Chapter 7

The Technology Windows-of-Opportunity Oil Spill Response Strategy*

7.0. Technology Windows-of-Opportunity

Definition: *Technology Windows-of-Opportunity:* The various time periods for effective utilization of marine oil spill response technologies and methodologies in clean-up operations.

This chapter is an overview of the Technology Windows-of-Opportunity Strategy from its development in the 90s as our understanding of the science of the weathering of spilled oil has evolved. The weathering (changes in an oil due to exposure to the environment) of oil was initially assumed to be a simple aging process of the mixture of oil in water. Studies have found it to be a complex physical, chemical and biological process, with our understanding of it still evolving today.

7.0.1. Introduction—Historical Perspective

In the late 70s, a few oil companies began to develop and market chemicals as dispersants or emulsion breakers, with the idea that they could be used to treat spilled oil and reduce clean-up and environmental damage. The early work was primarily with fresh oil, and stemmed from oil company laboratories and refineries. In the 80s, as these chemicals were tested and evaluated on oil spills, the results were found to be mixed and difficult to compare (Mackay et al., 1980; Mackay and Zagorsky, 1982; Ross, 1986). This led Esso, Exxon, and Fina to fund extensive research and development at IKU (Institutt for Kontinentalsokkelundersøkelser og Petroleumsteknologi), AEA (Warren Springs), and subsequently at Battelle Ocean Sciences and COSS at Texas A&M University to test the effectiveness of these products on oil spills. The results of early studies could not be compared, because the weathered oils were prepared

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in many different ways. The initial studies at IKU and in the North Sea led to the realization that the oil continued to change or weather after it was spilled and that it varied over time of exposure and conditions in the environment. In addition, early researchers realized a need for a standard method to prepare standardized weathered samples which were representative of a standard time period of exposure to the environment for treatment with dispersants or emulsion breakers (Brandvik and Daling, 1991; Daling and Brandvik, 1991; Nordvik et al., 1992).

The necessity was to develop a standard process that could produce a weathered oil, which would yield "standardized" or "reproducible" consistent weathered oil samples at different time intervals representing variable exposure of the oil to the environment. This led to the development of the Step-Wise-Laboratory Weathering Method/Process at IKU (Daling et al., 1990, 1993a; Daling and Almås, 1988; Daling and Brandvik, 1991; Hokstad et al., 1993; see Walker et al., 1993). With the Step-Wise-Weathering Method standardized, researchers could then develop response diagrams for a given technology measuring the efficiency of a given technology at different times (meaning time periods of weathering). Research at IKU by, Aamo, Daling, Reed (Aamo et al., 1993), and others (Johansen, 1991) led to the modeling of weathered oil.

Then the Oil Companies funded studies to test their dispersants and emulsion breakers with weathered oils. With the need to reduce recovered oil storage capacity on response ships by separating out the water that was initially picked up with the oil and discharging this water back overboard, Knappstad (1981), Lode (1981), Hokstad and Brandvik (1993), Hokstad and Daling (1993) and others tested the effectiveness of different emulsion breakers with specific oils. Subsequently, the International Advisory Committee on Water in Oil Emulsions (IACE) was established with the aim of improving the understanding of the formation and stability of emulsions needed for improvement of model predictions (Lee, 1999).

About the same time environmental regulatory agencies were becoming involved in regulating the development and production of oil from offshore waters. They quickly realized that the oil being produced from a given field was similar. They realized that in a given oil field that the oil spill response contingency plan for that field could specify that the responsible party use specific clean-up and response means—i.e., technologies. In addition, these spill response technologies could be specific to disperse a given produced oil and that these products be stored in that field in such a manner to be available for response to a spill. They also required platforms to have the "right" or correct emulsion breakers on hand. These actions brought together the interests of regulatory agencies and the public concern for protection of the environment for the utilization of the most effective products and equipment used to reduce environmental damage. Cost benefits were also obtained because the chemicals were NOT used on the wrong oil or at an inappropriate time period.

The development of the Step-Wise-Weathering Process was a significant advancement in the field of oil spill response, it led to the implementation of testing under different types of oils and degrees of weathering. For dispersants, an international committee was established: "International Dispersant Effectiveness Testing Committee" (IDETC). Standardization led to the ability to compare and accept results from different institutions. Data from different institutions could be combined in databases allowing plotting of efficiency diagrams over a range of environmental conditions and for different oils. In 1994, the International Oil Weathering Committee (IOWC) was established in order to improve the overall modeling effort.

The following were extensively involved in this early work:

In Norway:	**IKU:** *Per S. Daling, Per J. Brandvik, T. Strøm-Kristiansen,* Ivar Singsaas which subsequently was reorganized in to SINTF Chemistry **SINTF:** *O. M. Aamo, Mark Reed, Hans Jensen*
In France:	**CEDRA:** *Franqois_X. Merlin*
In the UK:	**AEA:** (former Warren Springs Laboratory): *Alan Lewis, Tim Lunel*
In Canada:	*University of Toronoto: D. Mackay* **Environment Canada:** *M. Fingas, A. Harry Whitticar*
In the US:	**MSRC:** *Atle B. Nordvik* **Battelle Ocean Science:** *Stanley A. Ostazeski, Jerry M. Neff* **Ohmsett—MMS** *Joe Mullin and Ken Bitting* (**USCG**) began testing with Different Oils **IDETC** *Merv Fingas:* Environment Canada—Standard Methods *A. Harry Whiticar:* Environment Canada, Testing of Mechanical Equipment (Skimmers) *David Cooper:* Environment Canada, Testing of Sorbents *Richard Lessard:* Exxon R&D, Dispersants *Robert Fiocco:* Exxon R&D, Dispersants

7.0.2. Weathering of Oil

When crude oil and refined products are accidentally released to the marine environment, they are immediately subject to a wide variety of weathering processes that change the physical and chemical characteristics of the oil. The weathering processes include spreading, evaporation, water-in-oil emulsification, dispersion, dissolution, photochemical oxidation, microbial degradation, adsorption onto suspended particulate materials, sinking and degradation.

The largest activity is the uptake or incorporation of water into the oil. As oil emulsifies, it forms a stable water in oil emulsion, which can include up to 70 or 80% water. This affects the efficiency of a response (clean-up technology). For instance, a stable water-in-oil emulsion with over 50% water will not burn unless water is

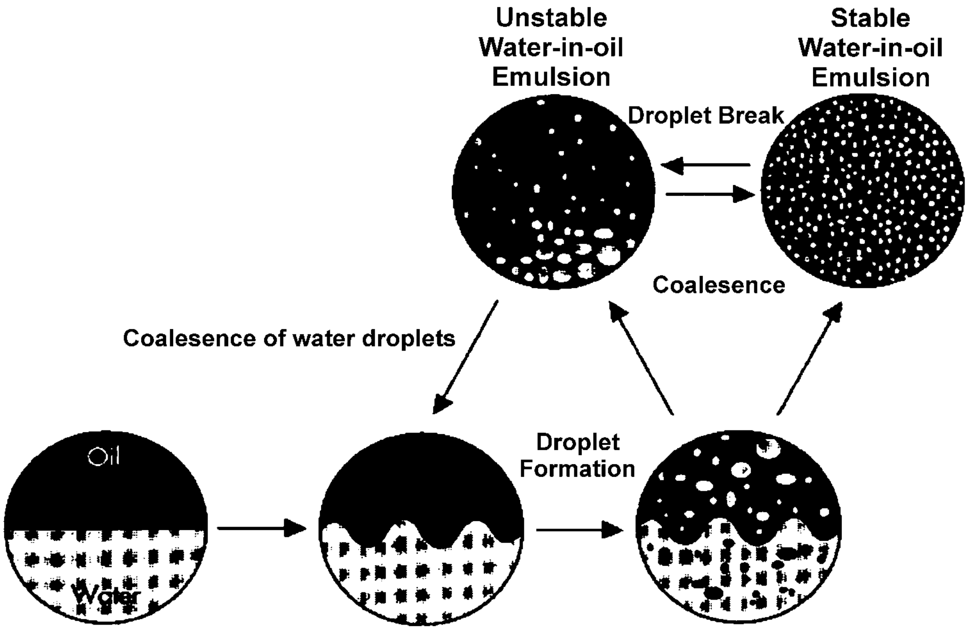

Fig. 7.1. Illustration of the formation of an emulsion as a spilled oil weathers into a stable water-in-oil emulsion which can incorporate up to 70–80% water in oil over time (Lewis and Walker, 1993; Lee, 1999).

removed by heat or an emulsion breaker. The amount of water incorporated into a stable* water-in-oil emulsion depends upon the type of oil and the environmental conditions (temperature, degree of mixing due to wave action, sea state, rain, etc) that influence the weathering of oil.

The three dominate weathering processes causing changes in oil characteristics over time are spreading, evaporation, and emulsification. They all occur progressively as oil weathers, at rates which depend on the oil composition and the prevailing environmental conditions (such as wind speed, waves, mixing, sea state, seawater and air temperature). Spreading reduces oil thickness, and evaporation increases flash point, pour point, density, and viscosity. In addition, emulsification significantly increases the viscosity of spilled oil and reduces the differential density of seawater and oil residue emulsion, which can reduce the reserve buoyancy of oily sorbents.

In the US, the USCG was focusing on obtaining what would subsequently be called **Best Response** given weather and available equipment, people, and technologies (see Section 2.3 of this book). In contingency planning, massive warehouses were being developed to have oil spill response technologies, equipment and supplies as close as possible to potential sites of spills to expedite the response. At the Marine Spill Response Corporation (MSRC), projects lead by Atle B. Nordvik in Research

* When the droplet size in emulsified oils have reached a small enough size so that the forces of gravity do not naturally separate them, the emulsion is termed stable.

and Development were trying to calibrate weathering of oil against the effectiveness of a given technology. The researchers realized that efficiency of a given technology was not only linked to operator efficiency but also to the stage of weathering that the spilled oil had undergone.

This led Nordvik (at MSRC R&D) to fund standardized testing protocols that could be used in the field to measure the degree of weathering or emulsification of spilled oil in equipment (technology) performance tests (Nordvik et al, 1992, 1993, 1994, 1995). As the IKU models were verified through mesoscale (Singsaas et al., 1992) and field-testing (Lewis et al., 1998a, b) and more oils evaluated, it became apparent to Nordvik that time periods of effectiveness could be predicted for a given spilled oil. These time periods could be correlated to the performance effectiveness data of a given technology to provide the necessary data to make it possible to predict the most appropriate time periods to utilize a given technology following a spill (Nordvik et al., 1993).

This led to the development of the "Technology Windows-of-Opportunity Concept" with a direct scientific and engineering technical basis for oil spill contingency planning and decision making for response (Nordvik, 1995; Nordvik et al., 1995a, b, c; Champ et al., 1997a, b, 1998; Champ and Ornitz, 1999). The delineation of these windows then facilitates the optimization of different response technologies and strategies. This optimization is the basis for Best Response (see Sections 2.2 and 2.3 of this book).

The concept utilizes technology performance effectiveness data of a given technology derived from scientific and engineering laboratory, mesoscale, and experimental field studies. In this approach, performance effectiveness data have been correlated to a wide range of viscosities of different weathering stages of oils into a dynamic oil weathering database to identify and estimate time periods, called "technology windows-of-opportunity".

In these windows, specific response methods, technologies, equipment, or products are more effective during clean-up operations for specific oils as influenced by different degrees of weathering under a range of environmental conditions. Figure 7.1 is presented to illustrate the formation of an emulsion as a spilled oil weathers. Combining spill trajectories with natural resource maps and sensitive environmental areas to the windows approach will provide a significant improvement in planning and response.

Evaporation and emulsification are the two dominant processes that cause changes in oil characteristics. Both significantly increase the viscosity of spilled oil. Evaporation of the more volatile components and the formation of a water-in-oil emulsion during weathering occur simultaneously during and after a spill. Emulsification is the incorporation of water into oil and not visa versa (see Figure 7.1).

The relationships between these physical factors and the changes in key properties during weathering and the effectiveness of specific response technologies under these conditions needs to be well understood in order to estimate and delineate windows-

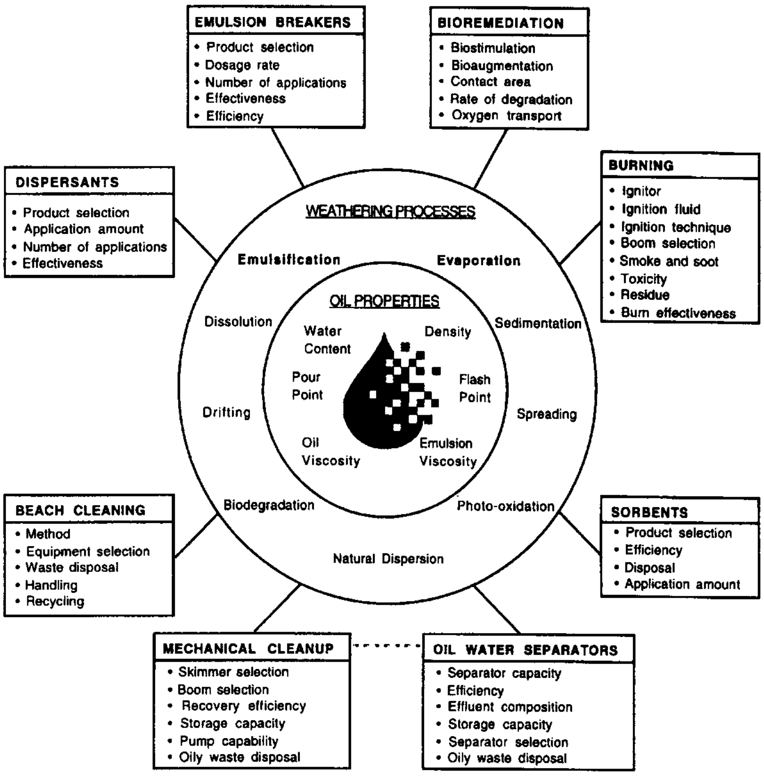

Fig. 7.2. Oil weathering processes impacts the effectiveness of selected technologies for oil spill response.

of-opportunity for specific clean-up methodologies and technologies. Maximum environmental and cost benefits in implementing response strategies are achieved when responders choose tactics and technologies to fit the windows-of-opportunity for each technology.

In Figure 7.2, an illustration of the technology windows-of-opportunity concept is presented that was first published in Nordvik (1995) to identify the properties of oil and how the oil weathering process impacts the effectiveness of selected technologies.

7.0.3. IKU Oil Weathering Model and Technology Performance Databases

Collecting oil weathering data at sea during an open ocean oil spill has many limitations including a rapid "standardized" field measurement method, variation to relative position to the discharge, relative position in the slick (downstream, or across the plume) and sea state at the least. This has led to the development of oil weathering models based on data collected from laboratory, mesoscale and field studies. Mullin and Lane (2000) have discussed the pros and cons of these test strategies relative to testing, calibrating and evaluating the effectiveness of marine spill response technologies and equipment (see box below).

Marine Spill Response Equipment Testing comes in three sizes and capabilities:

(1) **Laboratory**—Bench Top Testing or Modeling—with maximum control of selected test conditions over environmental conditions, providing a high degree of precision, sensitivity and reproducibility for data, information, and understanding of processes involved.
(2) **Mesoscale**—Outdoor Environmental Testing—is a system simulating environmental conditions with a limited range of controls and conditions, offering repetitive evaluation of full scale equipment or technology performance under repetitive test conditions to determine variability of performance.
(3) **At-Sea Trials**—Open Ocean Testing with minimum experimental controls and control of environmental conditions and exposure to maximum natural variabilty and number of variables, providing maximum verification.

Environmental equipment and technology testing is usually considered a three-step process. Results from all three are used to redesign and or develop new technologies. Data and information from each step of testing are used to refine a product. Success in the laboratory or modeling usually leads to onshore mesoscale testing (wave tank), which is considered a screening test or first real equipment performance test because actual (either full size or to scale) equipment can be tested. Mesoscale tank testing of actual equipment is highly desirable because it is less expensive than offshore testing and has far less environmental impact and offers a range of environmental and experimental controls that are not available offshore. Equipment or technologies failing at this test level will not be tested offshore. Offshore testing is considered the final test for verification. For final product marketing, at sea testing is more valuable than tank testing, because most tank testing have limitation on wave heights (max 1.0 m), sea states or environmental conditions that it can generate. Since many oils spills are associated with storm events and high sea state, at sea testing is considered final verification of both equipment and support personal performance and requirements.

To enhance the effectiveness of clean-up operations, decision makers need rapid and accurate tools for predicting changes in oil properties, and a dynamic database containing data and information on the capabilities, capacities, effectiveness, and limitations of response technologies and methodologies (Engelhardt, 1994). These databases will lead to the development of oil weathering models to predict the change in weathering over time as related to environmental conditions (salinity, temperature, waves, wind, and sea state).

Models have been developed to predict oil weathering, trajectory, and dispersion for use in contingency planning and response decision making. Their reliability and operational output values have greatly improved over the past several years. This progress is a result of advances in model development, data quality and quantity (Nordvik et al. 1992; Yapa et al., 1997; Reed et al., 1999; Reed, 2000) and the papers and references cited in these special volumes of *Spill Science & Technology Bulletin* that were dedicated to modeling. In addition, an excellent summary is presented in McCay (2001). However, to predict changes in oil properties and weathering over time, a dynamic database containing information on the physical and chemical properties of weathered oil is required.

The approach developed for the windows concept combines data from an Oil Weathering Model (Aamo et al., 1993) developed by IKU in Norway with a technology performance database to predict changes in performance characteristics over time and a wide range of environmental conditions. The oil-weathering model has been calibrated by an empirical approach using data obtained from laboratory analyses, oil data derived from a comprehensive stepwise weathering test procedure in flume tank testing, and experimental spills at sea.

The experimental results lead to subsequent development and modification of algorithms and use of correlation factors for individual oils to allow for the prediction of the response curve for a selected property (evaporation, emulsion viscosity, pour point, etc.) of an oil as it weathers over time, see Figure 7.3 (from Strøm-Kristiansen et al., 1993a). The strength of the IKU model lies in its use and verification of oil weathering data (Strøm-Kristiansen et al., 1993b).

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7.1. Examples of Technology Windows-of-Opportunity

The delineation of technology windows-of-opportunity for a given technology requires: (1) the integration of environmental and technical data and information to provide a scientific and engineering foundation for rapid decision-making in oil spill planning and response. This process will optimize environmental and cost benefits by the selection and use of different oil spill response technologies and methodologies at the most appropriate time periods. The concept utilizes the following datasets: (1) dynamic oil weathering data for selected oils; (2) actual environmental data; and (3) dynamic performance data of oil spill clean-up technologies.

Changes in oil properties as a function of time can be measured by use of the Step-Wise Oil-Weathering Laboratory Method (see Section 7.0.1 of this book). This weathering method determines changes in evaporation, density, viscosity, pour point, flash point, and emulsification at different degrees of distillation, (weathering) representing different time intervals of spilled oil. Recent studies have found that the time

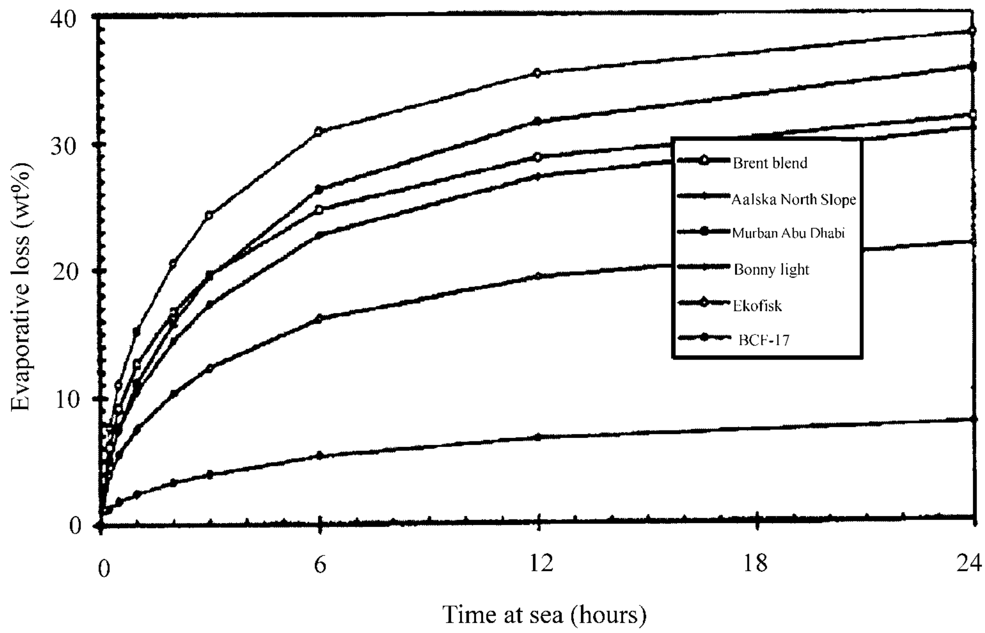

Fig. 7.3. IKU Oil Weathering Model predictions for the degree of evaporation as a function of time at sea for selected crude oils. Predictions have been calculated at 5 m/s wind speed and with a water temperature of 15 °C.

period available for response within a window-of-opportunity will vary with environmental conditions, oil type, and the degree and rates of changes in oil properties (Nordvik, 1995).

The two dominant processes that cause changes in oil characteristics over time are evaporation and emulsification, which significantly increase the viscosity of spilled oil. In this book, viscosity is used as a time period reference for estimating the window-of-opportunity for different oil spill response technologies. These technologies include in-situ burning, dispersants, mechanical recovery equipment and sorbents. Density is used as a time period reference for density differential oil water separators and emulsification (water content) is used for booms and in-situ burning.

Evaporation of the more volatile components and the formation of a water-in-oil emulsion during weathering occurs simultaneously during and after a spill. The rate and extent to which they proceed depends on the chemical composition of the oil and prevailing environmental conditions (such as wind speed, seawater and air temperature, and sea state).

An example of estimated technology windows-of-opportunity in hours for selected technologies and for indicated specific oils that data are available for is presented in Table 7.1 (from Nordvik, 1995). These windows are presented as a comparative example of the uniqueness and specificity of the technology windows-of-opportunity concept for selected oils, response methods and technologies under given environ-

Table 7.1

Summary of estimated windows-of-opportunity for selected marine spill response technologies for specific oils under certain environmental conditions. The oils are Bonnie Light, Alaska North Slope (ANS), BCF 17, and BCF 24. The environmental conditions include a wind speed of 5 m/s with a seawater temperature of 15 °C. Windows-of-opportunity have been estimated for the indicated technologies and oils.

Technology/oil	Bonnie Light	ANS	BCF 17	BCF 24
In-situ burning	0–1	0–36		
Oil-water separator	0–24	0–18		
Disk skimmer			0–10	0–72
Brush skimmer			0–10*	0–72*
			>10	>72
Dispersant	0–4	0–26		
	4–8*	26–120*		
Sorbent			0–36	0–12
			36–96*	12–240*

* = Reduced effectiveness.

mental conditions as determined by relationships of physical and chemical properties data from the IKU Oil Weathering Model (Nordvik, 1995).

7.1.1. Dispersants

The early research on dispersants has been summarized in several documents (API, 1986) and by the Committee on Effectiveness of Oil Spill Dispersants (NRC, 1989) and the references therein. In addition, many dispersant papers have been published in the Proceedings of the International Oil Spill Conference (IOSC) and the some 23 published proceedings of the Arctic and Marine Oilspill Program (AMOP) Technical Seminars. At the 1997 International Oil Spill Conference, a special summary was prepared by Lewis and Aurand (1997) on “Putting Dispersants to Work: Overcoming Obstacles.” Dispersants have suffered limited acceptance as a spill response technology by being considered another chemical that would be added to the marine environment during an oil spill. The operational limitations of dispersant applications are dependent on:

- Application methods;
- Equipment;
- Average droplet sizes of the dispersant;
- Environmental conditions (such as wind speed, sea state, salinity; and temperature);
- Oil thickness and dosage rates; and
- The distribution of oil, on-the-sea-surface, at the point of application.

Table 7.2

Estimated dispersant time windows-of-opportunity for dispersibility of ANS and Bonnie Light emulsions if treated with Corexit 9527® based on emulsion viscosity data as developed from the IKU Oil Weathering Model for 5 m/s wind speed and 15 °C seawater surface temperature.

Oil	Viscosity (cP)/(hrs)		
	Dispersible	Reduced dispersibility	Not dispersible
ANS	<1000/(<26)	1000–10,000/(26–120)	>10,000/(>120)
Bonnie Light	<500/(2)	500–2000/(2–4)	>2000/(>4)

The use of a dispersant is considered to be a rapid response method and has the potential to greatly enhance the degree of natural dispersion. Dispersants also have logistical advantages compared to contained in-situ burning and mechanical clean-up. For example, there is no waste to process from the use of dispersants. Effective use of dispersants for some oils is very limited in time. A dispersant can be applied in relatively high sea states (with low wind) as long as the plane can fly and the dispersant can be sprayed and reach the surface of the slick. Four factors have a major impact on the effectiveness of dispersants:

- Pour point;
- Viscosity of the oil and emulsion;
- Emulsion water content; and
- Emulsion stability.

Most crude oils and heavier refined products will form emulsions. Weathering causes an increase in the viscosity of oil, raises its pour point, and increases the water content and the degree of stability of an emulsion. All of these changes tend to make oil less dispersible as the viscosity of the oil or emulsion approaches its limiting value. The value of this limiting viscosity depends on the type of the spilled oil and the prevailing environmental conditions.

For a given oil emulsion, dispersant treatment windows-of-opportunity can be estimated by combining emulsion viscosity data from dispersant effectiveness testing data with IKU Oil Weathering Model prediction of emulsion viscosity as a function of time, see Figure 7.4 (Strøm-Kristiansen et al., 1993b).

The data presented in Table 7.2 identify three windows of defined dispersibility as defined from the MNS and IFP test criteria. Comparative data for ANS and Bonnie Light have been extrapolated from Figure x type plots and presented in Table 7.2 to identify the estimated time windows for dispersibility for the three defined dispersant windows-of-opportunity categories (dispersible, reduced dispersibility, and non-dispersible) from the MNS and IFP test criteria for Corexit 9527®.

Laboratory effectiveness results for dispersants can not be directly transferred into performance data during spill response, due to limitations in laboratory test methods

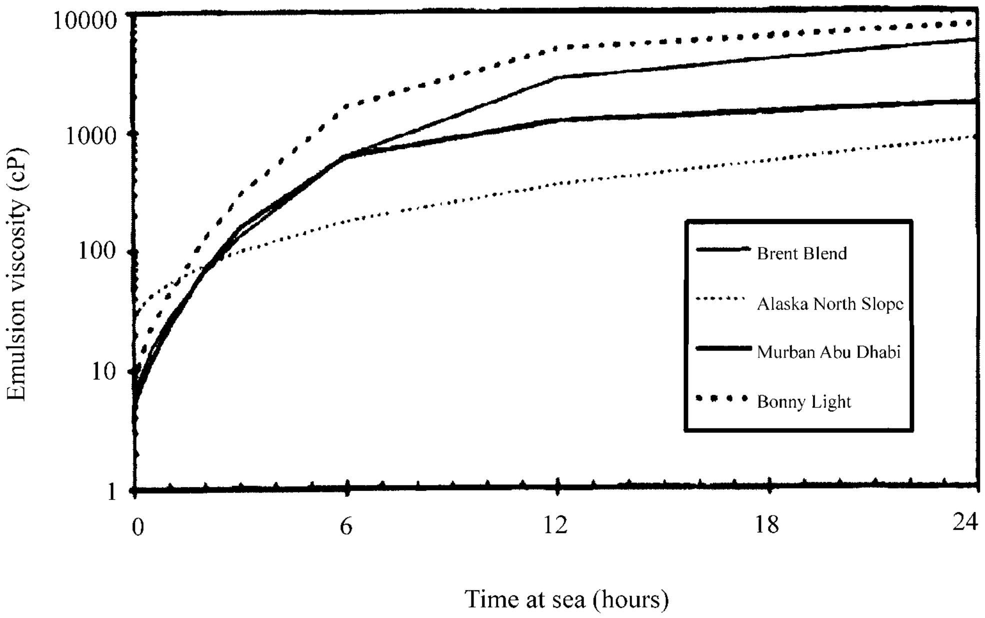

Fig. 7.4. A plot from the IKU Oil Weathering Model of viscosity over time for Bonnie Light emulsions at 5 m/s wind speed and with a seawater temperature of 15 °C.

to mimic environmental conditions at sea and the lack of field operational effectiveness data. However, laboratory results are of value for guiding the selection of an appropriate dispersant during contingency planning and response. Recent dispersant field-testing has established a ranking between laboratory and field effectiveness data for good, medium and poor dispersants (Lunel et al., 1995).

7.1.2. In-Situ Burning

A good source of background information relative to in-situ burning, is the Proceedings of a Workshop held in New Orleans by NIST (National Institute of Standards and Technology) and MMS (Minerals Management Service), Walton and Jason (1998) and a recent publication by Environment Canada (Fingas and Punt, 2000) which is an extensive overview of the science of burning. In addition a paper by Nordvik et al. (In Press), is a review of the processes and factors for estimating time windows for in-situ burning at sea. The interest in using in-situ burning as a spill response technology is related to its ability, if implemented at the start of a spill, to greatly reduce the volume of spilled oil.

The window-of-opportunity for ignition and burning will vary, depending on environmental conditions, physical properties and chemical composition of the spilled oil. The rate of evaporation and emulsification and the subsequent changes in flash point, viscosity, water content, and stability of an emulsion have a major influence on ignition technologies and the usefulness of in-situ burning. In addition, sea temperature, wind speed, thickness of the oil layer, heat transfer from the burn to the surface of the oil or emulsion, and the loss of heat through the oil to the underlying water limit the use of in-situ burning as a response method (Guénette et al., 1994). The removal effectiveness under experimental conditions has been reported from 0% for evaporated and emulsified oils up to 99% for fresh oils.

The method of calculating in-situ burning effectiveness is based upon a volumetric reduction of oil from a closed system. In comparing data for burning operational effectiveness using a fire resistant boom with mechanical or dispersant operational effectiveness data, one must consider the loss of oil from the towed boom system. Under environmental and operational conditions loss can vary widely (Nordvik, 1995). The release of soot and smoke can account for 10–15% of the removed mass of oil (Fingas et al., 1996a, b; Walton et al., 1994, 1995; Wang et al., 1999.)

The preliminary and valid arguments for considering in-situ burning are that it extends the options for response by providing a useful supplemental tool, while decreasing the dependency on recovered oil and water storage needs. The latter remains a limiting factor for large catastrophic spills, especially for response technologies built for vessels of opportunity.

In addition, in-situ burning may protect the environment, wildlife resources, and human health and safety by removing oil quickly and effectively from the sea surface. In-situ burning can be considered a viable oil spill response method, only if data on ignitability for fresh and weathered crude oils and refined products are available to estimate the time window-of-opportunity in contingency planning and response. Appendix V is a draft manuscript developed by Nordvik, Champ and Bitting for the USCG that focuses on the science of in-situ burning and prepares a case example of the steps that one would undertake to estimate the time windows to in-situ burn a spill of Alaska North Slope (ANS) oil.

For in-situ burning, this requires the development of an ignitability database, based upon basic physical and chemical processes of weathered oil. It is pointless to consider the use of in-situ burning as a response in circumstances where it will not be feasible, such as where the oil will not burn. Several groups of key factors determine the success of an in-situ burning operation.

The first group is related to *flammability* and *ignitability* of floating oils and are tied to:

- Oil composition and molecular weight;
- Vapor pressure, flash point, boiling point and evaporation rate; and
- Sea temperature and air movements (wind).

The second group is related to the *changes in oil properties* due to oil weathering during the response time, defined as the time from the onset of the spill to ignition.

Weathering processes that have great influence on ignitability and effectiveness of in-situ burning are evaporation and emulsification.

The third group contains operational and technical considerations, and includes the capability of the resources (vessel and booms) to contain and thicken floating oil, durability of fire-resistant booms and the capabilities of the ignition source to elevate the oil surface temperature to the fire point temperatures where ignitable vapor–air mixtures can be developed.

Use of in-situ burning require knowledge and understanding of the basic processes that limits and leads to formation of ignitable vapor–air mixtures, and how changes in oil composition will affect ignition and sustained burning.

Ignition and combustion are dependent on the flash point and release of ignitable and combustible vapor. It is the vapor released from the oil that burns, not the oil as a liquid (Guénette et al., 1994). Thus, the mechanism for maintaining a sufficient amount of vapor for continuous burning is vital to in-situ burning. When the flash point temperature of the oil exceeds the sea temperature, the surface of the oil needs to be heated by an external source to promote the release of flammable vapor that can be ignited.

Ignition and burning is restricted by increased water content, heat transfer to the underlying seawater, viscosity and stability of the emulsion. When water-free oil is burning on the top of a layer of emulsion, the temperature within the emulsion can not exceed approximately 100 °C. A limit for ignition may also occur if the flash point of the oil is above the temperature that can be created or maintained on the surface of an emulsion.

The rates of evaporation and emulsification and subsequent changes in flash point, viscosity, water content, and stability of an emulsion have a major influence on ignition technologies and the usefulness of in-situ burning. In addition, sea temperature, wind speed, thickness of the oil layer, heat transfer from the burn to the surface of the oil or emulsion, and the loss of heat through the oil to the underlying water limit the use of in-situ burning as a response method. Estimated in-situ burning windows-of-opportunity for several oils are plotted in Figure 7.5 utilizing water content and flash point as a function of time to present the difference between oils. Estimates have been made at 5 m/s wind speed and with a seawater temperature of 15 °C using data from the IKU Oil Weathering Model. Oils in the bottom 1/3 of the graph can be highly flammable, the next 1/3 will burn and the last 1/3 are above the flash point.

7.1.3. Mechanical Clean-up Technologies

The windows-of-opportunity time periods that exist for use of mechanical clean-up response methods and technologies can be based on two different variables. The first is related to the changes in oil properties (weathering over time), and the second is related to environmental conditions due to limited maneuverability, operability, and capabilities of resources, techniques, and equipment. Both are dependent on environ-

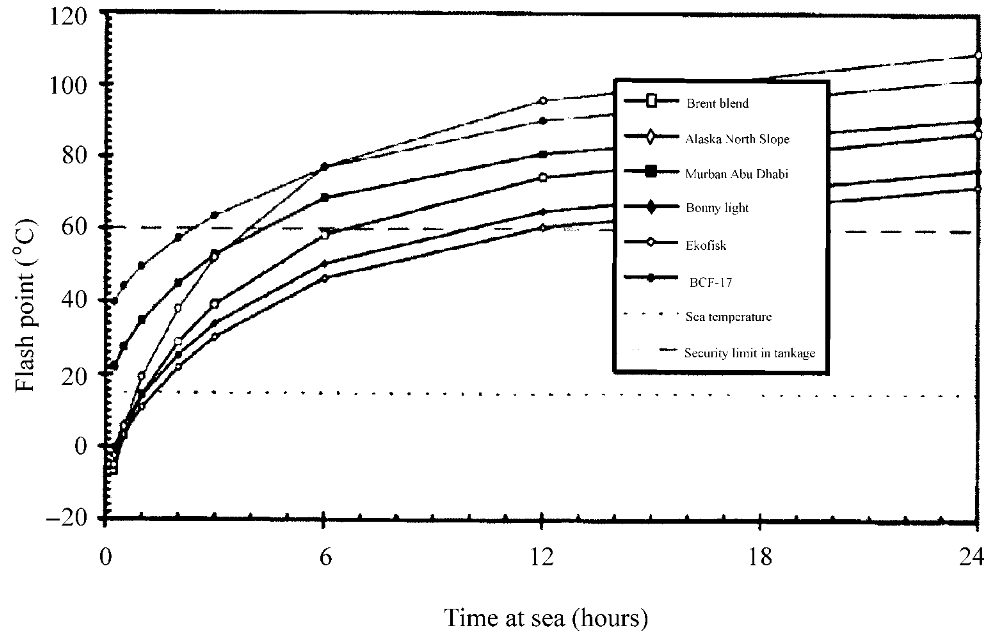

Fig. 7.5. IKU Oil Weathering Model predictions of flash point as a function of time at sea for selected crude oils. Predictions have been calculated at 5 m^{-1} wind speed and with a seawater temperature of 15 °C.

mental factors such as wind speed, currents, visibility, sea state, and air and seawater temperatures. Nordvik (2000) is a review of field testing with data and results from over 10 years of study in the development of the Transrec Oil Recovery System. This study demonstrates how the windows concept was utilized to refine the design of test prototypes to provide wider windows of opportunity. In doing so, the weather-window for mechanical recovery operation was increased from 1.5 to 3 m significant wave height.

The effectiveness of mechanical (i.e., booms, skimmers, oil-water separators, and sorbents) clean-up operations in the marine environment will vary depending on selection of skimming principles, oil properties, environmental conditions, response time, platforms, equipment used, drift, spreading, type of oil, level of training, education, organization and management of clean-up operations, and use of resources. The time window for mechanical technologies is not as sensitive to the changes in oil properties as it is for in-situ burning or use of dispersants and/or chemical agents.

- The effectiveness of mechanical clean-up can be separated into three main categories: the first is related to skimmer effectiveness only;
- The second is the system effectiveness that includes vessel, skimmer and boom; and

- The third is the operational mechanical effectiveness (OME), defined as the relationship between oil recovered and oil spilled.

Users of mechanical oil recovery systems during experimental spills over the past 10 years have reported system effectiveness data that typically range between 60–95% efficiency (vessel, boom and skimmer) and 65–95%, for operations in wind speeds up to 20–25 knots and significant wave heights up to 2.5 m (Nordvik, 1987).

Vital boom characteristics that affect wave conformance are:

- Flexibility of boom material;
- Stabilization weight;
- Distribution of longitudinal forces;
- Vertical and horizontal flexibility of the body; and
- Reserve buoyancy to weight ratio (B/W).

To optimize the operational capacity and effectiveness of skimmers, the skimmer and the boom need to be integrated into a system so as to increase oil thickness and maintain the flow of oil to the skimmer head. For effectiveness of oil-water separators, the windows-of-opportunity is defined by a series of factors, depending on skimming principles: changes in differential density between water and oil/emulsion, oil thickness, debris, viscosity of the oil and emulsion, water content and stability of the emulsion, interfacial tension between oil and water, level of turbulence within the skimmer, oil droplet sizes, the resident time of the oil inside the separation unit, and environmental conditions.

Users of mechanical oil recovery processes during experimental spills over the past 10 years have reported system effectiveness data (vessel, boom and skimmer) that typically are in the range between 60–95% in wind speeds less then 20–25 knots and significant wave heights below 2.5 m.

The practicality of operations are also limited by daylight hours and reduced visibility. Remote sensing technologies and use of a real-time downlink connection that provides a real image of the spill situation to the oil recovery vessels, will improve the effectiveness of an operation and extend the window-of-operations by providing vision, day, night and during periods of reduced visibility, for location of slick and thicker areas (Nordvik, 1990).

7.1.3.1. Booms

The window of opportunity where boom technologies are most effective have been found to be related to towing operations, environmental conditions, boom characteristics, and oil properties. For oil properties, water content and viscosity impact boom effectiveness (reduced oil loss rate from a towed boom) more severely. Vital characteristics of booms that affect wave conformance are flexibility of boom material, stabilization weight, distribution of longitudinal forces, vertical and horizontal flexibility of the body, and reserve buoyancy to weight ratio (B/W). The flexible structure incorporated into the design of the Barrier Boom TM (Svendsen, 1994) is an example of these characteristics. Studies in the North Sea (NOFO, 1989) have found that as viscosity of emulsions reaches 1000 cP s-10 (increased water content), the net loss of pure oil from towed booms is reduced. Estimated time windows-of-opportunity for booms are presented in Table 7.3 for ANS and Bonnie Light emulsions.

Table 7.3

Estimated time windows-of-opportunity for minimum loss of oil from booms for ANS and Bonnie Light emulsions.

Oil	Time to reach 1000 cP @ S^{-10}	Time to reach max. water content	Least effective	Most effective
ANS	26 hr	120 hr	<26 hr	>120 hr
Bonnie Light	3 hr	6 hr	<3 hr	>6 hr

7.1.3.2. Skimmers

To optimize the operational capacity and effectiveness of skimmers, the skimmer and the boom need to be integrated into a system. This integration is necessary to maintain increased oil thickness and the flow of oil toward the skimmer head. The effectiveness is influenced by: changes in oil characteristics; choice of skimmer technology and engineering design; the use (including placement) of selected boom technology; environmental conditions; and the responder's operation of the equipment.

The window-of-opportunity for use of skimming equipment, related to changes in oil properties, is the widest among the three primary response methods. The window is dependent on the rate of evaporation, emulsification, the subsequent increase in the viscosity, and their effect on the various skimming principles such as disc, belt, brush, mop, drum, and weir. Table 7.4 presents the estimated time periods of the window-of-opportunity for use of disc and brush skimming principles, using viscosity data of BCF 17, BCF 24 crude oils over time. It is noted that for BCF 17 that the window-of-opportunity for maximum effectiveness for disk skimmers never opens because the viscosity of the fresh oil is above 2000 cP.

Table 7.4

Estimated windows-of-opportunity (most and least effective time periods) for two skimming principles. The windows are based upon the results of tank tests for skimmer capacity and effectiveness at different viscosities correlated to viscosity data from the IKU Oil Weathering Model.

	Disk	Skimmer	Brush	Skimmer
Oil	Most effective 200–1000 cP	Least effective 4000–10,000 cP	Most effective 400–1000 cP	Least effective 10,000 + cP
BCF 17	Not open	3–10 hours	0 hours	10+ hours
BCF 24	0–4 hours	2–3 days	1 hour	3+ days

7.1.3.3. Oil-Water Separators

The window-of-opportunity and the effectiveness of an oil-water separator will vary widely, from pure water to pure oil. It is defined by a series of factors: skimming principles; oil thickness; by debris; the difference between the density of the oil/emulsion and seawater; viscosity of the oil and emulsion; water content and stability of the emulsion; interfacial tension between oil and water; level of turbulence within the skimmer; oil droplet sizes; the resident time of the oil inside the separation unit; and environmental conditions (Nordvik et al., 1994).

Capacity will vary depending on the selected skimmer system. In general, separators perform better when skimmer capacity is low and the oil content in the oil water mixtures is less than 40–50%. A skimmer with an effectiveness higher than 40–50%, used in line with a separator (as a system), may cause a drop in the effectiveness of the separator. If the skimmer and separator are not well matched, it may result in more water being discharged through the oil effluent storage line (with water being added to stored oil) and therefore cause more frequent transportation and discharge operations, less time for skimming, extended time of a clean-up operation and higher clean-up and disposal costs. Separators utilizing the principle of differential density of fluids are particularly sensitive to the changes in the density of spilled oil. The increase in density is dependent on evaporation, emulsification and the salinity and the water content of the emulsion, which can reach a level of 70–90%.

The window-of-opportunity for oil-in-water separators can be estimated for example using a differential density of 0.025 g/ml between seawater and an oil emulsion. (See Table 7.5.)

Table 7.5

Window-of-opportunity for a selected centrifugal separation unit as related to density of emulsions. Data were developed from the IKU Oil Weathering Model.

Oil	Density seawater (g/ml)	Density emulsion (g/ml)	Time (hrs)	Viscosity (cP)
ANS	1.020	0.995	18	6000
Bonnie Light	1.020	0.995	24	8000

7.1.3.4. Sorbents

Sorbents are used as a mechanical method for cleaning up oil spills in the marine environment, by either absorption or adsorption. Adsorption capacity is a function of the amount of surface area upon which the oil can adhere and the oligophilic properties of the sorbent. Absorbents soak up oil like a sponge, and the capacity is more of a function of the porosity of the material. Viscosity, stickiness, stiffness, and adhesion properties of the oil are believed to be the most important factors that influence the effectiveness of sorbent materials. Sorbents were among the first oil spill response technologies, from a rag being used to wipe up spilled oil, so historically this gives them the role of being a pioneer in the oil spill clean-up business. It also gives them the status of being a primitive or ancient not modern technology. This is a myth, because sorbents have been evolving since the early 70s and have become quite sophisticated. A problem for sorbents is the perception that all sorbents are pads. Sorbents are modern complex matrices that retain a liquid once exposed to the liquid. Dan Jones once described the problem that sorbents have is the Free Liquid Law, which is when a liquid that will separate from a solid under ambient pressure and temperature and therefore shall not be considered adsorbed.

The world of sorbents is made up of three categories of materials:

- Natural Sorbents (straw, peat moss, corn cobs, feathers, sawdust), they have low efficiency and maybe limited in what and how much oil you can absorb with them;
- Mineral Absorbents—clays, quarts and crystalline silica and you may have some OSHA problems with breathing fibers and/or they need to be contained in a sock; and
- Man-Made Engineered Absorbents (designer sorbents to do a specific job) may be expensive.

A problem that sorbents have is that their use can be labor and time consuming as an oil spill response technology. This is looked upon by the responder as an economic engine, for example, the responder gets paid a dollar to put out pads and then gets paid a dollar to pick them up and then a dollar to dispose of them, and the overhead that he makes from these hours may keep him in business next year when spill events occur elsewhere. The company paying for the large ocean oil spill wants a technology that may recover 20,000 gallons an hour, because it may be dealing with thousands of barrels of spilled oil.

Nevertheless, sorbents should not be overlooked and considered a primitive technology. In certain situations, they may be the most cost effective and best response. In the future, significant advances are in store, which may significantly increase the use of sorbents because they will be used as multiple use technologies, perhaps in absorbent (for wicking) and in-situ burning booms.

Effective use of sorbents is limited in time and governed by changes in oil properties. The most efficient, environmentally preferred, and cost effective spill response is dependant on the following factors: chemistry of the spilled product, quantity, location, response time, environmental conditions, and effectiveness of available response technologies (given the first five factors).

An increase in oil and emulsion density over time will significantly reduce the buoyancy difference between the spilled product and the seawater and subsequently reduce the buoyancy of sorbents. The progressive changes in density, resulting from evaporation and emulsification oil and emulsion viscosity interfere with sorbent effectiveness. Most fresh crude oils and refined products have specific gravities between

0.80 and 0.98 g/cm^3. The density will increase with evaporation and emulsification and potentially bring the density above 1. Sinking of oily sorbents with high density close to 1 is therefore likely.

A discussion of terms and definitions related to sorbent use in oil spill response is necessary. A sorbent is a material that recovers oil through either absorption or adsorption and can further be classified as reusable or non-reusable. Sorbents are defined as cleaning agents or treating agents and the oil sorbent materials generally fall into three major classes: mineral products, vegetable products and synthetic products. Mineral products include: perlite, talc, vermiculite, clay, volcanic ash, fly ash, and others.

The adsorption capacity is a function of the amount of surface area upon which the oil can adhere.

- **Adsorbents** are defined as materials in which the sorbent process is the external physical coating of a sorbent with oil and not incorporation into the material.
- **Absorbents** soak up oil, and the capacity is a function of the porosity of the material. Absorbents are defined as materials, which the sorbent process is to incorporate the oil internally into the material.

To optimize the cost effectiveness of a sorbent clean-up operation, materials that have unusually low densities, pickup ratios in terms of volume rather than weight should be considered.

The window-of-opportunity for an absorbent can be estimated from viscosity data from the IKU Oil Weathering Model. It should be noted that the viscosity limitation for effective use of sorbent is approximately 15,000 cP (Newtonian behavior) In Table 7.7, the window-of-opportunity is estimated for one type of sorbent (polyamine flakes) for two fresh oils. The two fresh oils, have the following respective viscosities 180 cP (BCF 17) and 2,000 cP (BCF 24), when spilled. For example, 50% of the sorbent's capacity will have been achieved in 36 hours with BCF 24. In 240 hours, BCF 24 will have reached a viscosity of 15,000 cP, at this viscosity, the sorbent materials will have zero capacity to adsorb this oil (see Table 7.6).

Table 7.6

The estimated window-of-opportunity for the absorbent polyamine flakes from viscosity performance data combined with viscosity data from the IKU Oil Weathering Model.

Oil	Synthetic sorbent (polyamine flakes)			
	Viscosity range (cP)	Time to reach 15,000 cP viscosity	Time to reach 50% saturation	Max. capacity saturated g oil/g sorb.
BCF 24	180–15,000	240 hr	36 hr	54 (180 cP)
BCF 17	2000–15,000	96 hr	12 hr	40 (2000 cP)

7.2. Universality of Application

The application of windows as a scientific and engineering planning and decision-making tool for marine oil spill *contingency planning*, *education*, *training*, and *response*, is not difficult but specific data are required as discussed in the above sections. It requires integration of performance effectiveness data for oil spill response technologies derived from laboratory, mesoscale, and experimental field studies, with real-time environmental data. The performance effectiveness data must be correlated to a wide range of viscosities of different weathering stages of tanker transported oils into a dynamic oil weathering database. This will allow for one to identify and estimate time periods that are the windows of opportunity of maximum effectiveness for a given technology, depending on environmental conditions and the degree of weathering. In these windows, specific response methods, technologies, equipment, or products are more effective during clean-up operations for specific oils. The major contribution of the "windows" concept is to create significant environmental and cost benefits in oil spill response.

7.2.1. Future Data and Information Needs for Application

- Identify and characterize oils transported.
- Determine physical, chemical, and weathering properties for major oils transported.
- Create an oil database for general physical and chemical properties.
- Create an oil weathering database for physical and chemical properties of oils.
- Create a database for effectiveness of available oil spill response technologies stockpiled under normal range of environmental conditions.
- Develop estimated technology windows-of-opportunity for predominate oils transported under a normal range of environmental conditions (waves, winds, and for coastal and near shore seawater temperatures) from the IKU model.
- Integrate real-time tabs data into dynamic database for IKU model.
- Create a certification protocol for oil weathering data and technology effectiveness data, and develop an at sea visible—color code for calibrated and verified effectiveness of technologies (i.e., a red color means seastate 3 mm certified).

7.2.2. System Output

Application of the above databases will produce these results:

- Generic oil spill response advisories (from chemical and physical data);
- Estimated technology windows-of-opportunity for oils transported in coastal waters from general physical and chemical properties database;
- Specific oil spill response advisory (from weathered predominate oils);

- Estimated technology windows of opportunity for oils transported in coastal waters (from weathered oils);
- Dynamic databases for oil, physical and chemical and weathering properties;
- Certification protocols for effectiveness of technologies;
- Review marine coastal contingency plans; and
- Windows-based education and training curriculum/program.

7.2.3. Oil Spill Contingency Planning and Response

Oil spill contingency planning and response is an extremely complex and challenging cross—disciplinary experience. In the operational decision-making system, it combines a wide range of issues and activities under emergency response conditions that include: the nature of the material spilled, which undergoes changes in physical and chemical properties (weathering) over time, local environmental conditions, sensitivity of impacted natural resources, and selection and effectiveness of response/clean-up technologies. This also encompasses emergency mobilization, marine operations and effectiveness of operations, air surveillance, remote sensing, on site and regional spill trajectory, human protection, safety assessments, oily waste minimization, handling and disposal, and education and training. Effective oil spill planning and response today requires a large amount of available data and information and the ability to rapidly process and manage this information. The technology windows-of-opportunity concept is very compatible to extensive data and information requirements. In Japan, several groups have been developing very advanced integrating data and information systems (Matsumoto, 1991; Tsukihara, 1995; Miyazoe and Hashizume, 1995), but these systems are not based on weathering of oil. It would NOT be very difficult to add windows strategy to these systems.

Planning and decision making in oil spill response requires an understanding of oil weathering processes and subsequent changes in an oils characteristics and the effect of these changes on response technologies over time. These changes have an important influence on the usefulness and effectiveness of response methods and technologies. Three major categories of response (clean-up) methods are available: (1) mechanical recovery; (2) chemical treatment; and (3) in-situ burning. Methods and technologies in each of these categories are limited by environmental conditions both operationally and as a result of the changes in oil characteristics over time. Dynamic oil weathering models have been developed to predict changes in oil properties over time and have been used as a decision-making tool in actual spill and spill scenario over the past several years in particular to assess use of dispersants (Reed and Nordvik, 1993; Reed et al., 1999; Reed, 2000). The integrated windows concept has linked changes in specific oil characteristics (weathering over time) to environmental conditions, and the effectiveness of technologies under those given conditions as a method to improve decision-making capabilities in oil spill planning, response, education and training.

Effective use of dispersants, in-situ-burning and some mechanical technologies is limited in time and governed by changes in oil properties. The most efficient, environmentally preferred, and cost effective spill response is dependant on the following factors:

- Chemistry of the spilled product;
- Quantity;
- location;
- Response time;
- Environmental conditions; and
- Effectiveness of available response technologies (given the first five factors).

Utilization of multiple response technologies requires a rapid and scientifically-based decision-making tool and an integrated system of response capabilities.

In the US, the technology windows-of-opportunity concept has the potential to require significant changes in the OPA 90 Area Contingency Plan (ACP) requirements, the National Contingency Plan (NCP), the Coast Guard Navigation Safety Regulations 33 CFR 160—Advance Notice of Arrival, and the OPA 90, and Vessel Plan (VRP) requirements. Under these requirements, It is quite possible that vessel owners will have to demonstrate that they have sufficient resources to respond to a spill geared to the characteristics and weathering properties of oil the vessel is transporting, ambient environmental conditions, effectiveness of available technologies, and its trackline. Vessel owners may be required to provide this information at least 24 hours prior to arrival. The qualified individual, QI, would be required to demonstrate he/she is aware of this information. (See Sections 2.3, 2.4, 2.5 and 2.6 of this book.)

It will be critical in future contingency planning, that a spill response plan be developed for a suite of oils transported in coastal waters, and maximize the cost benefits from the purchase and storage of the most effective appropriate equipment and technologies at sites close to the shipping lanes of specific oils.

It is expected that in the near future, that the Area Committee would be required to study all oil types transported in a region and develop worse case scenarios geared to each oil type and incorporate this information into the Area Contingency Plan. The NCP would require incorporation of this more detailed information by the Area Committees and vessel and facility owners. The concept of cascading equipment for response would need to be closely reexamined so that the right equipment and technologies were being employed at the right time. The Pollution Response Exercise Program (PREP) would also have to be geared to this higher level of knowledge. Failure to account for the employment of the most effective—optimal technologies as a function of oil type and weathering (time) by the On-Scene Coordinator (OSC) and state officials, could place the federal and state governments at risk of lawsuit for negligent management, from the environmental community, vessel owners and insurers.

7.2.4. Education and Training Tool

Education and training programs are needed for all parties involved in oil spill response, which would cover:

- The basic science and engineering knowledge involved in the windows concept;
- The science and engineering knowledge involved in the design and development of equipment and technologies;
- An understanding of the changes in oil properties, physical and chemical processes involved; and
- The effects of changes in oil properties on spill response and technologies.

Specific training programs should be developed to maximize the experience and capability to utilize the windows concept on a local or regional basis. For example, for coastal waters, spill response contingency plans, equipment and technology, and training programs could be tailor made for the dominant oils that are transported to refineries providing a greater degree of protection, a faster and more effective spill response, minimize environmental impacts, all at significant cost savings. Basically the windows approach eliminates the need for the security and expense of the shotgun approach (which covers all bases) and replaces intuition with science in the spill response decision-making system.

In addition, and equally as important, this system allows for all management personal to communicate the critical scientific, engineering and reasoning aspects that underlie the decision-making system to everyone involved (from operations to the public and private sectors), which in turn can be evaluated on an equal basis by all parties. (See Section 2.3 of this book.)

7.3. Required Databases

The following data and information needs have been identified as required databases to better define the capabilities and estimate the technology windows-of-opportunity for spill contingency planning and response for Coastal Waters (Nordvik, 1995):

- Dynamic databases for oil, physical and chemical and weathering properties.
- Certification protocols for effectiveness of Technologies.
- Estimated Technology Windows Of Opportunity For Oils Transported in marine coastal waters (from weathered oils).
- Reviewed marine coastal contingency plans.
- Windows-based education and training curriculum/programs.

7.3.1. Transported Oils Database

- Identification and characterization of oils transported in coastal waters.
- Creation of a database of the actual fresh crude oils as well as refined oil products shipped in coastal waters for physical and chemical properties.

- Implementation of the IKU oil weathering testing methodologies for actual fresh crude oils as well as refined oil products shipped in coastal waters as an international standard method for laboratory oil weathering studies.

7.3.2. Technology Effectiveness Database

- Creation of a database for effectiveness of available oil spill response technologies for emulsified oils: dispersants, sorbents, and skimmers in both calm seas and high sea states.
- The creation of a database of for effectiveness of different technologies stockpiled (available) in the coastal waters
- The linkage of a dynamic oil weathering model to a dynamic performance technology database for oils shipped in costal waters to enhance the identification and quantification by responders of the technology windows-of-opportunity for selected methodologies and associated equipment.
- Further investigations are required in order to study the effect of emulsified oils, skimmer design, and wave actions on the window-of-opportunity. Data are needed for improvement of skimmer technologies, for establishment of data to meet existing and new capacity requirements, and for new designs of skimmers for vessels of opportunity.
- Create a certification protocol for oil weathering data and technology effectiveness data, and develop an at sea visible—color coded for calibrated and verified effectiveness of technologies.

7.3.3. Development of an Oil Weathering Database

- Determine the weathering properties for major oils transported.
- Create an oil database for general physical and chemical properties.
- Create an oil weathering database for physical and chemical properties of oils
- Develop estimated technology windows-of-opportunity for predominate oils transported under a normal range of environmental conditions (waves, winds, and for coastal waters temperatures) from the IKU model.
- Integrate real-time tabs data into dynamic database for IKU model.

7.3.4. Development of a Tides and Currents Database

- Collect tidal and current historical data for coastal waters
- Create a tidal and current historical database for coastal waters.
- Link historical database to real-time data from offshore oceanographic automated buoys.
- Develop an offshore oceanographic buoy system with current meters to cover the physical real-time data needs of the Windows System.

7.3.5. Development of the Technology Windows-of-Opportunity Database for Oils Transported in Coastal Waters

- Generic Oil Spill Response Advisories (from chemical and physical data).
- Estimated Technology Windows-of-Opportunity for oils transported in Coastal Waters from general physical and chemical properties database.
- Specific Oil Spill Response Advisory (from weathered predominate oils).
- Estimated Technology Windows-of-Opportunity for Oils Transported in Coastal Waters (from weathered oils).

7.3.6. Review of Oil Spill Contingency Plans in Accordance with Estimated Technology Windows

- Generic oil spill response advisories (from chemical and physical data).
- Estimated technology windows-of-opportunity for oils transported in coastal waters from general physical and chemical properties database.
- Specific oil spill response advisory (from weathered predominate oils).

7.4. Oil Spill Detection and Monitoring by Remote Sensing Advanced Technologies

Satellite imagery with selected sensors can be extremely valuable for detecting and monitoring the natural (seeps) and man-made discharge (ballast waster from ship or oil spills) occurrences of oil on the sea surface. Large-scale coverage that satellites provide can serve as an early warning system to detect and verify oil spills. A satellite placed in the proper orbit could provide nearly hourly coverage of high-risk coastal waters. Automated algorithms could automatically search the imagery for abnormal conditions locating spills or illegal discharges or dumps, serving as a coastal policing role.

The use of aerial surveillance to aid clean-up response efforts can mitigate the impact of the oil spilled as well as reduce clean-up costs (Lambert et al., 1992). Oil spilled or dumped at sea by ships can be monitored by satellites. Under favorable weather conditions, it is possible to acquire satellite observations and monitor oil slick movement occurring from natural or manmade sources (Bern et al., 1979). Oil spilled from the *IXTOC-1* Well blowout in the Gulf of Mexico (June–August 1979) was detected in images from satellite sensors such as MSS, AVHRR and CZCS (Alvarado, 1980). Also the *Kuwait Oil Spill* (Arabian Gulf, 1991) was tracked by satellite data. These were large spills in which oil was spilled continuously over a several month period. Satellites can be used for large and persistent oil spills because of their low spatial resolution (10×10 m pixel), untimely coverage and long post-processing delays.

The 1991 Gulf War produced what is estimated as the world's largest oil spill (c. 6–8 million barrels of crude oil), it was a deliberate act of war. A special issue of the *Marine Pollution Bulletin* was published in 1993 dedicated to summarize the environmental studies of the Gulf following the War (Price and Robinson, Guest Editors) Volume 27: 1–376. Photographs courtesy of NOAA Office of Response and Restoration.

Most oil spills today are smaller and occur over relatively short periods of time in near coastal waters and are relatively instantaneous dynamic events requiring quick response and decisive action to reduce impacts and costs. However, for these spills, the same sensors and systems can be utilized from low altitude aircraft to obtain spatial, distribution, and volume data about spills and for tracking spills. During and following a spill, response management needs specific data and information about the oil and its trajectory to determine priority in protecting environmental resources and to maximize the utilization of selected technologies to isolate or to separate and recover (clean-up) oil at sea rather than on land which has significantly higher total costs and environmental impacts.

Remote sensing is an increasingly important part of oil spill response and countermeasures. The public at large expects that the government and the spiller at least know the location or trajectory and the extent of the contamination. Remote sensing can help provide data and information to the legal process that will validate the extent of contamination. Clean-up personnel have also recognized that remote sensing can increase the efficiency of the spill clean-up and reduce costs by 20–30% because crews can work night and day using IR direct downlink to response ships from helicopters to locate oil at night.

Furthermore, recent advances in electronics and sensors have made instrumentation much cheaper and more effective. Despite this, the actual operational use of remote sensing worldwide lags behind the technology of sensor design. Much of this is due to a lack of a centralized response management capability rather than local authorities who may be responsible for the clean-up and lack awareness and training in remote sensing. Extensive capabilities for remote sensing as an oil spill management tool have been developed in the US, Canada, UK, Sweden and Norway.

Remote sensing technologies can provide oil spill response management with data and information for the following users:

- Response management;
- Policy and decision makers;
- Government information and documentation needs;
- Regulatory actions;
- Resource damage assessment;
- Impacts on mariculture/fisheries;
- Impact on recreation;
- Spill liability; and
- Insurance adjustments.

Several Variable Remote Sensing Systems are available on the market that integrate a series of sensors into a system that allows operators to enhance, integrate imagery and to maximize the data and information available to oil spill response management. The use of low altitude aircraft have proven to be the most cost effective and tactical method for obtaining information about oil spills. Combined with accurate oil drift computer model forecasting, these two methods were the primary strategic tools used for environmental response planning during the IXTOC-1 and Arabian Gulf spills. These systems can provide real-time displays to response management and to recovery vessels, images can be enhanced to allow extensive image analysis.

Research is needed to detect and link at sea (In-situ) weathering—emulsification of the specific spilled oil to an irradiant energy spectrum to increase the precision and timing of technology windows-of-opportunity. This would maximize the use of windows as a decision-making tool in oil spill response.

7.5. Integration of Databases and Information into an Oil Spill Response Decision-Making Tool

Oil spill response management in the past decade has evolved advanced remote and mobile systems to collect data and information and to transmit it directly from the spill to response policy and decision makers. Advances have been made in developing a series of new tools for contingency planning, response and training. These new scientifically-based tools can collect data from multiple sources, to bring together the impact of weather, sea state, wind, current and water temperature, the physical and chemical properties and characteristics and trajectory of the spill oil for identification of the time periods that specific response methods and technologies are most effective.

There is a need to develop an integrated oil spill response management advisory system that can:

- Integrate satellite and airborne remote sensing data with GIS mapping of coastal and environmentally sensitive areas and resources to identify and monitor the presence and transport of spilled oil and to direct response (clean-up) operations in real time (24 hours/day in bad weather or darkness).
- Model current, tidal and wind data to model oil transport and predict trajectory patterns for spilled oil, which can predict in advance where the oil might come ashore, allowing for greater efficiency in clean-up and protection of natural resources.
- Integrate the following data: weathering of oil; physical oceanography data (wind speed and direction, currents, water temperature and salinity); technology and equipment efficiency data for a range of environmental condition; and operations data to estimate the "Windows-of-Opportunity" for available spill response technologies.
- Integrate operations data from many different sources; and local and regional scenarios to provide response management with recommendations that can support contingency planning, training, and oil spill response management.
- The Advisory System needs to be able to integrate real-time data from advanced remote sensing systems, oceanographic physical data, with databases for weathering of different oils transported in coastal waters with databases for technology effectiveness to delineate Technology Windows-of-Opportunity to provide Best Response. (See Sections 2.2, 2.3 and 2.4, of this book.) Figure 7.6 presents an overview of the components of the Advisory System. Its value is that the system provides for an integrated cost effective and scientifically-based response.

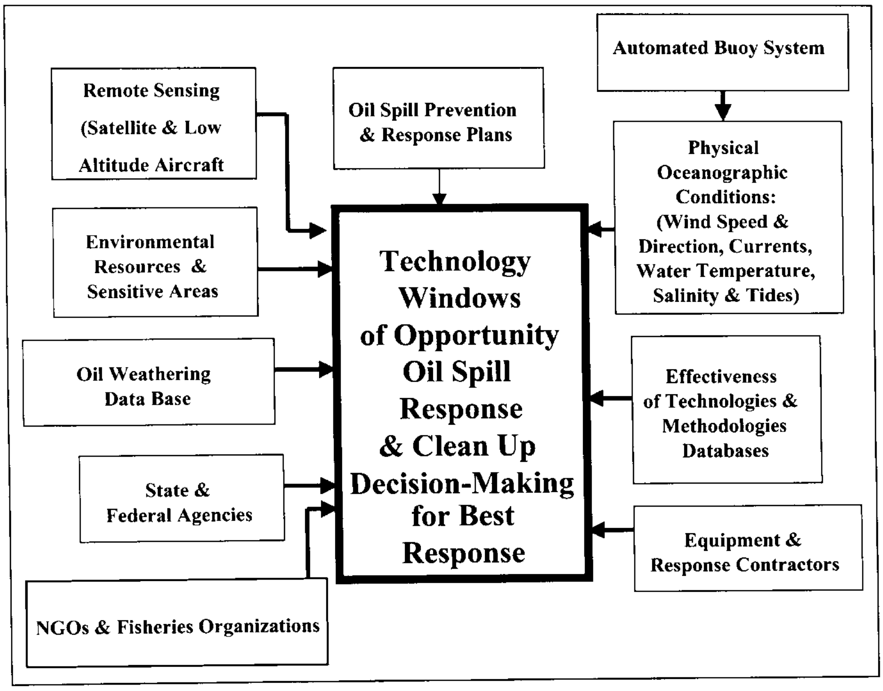

Fig. 7.6 An illustration of the technology windows-of-opportunity oil spill response management decision-making system. The system integrates real-time data from advanced remote sensing systems, oceanographic physical data, weathering of oil databases, available equipment databases with databases for technology effectiveness to delineate technology windows-of-opportunity to provide best response.

Utilization of multiple response technologies requires a rapid and scientifically-based decision-making tool and an integrated system of response capabilities. Rapid oil spill response decisions are of vital importance to mitigate and reduce environmental damage (see Sections 3.1 and 3.2 of this book). Remote sensing data have become an important factor in the decision-making process in order to determine the extent of the spill (satellite images) and level of response needed and for operational direction of resources (aircraft images) in clean-up. For dispersant and in-situ burning, decisions needs to be made immediately in order to respond within the first 2–24 hours after a marine oil spill has occurred.

Major oil spill incidents over the past decade have led to development of more specific and stringent requirements and regulations in many countries around the world, followed by establishment of response organizations using clean-up methods, ruled by governmental policies and environmental concerns. Response methods are therefore quite varied among the countries around the world, even for the same spill of oil. The ability of a spill responder to use the most effective or multiple response methods in dealing with oil spills has been quite limited.

Ideal marine oil spill response strategy and tactics should focus on the use of the most rapid, efficient and cost effective response methods and technologies including "no-action" except perhaps monitoring if the spill is well offshore and has limited environmental impact. Use of the most effective response method and technologies requires access to reliable, national and international accepted data, based upon a scientific and engineering approach. The windows-of-opportunity concept with the combined information from dynamic oil weathering model and performance technology databases can become a decision-making tool identifying and defining the window of effectiveness of different response technologies (methods and equipment) under given environmental conditions. The total costs (including environmental, social and economic) from most oil spills could be greatly reduced if such a system were available today. Most important, the response actions would be scientifically based, cost effective and stand up in the courts as indeed the Best Response.

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