100 to 1000 cSt, the dispersion coefficient was found to be reduced by about two orders of magnitude (Delvigne and Hulsen, 1994). This agrees with observations that the dispersion rates of emulsified oils will be significantly reduced compared to non-emulsified oils (e.g. Reed et al., 1994a).

The dispersion rate applies to the mass entrained by each breaking wave. In order to obtain an expression for the entrainment rate, the equation must be multiplied by a rate factor F_w. This factor is obtained from the white cap coverage, which is divided by the mean wave period to obtain the fraction F_w of the sea surface hit by breaking waves per unit time.

The authors suggest that the oil droplet dispersion may be assumed to follow this empirical relationship for the range from the smallest size classes to the size where the entrained mass equals the local surface concentration of oil (oil mass per unit area). This implies that the predicted maximum droplet size will depend on the oil film thickness, as well as the sea-state and the type and weathered state of oil.

Summary

The method of Delvigne and Sweeney, which estimates the entrained oil mass per unit area and unit time, is the most common in use today. This basic methodology is used in the ADIOS model (NOAA, 1994), the SINTEF oil weathering (Aamo et al, 1993; Daling et al, 1997), OSCAR (Reed et al, 1995; Aamo et al, 1997a,b), and OILMAP (Spaulding et al, 1992).

The implementation of the approach may significantly affect model behavior. In some models, droplets below a certain threshold diameter are presumed to be permanently dispersed. This threshold diameter is typically assigned a value of 70 to 150 μm, based on recent field measurements of the size distribution of dispersed oil droplets (Lunel, 1993). However, the use of a specific threshold diameter is questionable for several reasons. Entrained oil droplets tend to be dispersed permanently in the water masses when the magnitude of the vertical turbulent motions is high compared to the rise velocity of the droplets. When the turbulent motion dominates, dispersed oil droplets tend to be mixed down into the water column, and as a result, the rise time to the surface will increase. This implies that the limit for permanent dispersion should perhaps be related to droplet rise velocities and sea state, rather than the droplet size.

Moreover, dispersed oil droplets tend to lag behind the surface slick due to the wind-induced current shear in the upper part of the water column. The gradual resurfacing of droplets within a certain size range will then contribute to the observed elongation of the slick, where a tail of thin oil film will be formed behind a thicker portion of the slick. These processes have been included in oil drift models based on the particle concept (Johansen, 1987; Elliot, 1991; Reed et al., 1994a). This process results in a flow of oil mass from the thick to the thin slick area, from which dispersion becomes more rapid. Although the thin area represents only a small fraction of the total surface mass at any one time, it may represent a significant loss mechanism integrated over time. The consequences of the choice of a certain threshold diameter (or rise velocity) for permanent dispersion should therefore be evaluated by sensitivity analysis.

Emulsification

In many models, emulsification is computed with an implicit algorithm originally proposed by Mackay et al. (1980). The same authors in fact advocated the use of a simpler explicit algorithm, which could be expressed in differential form. This algorithm is used by NOAA in the ADIOS model, and also in a slightly modified form in the SINTEF weathering model. The simplified algorithm contains two parameters, defining the water uptake rate and the maximum water content. Both parameters may be derived from laboratory experiments, but the parameter for the water uptake rate must in some way be scaled to field conditions and different sea-states.

Experimental studies of emulsification for different crude oils have revealed that both the water uptake rate and the maximum water content vary significantly from one crude to the other, and that these parameters also are influenced by the state of weathering of the oils (Daling and Brandvik, 1988). In general, the maximum water content tends to decrease with the viscosity of the parent oil. The differences in the water uptake rate might be related to the chemical make-up of the oil (i.e. the content of resins, waxes and asphaltenes), but the results from a limited range of crude oils were not conclusive. Due to the significant differences in emulsification between different oils, Daling et al (1990) recommended that the emulsification parameters should be determined on the basis of experimental data for specific oils.

Fingas et al. (1997, 1998) have recently presented a literature review of emulsification and related model concepts. These authors conclude that past emulsification modeling was based on first-order rate equations that were developed before extensive work on emulsion physics took place. They suggest that empirical data should be used as a basis for further developments of emulsification models, and that such models also should take into account the stability of emulsions formed by different oils (stable, meso-stable, unstable). The stability is a measure of the decrease in the water content of an emulsion when kept in stagnant conditions. Meso-stable emulsions will lose some water when kept at rest for e.g. 24 hours, while unstable emulsions will lose practically all the water when kept at rest for the same period.

While the apparent viscosity of a stable emulsion may be two to three orders of magnitude larger than the viscosity of the parent oil, the apparent viscosities of unstable emulsions are typically no more than an order of magnitude greater than that of the parent oil. These observations should be taken into account in the predictions of the viscosity of emulsions, which normally are based on the water content, independent of the character of the emulsions. The SINTEF oil weathering model (Daling et al, 1997; Aamo et al, 1993) uses emulsion stability in the computation of the appropriate viscosity used in the dispersion calculation.

Summary

Reliable prediction of emulsification and the associated viscosity changes presently relies on empirical observations, since established prediction methods have proven unreliable. Predictions based on oil composition are anticipated to be possible in the near future.

Oil-ice Interactions

The behavior of oil in ice is complex, and difficulties in modeling the physics of ice movement and formation on scales of meters are magnified when the uncertainties of oil behavior are added. A very significant literature exists describing oil-ice interaction studies over the past 25 years. Fingas (1992) and Dickens and Fleet (1992) give extensive overviews of the subject up to the beginning of this decade.

More recent work has focussed largely on spreading of oil in an under ice (Yapa and Weerasuriya, 1997; Yapa and Belaskas, 1993; El-Tahan and Venkatesh, 1994), but calibrations rely largely on small scale, short term laboratory studies. After the first hour or so, spreading in the field will be governed by ice lead dynamics, which tend not to be included in these solutions.

The most realistic field data on the weathering of oil in the presence of sea ice is that reported by Singsaas et al. (1994). These data shows that the processes of evaporation, dispersion, and emulsification are all significantly retarded in ice leads, contrary to the conclusions drawn by Payne et al. (1987) from mesoscale laboratory experiments. Wave-damping, the limitations on spreading dictated by the presence of sea ice, and temperature appear to be the primary factors governing the observed weathering rates. A key problem in achieving any improvement in modeling these processes lies in our very limited ability to model the behavior of the ice itself at the necessary spatial scales, which are on the order of meters. The real time forecasting attempt reported by Reed and Aamo (1994), and the model development and hindcasting work by Johansen and Skognes (1995) exemplify the problems encountered when oil-ice interaction models are put into active use in the field. The present limited ability to model ice behavior at the 1-10 m scale also seriously limits the extent to which use can be made of the advances in modeling of oil spreading cited above. Ice coverage is a dynamic variable, and can change from 50% to 99% overnight, with extreme consequences for oil weathering due to changes in thickness.

Summary
The pessimistic view is that the modeling of oil weathering in the presence of sea ice remains at an *ad hoc* level, limited largely by the state-of-the-art in modeling sea ice physics at the appropriate scale. A more optimistic summary would take account of the advances that have been made in our understanding of oil weathering processes in the presence of sea ice. This new understanding has come primarily through fieldwork, the results of which have corrected misconceptions introduced through prior laboratory weathering studies. The optimistic conclusion, then, is that the next generation of oil-in-ice weathering models will simulate actual conditions better than earlier models, although remaining highly parameterized and lacking dynamic reliability.

Oil-Shoreline Interactions

Several published models now exist which include some level of dynamic representation of oil in the coastal zone The most comprehensive of these is the coastal zone oil spill model COZOIL (Reed et al., 1989c; Howlett, 1998). In addition to a relatively thorough representation of oil-sediment interactions, COZOIL incorporates a wave propagation model for the surf zone, a wave-induced long-shore velocity, and a representation of the shoreline that varies segment-by-segment. COZOIL was tested against wave data from the Alaskan Penninsula, and against data from the Amoco Cadiz oil spill (Reed and Gundlach, 1989).

Other models tend to assign a holding capacity and removal rate to each shoreline type (Seip et al., 1986; Reed, 1989; Shen et al., 1987; Torgrimson, 1980, Humphrey et al., 1993). Holding capacity, or how much oil a given sediment type will retain per unit length or per unit area, is not well documented in the literature. Gundlach (1987) presents a summary of observations focussed on this concept. Reed et al. (1989c) compute holding capacity from oil viscosity, sediment permeability and porosity, and tide level. Darcy's Law is used to compute penetration depth, allowing for the rising and falling of the tides while residual oil remains on the surface of the sediments. Humphrey et al. (1993) employ a simplified version of the approach, in which constant parameters replace the dynamic equations in COZOIL.

Summary
Most models reviewed calculate the mass remaining ashore as a first order process. Values of the removal rate constant vary among models. The COZOIL model does not actually assign rates, but computes them based on sediment and oil properties, and the wave environment. The model proposed by Humphrey et al. (1993), the most recent model focussed specifically on oil in coastal sediments, also uses a constant first order removal rate. This simplified approach does not reflect the importance and the state of understanding of environmental conditions, as reflected in the wealth of more recent observations (e.g. Baker et al, 1993; Hayes et al, 1991; Johns et al, 1991; Michel and Hayes, 1993; Owens et al, 1993; Pavia, 1992; Sveum and Bech, 1993). Such simplifications may remain useful in cases where one is unable to observe or model the physical environmental variables.

Future efforts would appear best focussed on models which include explicit descriptions of the processes active at the coastline, since continued use of highly parameterized models will not further our understanding of the underlying governing processes.

Oil Properties

A weathering model keeps track of the changes in the composition of the oil due to loss of volatile fractions. Changes in the oil density are typically computed on the basis of evaporative loss and water uptake (emulsification). Computation of the viscosity of the oil in terms of the viscosity of the remaining fractions has been attempted, but produces unrealistic values (Fingas et al, 1995; Payne et al, 1987). Instead, the viscosity of the weathered oil is often computed from the viscosity of the fresh oil at a standard reference temperature (25°C) and the fraction lost by evaporation. This viscosity can be scaled with temperature according to a chemical handbook formula. The increase in viscosity due to emulsification can then be computed from the viscosity of the weathered oil and the water content by a formula proposed by Mackay et al. (1980). Experience has demonstrated that this computational approach can also introduce serious errors into the viscosity estimate, such that empirical data for each oil remains the surest basis available (Daling et al, 1997). Fingas (1998) suggests a predictive methodology for emulsification based on oil composition, but the approach has not yet been tested.

Other properties, such as the pour point and the flash point of the oil, are also of interest in conjunction with assessments of different oil spill combat methods. These properties will also change with oil weathering, but predictions of these changes are probably best made in terms of empirical data for each individual oil.

Spill Response

A primary purpose of oil weathering and transport models is to reduce the environmental impact of spills through improved selection of response strategies. A few oil spill models include some capability to simulate spill response actions. Published descriptions of such models are few. Reed et al (1995, 1998) and Aamo et al (1997a, b) describe the oil spill contingency and response model OSCAR, developed specifically as a tool for quantitative comparison of alternative oil spill response strategies. The model couples weathering, surface trajectory, water column, and oil spill response components. The behavior of individual working groups, such as vessel-skimmer and helicopter-dispersant systems, are simulated, each with an assigned strategy and work area. Environmental factors such as winds and waves, and available daylight relate functionally to effectiveness of mechanical cleanup. The application of chemical dispersants is simulated based on observations from field trials (Daling et, 1995; Lewis et al, 1995)

Conclusions: Future Directions

Increasing computational power will continue to strengthen oil spill models, allowing more physical and chemical detail, and more direct coupling to hydrodynamic and meteorological models. However, there is no direct correlation between computational capacity alone and the quality of model results. Further research is necessary to further our understanding in some fundamental areas.

Oil Composition and Properties

Emulsification is a key process in determining spill lifetime as well as the window of opportunity for spill response (Nordvik, 1995). Reliable computations of emulsion formation, stability, and associated viscosity at present require laboratory or field observations. Such observational data sets are expensive to acquire. The development of correlations between parameters commonly available through crude assay data and anticipated emulsion characteristics would be a valuable contribution. Fingas (1998) suggests a solution to this problem, based on the percent asphaltene content in the weathering oil. This idea will clearly be pursued further.

Spreading and Advection

Spreading is important in determining the fate of spilled oil through evaporation, emulsificatoin, and natural dispersion. Emulsification and evaporation lead to decreased oil-water density difference, and increased pour point; these can be used to estimate the cessation of spreading as described by the classical gravity-viscous equations of Fay and Hoult. For most crude oils, this limit is attained very early in the development of an oil spill, at which point environmental forces govern. Processes at the scale of 10-1000 m, which are often at the sub-grid scale for hydrodynamic input data, need to be included in oil spill models. Langmuir circulation is a central process active at these scales, and several alternative approaches exist to allow this advance to take place (Li, 1996; Fallet and Auer, 1988; and Leibovich,1997).

The representation of realistic spatial variability in thickness is another area that is poorly developed in present models. The application of Thiessen polygons to estimate local thickness from Langrangian elements (Galt, 1995 and personal communication) may prove useful in resolving spatial variations in average thickness, if the appropriate physical processes are included in the weathering and transport.

Release conditions are also relevant in determining initial spreading. Underwater releases, for example, result in very different initial surface distributions of oil than surface releases (Rye and Brandvik, 1997).

Natural Dispersion and Emulsification

Natural dispersion and emulsification are competing processes in the sense that each reduces the rate at which the other occurs. Emulsification and slick thickness are important in determining slick lifetime, windows of opportunity for alternate response strategies, and environmental impact. Delvigne and Sweeney (1988) achieved a significant advance in algorithms for natural dispersion, but the resulting equation for dispersion rate is strictly a curve fit, with no grounding in fundamental physics or dimensional analysis. The same is true of all extant emulsification algorithms. Fingas (1998) appears to be close to a predictive capability for emulsification based on oil composition, but there is significant opportunity for new thinking and advancement in both these areas.

Oil-Ice Interactions

As discussed above, the prognosis for improved representation of oil behaviour in ice-infested waters remains bleak until our capability to model the behaviour of ice alone improves. The basic problem is that the processes governing oil behaviour occur at scales of a few centimetres to a few tens of meters within an ice field. Ice model resolutions are typically at scales of kilometres, to account for effects at active boundaries, such that very crude, ad hoc parameterisations become necessary. Knowledge gained from laboratory experiments is of limited usefulness, due to limitations imposed by edge effects.

Oil-Shoreline Interactions

The behaviour and fate of oil coming ashore has received extensive attention since the 1989 oil spill in Prince William Sound, Alaska. Model development has not made good use of this wealth of data, nor has development focussed on representation of the underlying processes that are active in the coastal zone. Here is another area in which increased computational resources can contribute to allow more detailed physics to be represented in models.

Spill Response

Oil spill response actions remain highly parameterised in most models. The leakage of oil from booms is an example of an area in which recent advances (e.g. Grilli et al, 1996; Goodman et al, 1996; Brown et al, 1996) appear mature enough for incorporation into spill model systems.

The effect of dispersant application on oil properties, particularly oil viscosity and emulsion stability, is key to accurate simulation of response success. Only limited data are available in this area, and the underlying mechanisms are incompletely understood. Applied research in this area could be fruitful.

Net Environmental Benefit Analyses (NEBA)

Objective evaluation of the net environmental benefit of alternate oil spill response strategies during contingency planning and response, requires the application of an oil spill model coupled to a biological exposure and effects model. Such systems of models are not new (e.g. Reed and Spaulding, 1981; Spaulding et al, 1985; Reed et al, 1989a; Reed et al, 1994b), and in some cases are in use under national legislation (French et al, 1996; Reed et al, 1989b). Improved biological impact models, and direct linkages to oil spill (and other pollutant fates models) will become more common in the near future, with development of a model specifically for NEBA already in progress (Singsaas, 1998).

Real-Time Data Acquisition

Improvements in the acquisition, interpretation, and transmission of remotely sensed data will contribute to oil spill modelling in several ways. First, real-time updating of drift and spreading computations will become possible, relying on direct transmission from over-flight aircraft. Second, as our ability to measure slick thickness from aircraft improves, mass balance estimates will be much improved, and dispersion rates, both natural and chemical, will be measured more accurately than is possible today. The remote estimation of water content may also become possible, in which case synoptic weathering pictures can be built up to supply calibration and test data sets for models.
The Internet is likely to result in significant changes in how oil spill models are designed in the future. Nearly real-time acquisition of input data, including winds, currents, and over-flight images can be achieved in this way, virtually world-wide. Model results can also be disseminated rapidly via the Internet. Whether or not advantages will be realised by executing model code at central locations, and downloading to branch nodes remains to be seen.

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The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

The Minerals Management Service Mission

As a bureau of the Department of the Interior, the Minerals Management Service's (MMS) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS), collect revenue from the Federal OCS and onshore Federal and Indian lands, and distribute those revenues.

Moreover, in working to meet its responsibilities, the **Offshore Minerals Management Program** administers the OCS competitive leasing program and oversees the safe and environmentally sound exploration and production of our Nation's offshore natural gas, oil and other mineral resources. The MMS **Royalty Management Program** meets its responsibilities by ensuring the efficient, timely and accurate collection and disbursement of revenue from mineral leasing and production due to Indian tribes and allottees, States and the U.S. Treasury.

The MMS strives to fulfill its responsibilities through the general guiding principles of: (1) being responsive to the public's concerns and interests by maintaining a dialogue with all potentially affected parties and (2) carrying out its programs with an emphasis on working to enhance the quality of life for all Americans by lending MMS assistance and expertise to economic development and environmental protection.