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**FROM CHALLENGES TO OPPORTUNITIES:
TOWARDS FUTURE STRATEGIES AND A DECISION SUPPORT FRAMEWORK FOR OIL SPILL PREPAREDNESS
AND RESPONSE IN OFFSHORE NEWFOUNDLAND AND LABRADOR**

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From Challenges to Opportunities: Towards Future Strategies and a Decision Support Framework for Oil Spill Preparedness and Response in Offshore Newfoundland and Labrador

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by

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EXECUTIVE SUMMARY

An oil spill is a form of pollution caused by an accidental or intentional discharge of liquid petroleum hydrocarbons into the environment. It often refers to marine oil spills, where oil is released into the ocean or coastal areas, including releases of crude oil from tankers, offshore platforms, drilling rigs and wells, spills of refined petroleum products (e.g., gasoline and diesel) and their by-products, heavier fuels used by large ships such as bunker fuel, and the spills of any oily white substance refuse or waste oil. Oil spills are catastrophic, and often have significant long-term adverse environmental and socio-economic consequences.

As the major energy source worldwide, oil products have been ever increasingly produced and consumed, so is the risk of spills involved. Despite significant progress in reducing spillage through a variety of technological and regulatory measures along with improving industry practices, oil spills continue to occur. On the daily basis, hundreds to thousands of spills are likely to occur worldwide in many different types of environments, on land, at sea, and in inland freshwater systems. Multiple sources of spillage are involved, such as from tankers, offshore platforms, drilling rigs and wells, as well as through a variety of processes of transportation, refining, storage and utilization of refined petroleum products and their by-products. The reasons are also diverse including structural failures, operational errors, weather-related events, earthquakes, human negligence, and even vandalism or terrorism. The biggest contributor to oil pollution in the World's oceans (some 45%) is operational discharges from tankers, although natural seeps are considered as of great magnitude, and the single most important source of oil that enters ocean. Oil spills in most occurrences (72%) are with small scales and the overall amount of these small spills accounts for less than 1% of the total spillage. The largest spills (over 30 tonnes) rarely occur (0.1% of incidents) yet involve nearly 60% of the total amount spilled. Over the history, some major oil spills such as the Exxon Valdez oil spill in 1989 and the recent Deepwater Horizon oil spill in 2010 have captured global attentions due to the catastrophic impacts.

Oil spills are raising more concerns across the world including Newfoundland and Labrador (NL) because of the significant negative and long-term impacts on the marine environment and eventually human health, as well as the difficulties in spill prevention, control and remediation. This study has attempted to get insight of the current methodologies and technologies in oil spill response and countermeasures,

identified the existing knowledge gaps and technical challenges, and proposed a new strategic and decision making framework and provided the recommendations for improving oil spill response capacity and effectiveness in NL offshore areas. Particularly the cold weather and harsh offshore conditions in NL and their effects on oil spill response and countermeasurements were reviewed and discussed. The major research findings are summarized below.

Offshore oil spills can cause enormous economic loss and harm to ecological systems, public health, and communities. These impacts have been reviewed in this study along with a variety of factors that determine the costs of oil spills such as type of spilled oil, physical, biological and economic characteristics of spill location, weather and sea conditions, amount spilled and rate of spillage, and effectiveness of clean-up as well as complex interactions among these factors. The economic impacts to some extent can be reflected on the total amount of liability and compensational funds which were regulated according to the legislation. The socioeconomic impact can also be evaluated due to the interruption of commercial, recreational fisheries and coastal tourisms. Environmental impacts have been reviewed in terms of mortality and community deterioration of seabirds, fish, shellfishes, benthos and wetland vegetation; however, the related costs of such damages are hard to directly measure and challenges exist in cost estimation particularly considering the associated long-term effects. The public health can also be compromised due to oil spills and transference to food chains. Epidemiological studies have been reported about the relationship between exposure to spilled oils and the appearance of acute physical, psychological, genotoxic and endocrine effects in the exposed individuals. Surveys have been conducted in the oil spill affected communities and shown the increased post-spill rates of generalized anxiety disorder, post-traumatic stress disorder, and depression as well as emotionally upsets due to intrusive recollections of spills such as unexpected negative pictures and thoughts.

The oil industry and regulatory authorities at different levels of jurisdictions including Canada and Newfoundland and Labrador have established series of policies, laws, and regulations to ensure the safe and environmentally sound activities related to oil spill prevention and response. These commitments demand preparedness and continuous improvement throughout every phase of exploration and production where oil is produced, transported, stored and marketed. All regulatory regimes under study acknowledge that the speed and effectiveness of a response operation can be greatly enhanced through improved planning, training and coordination of a response system. Extraordinary coordination of international, federal, state and local resources is required for a spill. Particularly at an international level, the International Maritime Organization (IMO) is usually responsible for coordinating different countries, including the assistance of international actions. The fast development and growing exploration efforts (especially in the Arctic regions) of oil and gas industry lead to some new and more complex challenges upon the existing cumbersome legislation and implement processes as well as the unclear effectiveness of the regulations. As a result, further

studies and efforts are desired in developing more effective legislation and response strategies.

Most oil spills are accidental and thus unpredictable. Spills can happen on land or in water, at any time of day or night, and in any weather condition. Prevention is considered as the most critical area in all jurisdictions, with considerable efforts being placed to ensure the risk of a spill is as low as reasonably possible. However, once a spill occurs, the best approach for containing and controlling the spill is to respond quickly following a contingency plan and in a well-organized manner. A contingency plan (or management strategy) looks at all the possibilities of what could go wrong and details upon actual events, including the contacts, resource lists, and strategies to assist in the response to the spill. The management of offshore oil spills may appear complicated because it provides many details about the numerous steps required to prepare for and respond to spills. It also covers many different spill scenarios and addresses multiple situations that may arise during or after a spill. Despite its complexity, a well-designed contingency plan should be easy to follow and usually includes hazard identification, vulnerability analysis, risk assessment, and response actions. The plan can help minimize potential harm to human health and the environment by ensuring a timely and coordinated response. Well-designed local, regional, and national contingency plans can assist response personnel in their efforts to contain and clean up oil spills by providing information that the response teams will need before, during, and after spills. Developing and exercising the plan provides opportunities for the response community to work together as a team and establish the interpersonal relationships to secure a smooth and functioning response. It is important to study previous spill incidents to learn how the oil has affected the environment, what clean-up techniques work, and what improvements can be made, as well as to identify the gaps in technology. Because oil spill response is constantly evolving and each oil spill help generate a better preparedness for future incidents, contingency plans are thus constantly improved, ensuring enhanced protection of human health and the environment.

The ability to detect and monitor oil spills at sea is becoming increasingly important. A variety of oil spill monitoring and analysis techniques have been reviewed in this study. Vessels, airplanes and satellites are major tools to conduct on-site monitoring. Although vessels are only able to detect oil at sea within very limited area, they remain necessary for oil sampling. Satellites monitoring can be used for a first warning, and aircrafts are more suitable to be applied to identify the polluter, extent, and type of a spill. Specifically, remote sensing for oil spill includes optical sensors, laser fluorosensors, microwave sensors, and slick thickness sensors. A common passive sensor is an infrared camera or an infrared/ultraviolet system, which is economical but with the inherent weaknesses including the inability to discriminate oil on beaches, among weeds or debris and under certain lighting conditions as well as in water-in-oil emulsions. The laser fluorosensor is widely applied because of its unique ability to identify oil in a complex matrix. Equipments that measure relative slick thickness are still under development. Passive microwave has been studied for several years, but many commercial instruments are lack of

sufficient spatial resolution. In recent years, some state-of-the-art technologies have been developed and applied for on-site monitoring, such as small remote-controlled aircraft, and underwater detection and tracking, and ship-borne radar for automated detection of spilled oil. There are growing interests and research efforts in these areas particularly making them available and feasible in field implementation.

During any uncontrolled release of oil, the physical properties (e.g., viscosity, density, specific gravity, flash point, pour point, distillation, and interfacial tension) of the spilled oil and their changes due to weathering must be available to support impact assessment and response actions. Meanwhile, the fate and behaviour of the spilled oil are strongly determined by their chemistries. Oil analytical techniques are a necessary part of the scientific, environmental, and engineering aspects of oil spills. There are different methods to classify the chemical compounds present in crude oil that allows analyzing their properties. The primary method for oil analysis, as well as for many chemicals in the environment, is gas chromatography (GC). Other analytical methods are also used for oils, such as high-performance liquid chromatography (HPLC), thin-layer chromatography, and some spectroscopic techniques like infrared spectroscopy, Raman, and nuclear magnetic resonance (NMR) spectroscopy and also mass spectrometry. Recently, environmental scientists have also considered fingerprinting the diamondoid hydrocarbons as a promising forensic technique for oil spill studies. These naturally occurring compounds are thermodynamically stable, and therefore, they may have potential applications both in oil-source correlation and differentiation for those cases where the traditional markers (e.g., terpanes and steranes) are absent due to removal in the refining processes. In addition, marine biological resources are sometimes monitored and analyzed to guide response options and clean-up activities, or to assist in media and public relations management. Biological monitoring includes responses at sub-individual and individual level (e.g., physiological and epidemiological markers, biomarkers of exposure/effect and/or biological responses in ecotoxicological assays), as well as monitoring studies at population or community level (population dynamic and/or community structure parameters). In terms of habitats, monitoring may be divided into three broad habitat areas - surface water, water column and seabed.

The response strategy of oil spills involves different stages aiming at the minimization of size of the affected area and damage to vulnerable resources. This can be achieved by operations launched to contain, recover, and/or eliminate the oil on the water and near or on the shoreline. The physical/mechanical, chemical and biological technologies and equipment have been reviewed in detail from the perspectives of types, characteristics, configuration, operation, performance and limitations. Among the various physical and mechanical methods, booms and skimmers were designed in such a diverse ways, while the recommended employment for certain type and scale of oil spills along with operational requirements are not clear enough. These techniques are primarily used as the emergent responding defenses that have limited operational time-window. Chemical methods such as in-situ burning, oil dispersion, solidification and surface

washing have received growing attentions on not only the effectiveness and advantages, as well as the toxicity and biodegradability of involved materials. It is important to better understand their long-term ecological effects particularly through large-scale and/or field trials to facilitate the application in real-world cases. Bioremediation and natural attenuation are two commonly referred biological methods requiring relatively long operational time but lacking of in-depth studies on their effectiveness and enhancement under different environmental conditions. These response and cleanup methods have also been compared comprehensively in terms of mechanisms, when to use, target oils and areas, characteristic of effective products, limiting factors, waste generation, and environmental impacts. Generally the studies on biological methods are limited, while these approaches may be more environmentally friendly and cost-effective. It is also recommended that more research efforts should be made on the scale-up and real-world application of these techniques and their merits to long-term remediation as well as the suitability in harsh environments.

Considering significant impacts being caused by offshore oil spill, it is important and necessary to provide both long-term effective strategies and on-site sound decisions for offshore oil spill response and countermeasures. Mathematical modeling has played a growing and critical role in this area and the main techniques include: 1) Warning and assessment - to assess spills in an early stage and provide warning messages and levels. The current techniques are mainly based on analyzing the monitoring information such as Synthetic Aperture Radar (SAR) images and using geographical information systems (GIS) as well as statistical analysis tools. Quantitative methods such as risk-based and safety performance based assessment to evaluate impacts and indicate warning levels have received growing interests in research and practice. 2) Classification and ranking - to determine the type of a spill and the levels of warning and impacts with assistance of visual detection. Models to screen response technologies are desired particularly with the improved features with which they can more effectively incorporate dynamic information with experts' knowledge, reflect system uncertainties and complexities, and quantify intrinsic value of the environment. 3) Simulation - to model ocean hydrodynamic conditions and oil weathering processes and to forecast spill trajectory in order to provide the emergency responders with information about the state of the spilled oil and the spatial and temporal distributions of the oil slicks. The oil transport and fate in the ocean are governed by physical, chemical, and biological processes (advection, diffusion, spreading, evaporation, dissolution, emulsification, degradation, sedimentation, etc.) that depend on the oil properties, hydrodynamics, and meteorological and environmental conditions. Consequently it is challenging to accurately and dynamically simulate all these processes and the complex mathematical treatments for idealized problems sometimes are not suitable for applications to real field problems. 4) Optimization - to seek the optimal decision sets of planning and operation in oil spill response given limited resources and time. Although optimization models have been widely used to support decision making in diverse fields, limited efforts have been reported to address the decision problems in oil response planning and on-site actions. 5) Decision support systems (DSS) - to

comprehensively consider multi-dimensional factors, to integrate different modeling efforts, to evaluate alternative decision scenarios, and to help responders make response decisions in a more efficient and effective manner. Compared with the emergency responses to natural disasters (e.g., flood, hurricane, and tsunami), the research and development efforts in DSS for supporting offshore oil spill response are very limited and much desired. Particularly it is much desired to comprehensively incorporate early warning, risk assessment, spill simulation, and response optimization into a general decision making framework.

With estimated undiscovered potential of 6 billion barrels of oil, Newfoundland and Labrador (NL) accounts for about 40% of Canada's conventional light crude output with promising prospects. Increasing risk of spills in the northern Atlantic and Arctic oceans have been widely recognized due to the expansion of oil and gas industry and the openings of new transportation passages as a result of global warming. NL has a harsh environment characterized by strong wind, low visibility, low temperature, rough seas, and ice coverage, which poses unique challenges for oil spill response. For example, the waves are too strong to allow containment of oil slick with booms from October to next March. The occurrence of visibility restricted to less than 1 km could be as high as 30% from May to July. The daylight hours in winter are less than 9 hours in various areas. The water surface can experience considerable amounts of ice during the winter months (e.g., over 70% ice coverage at Labrador Shelf in February). Oil spill is more problematical in such harsh conditions because of the simple and highly seasonal ecosystems and the logistic challenges of cleaning up spills in remote regions. The low temperature will also make hydrocarbons persist, making ice-edge communities particularly vulnerable.

In the aspect of oil spill detection, numerous difficulties are encountered. For example, ice is never a homogeneous material but rather incorporates air, sediment, salt, and water, many of which may present false oil-in-ice signals to the detection mechanisms. Snow on top of the ice or even incorporated into the ice adds complications. During freeze-up and thaw in the spring, there may not be distinct layers of water and ice. There are many different types of ice and different ice crystalline orientations, making oil spill monitoring in harsh environment more challenging. Crude oils and oil products behave quite differently if spilled in the cold weather/water and harsh conditions, due to the variations of their physical and chemical properties. These properties influence the selection of techniques and equipment applicable for monitoring and sampling.

Oil spill forecasting and modeling in NL also face challenges due to the harsh environments. Oil spill models are very sensitive to errors in the initial input data, such as the details of the release and the wind and current forecasts. Furthermore, the mathematical equations used to simulate oil movement are likely based on empirical approximations and assumptions and are subject to time step and grid limitations. Trajectory model uncertainty refers to changes in the forecast as a result of these errors. Unfortunately, quantitative assessment of the errors in trajectory

modeling is difficult and limited. In addition, oil spills are notorious for usually occurring in areas where the environmental data are temporally and spatially incomplete. This leads to a forecast process that often relies on the forecaster's subjective judgment and approximated input. Therefore, it become significantly challenging in oil spill early warning and modeling in offshore NL, especially in winter. In harsh environments, it is also extremely important to respond to offshore oil spills in a timely manner, and thus requires more reliable and effective decision making schemes considering limited access time/sites, equipment and man power. Unfortunately there is still no integrated DSS to incorporate modeling processes and support offshore oil spill response in NL.

The harsh environments prevailing in NL offshore also significantly hinder the application of oil spill countermeasures and reduce the effectiveness. Presence of ice is a key factor affecting the ability to respond to a spill. The fate and behavior of oil in ice-covered waters is governed by a number of important weathering processes have a direct bearing on oil recovery operations. The physical distribution and condition of spilled oil under, within or on top of the ice plays a major role in determining the most effective response strategies at different stages in the ice growth and decay cycle. Before oil spill response plans are developed or approved, it is important to understand the chemistry and physical behavior of the oil and how its characteristics change over time in harsh environments. Spill response operations in ice and open water are fundamentally different. These variances must be recognized when determining the most appropriate strategy for dealing with oil in specific ice conditions and seasons, including freeze-up, winter, and break-up. Because of the vastly different ice environments and oil-in-ice situations, over-reliance on a single type of response will likely result in inefficient, ineffective clean-up after an actual spill. Also, each season presents different advantages and drawbacks for spill response. During freeze-up and break-up, drifting ice and limited site access restrict the possible response options and considerably reduce recovery effectiveness. Mid-winter, although associated with long periods of darkness and cold temperatures, provides a stable ice cover that not only naturally contains the oil within a relatively small area but also provides a safe working platform for oil recovery and transport. In fact, presence of ice is not the only environmental factor affecting spill response. Temperature affects the consistency of oil and the speed at which it degrades. Winds and the resulting wave action are another two factors. High energy from wind and waves can help oil to disperse naturally, but it also breaks up a thick slick into multiple thinner slicks, which are more difficult to be addressed. In addition, waves are less effective at naturally dispersing oil in broken ice. Besides, most of the established countermeasures require the support of aircraft, vessels, and trained personnel to properly deploy and operate them. Remote locations and lack of infrastructure can impede these systems considerably. The cumulative impact of such limiting factors can make marine spill response operations near impossible for long periods of time in offshore NL.

Based on the comprehensive review, this study has made a set of general recommendations to help guide research and development efforts in oil spill response and countermeasures from the aspects of impact assessment, regulations and coordination, monitoring and analysis, modeling and prediction, preparedness and response, countermeasures, and decision making. Special recommendations are also given to address the above mentioned challenges associate with the harsh environments prevailing in NL offshore areas in order to address the associated knolwege gaps and technical challenges such as: baseline conditions and comprehensive monitoring methods of marine ecological systems and water quality; social-economic and ecological impacts as well as health risks caused by oil spills due to the expansion of petroleum and shipping industry and the openings of new transportation passages in the Arctic ocean; vulnerability and risk of the remote and/or ice-edge communities affected by oil spills; chemistry and physical behaviors of spilled oil on/in/under ice and how its characteristics change over time in harsh environments; effects of presence of sea ice on oil weathering and movement as well as the feasibility and effectiveness of monitoring, modeling, response and cleanup techniques; persistence and degradation changes of spilled oil due to low temperature; effects of wind and waves at different energy levels on weathering, movement and containment of oil slicks; influences of reduced visibility in oil spill monitoring and response effectiveness and technical feasibility; uncertainties associated with the weather and ocean conditions and the impacts on spill modeling and response decision making; logistic issues and possible solutions of cleaning up oil spills in remote regions; advantages and drawbacks for spill response due to seasonal changes as well as the adaptation techniques; adaptation of long-term contingency plans, management strategies, on-site response decision to harsh environmental conditions as well as climate changes; reliability and effectiveness of decision making schemes and approaches considering limited access time/sites, equipment and man power in harsh environments; and integration of monitoring, assessment, simulation and optimization into offshore oil spill response decision support systems.

In order to better support offshore oil spill response and countermeasures, new decision making approaches and systems are desired for providing more effective support to stakeholders or decision makers at different levels such as: 1) general policy makers (e.g., regulators and oil producers) for long-term policy making and trade-off, risk and reliability analyses of the offshore oil spill management; 2) project/production managers and spill responders in designing of contingency plans and/or planning of oil and gas production and transportation in medium-term arrangements; and 3) operators in making on-site decisions and carrying out response and cleanup actions. Risk-based or simulation-based optimization models that can timely determine the best combination of technologies and allocation of resources at different response stages should be developed in order to achieve a most time-efficient and cost-effective response to an oil spill. This would be especially valuable for the areas where unpredictable weather conditions and harsh environments prevail.

In NL, it is particularly urgent and critical to improve the management strategies and decision making effectiveness in offshore oil spill response and countermeasures. To help address this concern, this study has proposed a general decision making framework with the following features: 1) integration of oil spill databases, early warning, risk assessment, technology screening, weathering and movement simulation, and response optimization; 2) quantitative reflection of system uncertainty (probabilistic and possibilistic) and complexity (dynamics and factor interactions) during modeling, response and countermeasures; 3) coupling approaches for interlinking system components (e.g., risk-classification, risk-optimization, simulation-optimization); and 4) special considerations of environmental conditions, resource availability, and time/site constraints during offshore oil spill response in the harsh environments prevailing in NL offshore areas.

It is also recommended for an exploration and review in greater detail of the structures, responsibilities, roles, and capacities of the responsible parties in NL including petroleum producers (e.g., Exxon Mobile, Husky, Chevron and Suncor), regulators (e.g., C-NLOPB), and response organizations (e.g., ECRC). A greater collaboration between these parties should be promoted for preparing, responding and practicing in advance of a spill event. Besides, comprehensive studies are also suggested focusing on the issue of liability, including whether the thresholds should be adjusted to reflect current economic and environmental realities.

Offshore operators are required by the Atlantic Accords to put aside a fraction of project revenues towards research and development as well as education and training activities in NL. These benefit plans may emphasize on addressing challenges concerning the unique features of the harsh conditions in NL offshore areas. Investigations on how the existing technologies for oil spills monitoring, forecasting and response perform in these conditions should be conducted to fill the knowledge and technical gaps. Meanwhile, more research and development expenditures should be paid into the innovation of novel technologies customized with the specific characteristic of NL offshore oil spills.

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CHAPTER 1

INTRODUCTION

1.1 Oil Spills and Oil Spill Response

An oil spill is a release of liquid petroleum hydrocarbon into the environment due to human activities. It often refers to marine oil spills, where oil is released into the ocean or coastal areas, including releases of crude oil from tankers, offshore platforms, drilling rigs and wells, spills of refined petroleum products (such as gasoline and diesel) and their by-products, heavier fuels used by large ships such as bunker fuel, and the spill of any oily white substance refuse or waste oil as well. Oil spills are serious environmental disasters often leading to significant negative and long-term impacts on the environment, ecology and socio-economy of the area. World-wide from 1978 to 1995, there were more than 4100 major oil spills of 10,000 gallons or more (Etkin and Welch, 1997). Several serious oil spill incidents also have taken place since 1995, notably examples like Sea Empress oil spill in which approximately 72,000 tons of crude was released (Edwards, 2000). The logistical financial cost of the oil spill was estimated to be \$120 million. When the effects to the economy and environment are taken into account, the final cost is estimated to have been twice that at \$240 million (Li et al., 2000). Another more recent example is the Deepwater Horizon oil spill (or called the BP oil spill or the Gulf of Mexico oil spill) (White, 2010; Whitehouse, 2010; Guegel et al., 2010) which was an oil spill in the Gulf of Mexico lasted for three months in 2010. It is the largest accidental marine oil spill in the history of the petroleum industry. The spill released about 4.9 million barrels of crude oil (Hoch, 2010). Some estimates suggested the total liability could amount to as much as US \$100 billion by the conclusion of the disaster (Spillius, 2010). The impacts from the spill still continue even after the well was capped.

With significant harsh environment, Newfoundland and Labrador (NL) produces about 270,000 barrels of crude oil, from three active offshore oil fields which are Hibernia, Terra Nova, and White Rose, representing 10 percent of Canada's total crude oil production. It is estimated that about 100 million barrels of oil were produced in the three active oilfields of Newfoundland in 2010 (C-NLOPB, 2011). Oil spills in NL offshore happen more often than environmental assessments predicted. While the oil spill becomes problematic, it is more risky of the lack of response on the issue (Terry, 2008). Since 1997, it is estimated that roughly 2,703 barrels of drilling fluids and other hydrocarbons have been spilled into the ocean through the about 340 spills reported from NL's offshore (Terry, 2008). In 2004, about 1,040 barrels of crude oil were spilled at Terra Nova, followed by a penalty of \$290,000 (C-NLOPB, 2007). In 2004, approximately 96.6 m³ of synthetic based mud was spilled at the surface at White Rose. Husky Energy pleaded guilty to two of three counts in connection with this spill, with a penalty of \$50,000 comprised of a fine of \$10,000 for each count, and \$30,000 to the Environmental Damages Fund (C-NLOPB, 2008).

Oil spill preparedness and response is a set of complex activities (Ornitz and Champ, 2002; Tuler et al., 2007; IOSC, 2008; Bambulyak and Frantzen, 2009). It includes the prevention, reduction, monitoring, compartment, and remediation of oil pollution (IMO, 1995). An oil spill emergency response (OSER) system is

commonly based on the interaction of multiple organizations with functionally specialized tasks (Walker et al., 1995). The effective functioning of the system relies on interorganizational coordination mechanisms, to combine the resources and efforts of multiple independent organizations to perform tasks beyond their individual capabilities (Walker et al., 1994; IMO, 1995; Tuler et al., 2007). As such, the function of coordination provides a unified functioning structure and ensures that all tasks are accomplished and services provided timely and professionally (Tuler et al., 2007).

1.2 Statement of Problems

Oil spills are arising more and more concerns of its significant negative impacts on the marine environment and eventually human health. Especially in the harsh environments prevailing in NL offshore areas, difficulties arise in the response to oil spills.

1) Major oil spills and the associated environmental and economic impacts

It is always important and necessary to review the previous oil spills and the associated reasons and response actions in different aspects, such as the environmental conditions, facility (production platforms and floating production, storage and offloading vessels) conditions, spill amounts and effects, applied technologies for control and remediation, etc. Furthermore, the analysis of the operation conditions, management practices and existing/potential problems of the current and newly designed offshore oil and gas production and transportation facilities, and the corresponding safety and risks are also critical for the impact assessment from the environmental, social and economic perspectives due to oil spills. Such information can be further utilized for developing either long-term contingency plan or on-site emergency response options.

2) Oil spill monitoring, warning, and response policies and regulatory requirements

Currently many countries lack a regulatory processes effectively governing whether or where oil spills happen particularly in the Arctic region based on monitoring and warning, followed with response. However, strict policies and regulations, and the will to adhere to them and enforce them, are absolutely essential for safe, sustainable oil and gas development off of the shorelines. Monitoring includes electronic and visual surveillance of critical parameters in offshore oil production identified during the fault tree analysis design stage. The data can be analyzed using statistical techniques (e.g., Weibull analysis and linear regression), failure mode and effects analysis, and fault tree analysis, to ensure the system reliability meets requirements. Any changes to the offshore oil production system, such as field upgrades or recall repairs, require additional reliability testing to ensure the reliability of the modification. Reliability data and estimates are also key inputs for diagnosis of an alert of offshore oil spills. Even with preventive measures in place, accidents are certain to occur, thus it is also important to provide

the general guidelines of control or clean-up strategies when an oil spill is determined in relative regulations.

3) Oil spill modeling, impact and risk assessment, and cleanup options

A few models have been developed for oil spill response planning (Fingas, 2001; Ornitz and Champ, 2003), along with some models for identifying and graphically presenting oil spills based on geomatic analysis techniques (e.g. Assilzadeh et al., 2001; Brimicombe, 2003). However, these models usually emphasize either response operations or early monitoring and assessment processes (Wilhelm and Srinivasa, 1997; Reed et al., 1999; Brebbia, 2001). There is also a lack of methods capable to cover the whole process holistically (i.e., monitoring, pollution prevention, early warning, impact/risk assessment, emergent response, clean up, and post-event evaluation) (Ping et al., 2007). Also, no existing system could effectively integrate characterization, assessment, simulation and optimization along with geomatic analysis techniques into a general framework for supporting offshore oil spill mitigation. Risk analyses can be characterized as hazard-based or risk-based. A hazard-based analysis examines possible events regardless of their low (or high) likelihood. For example, a potential impact would not lose significance because the risk has been reduced due to an increase in the level of control, such as engineering standards. A risk-based analysis, on the other hand, does take into account the likelihood of the event occurring or the measures that can be taken to mitigate its potential impacts. The reliability assessment helps monitor, assess, and correct deficiencies of the operational production of offshore oil. Clean-up and recovery from an oil spill is difficult and depends upon many factors, including the type of oil spilled, the temperature of the water (affecting evaporation and biodegradation), and the types of shorelines and beaches involved (Marybeth, 2004; Zhang et al., 2008; Qin et al., 2009). Methods for cleaning up include: bioremediation, controlled burning, skimming, solidifying, and vacuuming and centrifuging, etc. (Patents and patent applications, 2011). Usually, due to complex situations more than one of the above methods are combined or integrated in a spill. Therefore, in order to most effectively clean spill oils, decision support to the combination of technologies is of importance.

4) Challenges and opportunities in oil spill response and countermeasures in harsh and arctic environments

Besides the above concerns, the harsh environment in the northern regions such as North Pacific/Atlantic and Arctic Oceans is another important issue that needs to be considered during oil spill management and planning. These regions have a more variable and cold climate than most other regions where oil production and shipping industries prevail (Chen et al., 2010; Jing and Chen, 2011). The unpredictable weather conditions and harsh environments may affect the applicability and effectiveness of prevention, control, and clean-up technologies for oil spills as well as significantly slow down the degradation process of spilled oil. A review will be carried out on these aspects to benefit the offshore oil and gas industry in cold regions as well as to explore the associated opportunities for both industry and government.

5) Decision making frameworks and systems for oil spill response and countermeasures

One major functionality of the diagnosis for rapid responses to an oil spill event is provision of real-time, medium-term and long-term alert information. There are very limited research efforts in developing effective and integrated decision making frameworks and systems to support oil spill response. This is particularly true in harsh environmental conditions prevailing in NL offshore areas. A sound system should be able to help decision makers timely track the transport and fate of pollutants in the affected marine environment, assess the relative and accumulative impacts to ecosystem and human health, and eliminate these impacts in a cost effective way and timely fashion, and provide great benefits to the offshore oil and gas industries, stakeholders, local communities and government. The system should provide effective support to three levels of targets: 1) to help the offshore oil and gas industries effectively reduce the risk to marine systems and prevent the occurrence of oil spills by directly guiding prevention, control, and clean-up actions via a cost efficient and environmental friendly manner; 2) to provide decision support for the governments to effectively regulate and supervise the offshore oil production industries in reducing environmental pollution and avoiding oil spills; and 3) to help protect local communities and fisheries from oil pollution and reduce the risks to human health and ecosystems.

1.3 Research Objectives

The objective of this project is to get insight of the current methodologies and technologies in oil spill countermeasures and further to formulate a new strategic and decision making framework for supporting oil spill diagnosis, warning and emergency response in a more cost-efficient and environmental friendly manner. Particularly the cold weather and harsh offshore conditions in Newfoundland and Labrador and their effects will be considered in the study. The main objectives of this research include:

- 1) To collect and analyze of background information and data in terms of historical oil spills and the associated environmental, economic and social impacts as well as relevant policies and regulations;
- 2) To review current offshore oil spill response and countermeasure protocols and practices;
- 3) to review the natural and social conditions, spill prevention, monitoring and analysis, assessment and modeling, and response and clean-up technologies, as well as their effectiveness and suitability in harsh environments prevailing in NL offshore areas;
- 4) to identify knowledge gaps and technical challenges in offshore oil spill response and countermeasurements particularly in harsh environmental conditions;

- 5) to formulate a general decision making framework for integrating methods and techniques during oil spill monitoring, early warning, assessment, simulation, response and cleanup processes; and
- 6) To recommend oil spill management strategies and disclose the research and development needs particularly for NL offshore industry and regulatory authorities.

1.4 Structure of Chapters

Chapter 2 mainly focuses on the reviews of oil spill, including the production of oil, sources of oil spill, as well as the reviews in oil spill events in Worldwide and North America, especially in Newfoundland Labrador.

Chapter 3 reports the impacts caused by oil spills in the perspectives of economy, environment, ecology, human health, society, etc. Furthermore, these impacts in Newfoundland Labrador are highlighted.

Chapter 5 provides the reviews of policies and regulations in the United Nation, The United Kingdom, Norway, Australia, The United States, Canada and Newfoundland and Labrador as well as their challenges.

Chapter 6 presents the reviews in oil spill monitoring and analysis technologies, including the onsite and remote monitoring as well the oil spill analysis for physical, chemical, and biological parameters. The challenges in harsh environments and the Newfoundland offshore area are also reviewed.

Chapter 7 provides the review in oil spill prevention and clean-up technologies in pollution prevention, physical clean-up, chemical clean-up, biological clean-up of oil spills. The comparison of these technologies and their application in offshore Newfoundland and Labrador are also stated.

Chapter 8 gives the review in decision making for offshore oil spill response, including diagnosis and alert, modeling of offshore oil spill weathering and movement, classification and ranking, response optimization, decision support system. The challenges in the current decision support system are discussed and a novel decision support framework for oil spill preparedness and response in offshore NL is introduced.

Chapter 9 concludes this study with recommendations.

CHAPTER 2

BACKGROUND

2.1 Definition of oil spill

Oil is a necessity in our industrial society and a major element of our lifestyle. Most of the energy used in much of the developed world is for transportation that runs on oil and petroleum products. As current energy usage trends show, this situation is not likely to change much in the future. Industry uses oil and petroleum derivatives to manufacture such vital products as plastics, fertilizers, and chemical feedstocks, all of which will continue to be required in the future. In fact, production and consumption of oil and petroleum products are increasing worldwide, and the risk of oil pollution is increasing accordingly. The movement of petroleum from the oil fields to the consumer involves as many as 10 to 15 transfers between many different modes of transportation, including tankers, pipelines, railcars, and tank trucks. Oil is stored at transfer points and at terminals and refineries along the route. Accidents can occur during any of these transportation steps or storage times. Despite significant progress in reducing spillage through a variety of technological and regulatory prevention measures along with better industry practices, the risk for significant oil spills remains.

A “spill” is a discrete event in which oil is accidentally or, occasionally, intentionally released. Oil spills are depicted as catastrophic disasters by most people, envisioned from some historical major events such as the Exxon Valdez incident, the Hebei Spirit spill, or perhaps the Prestige spill. Much more commonly, however, oil spills are much smaller in scope. On any given day, hundreds, if not thousands, of spills are likely to occur worldwide in many different types of environments, on land, at sea, and in inland freshwater systems.

2.2 Oil spill sources and types

The spills are coming from the various parts of the oil industry – from oil exploration and production activities, from transport of that oil by tank ships, pipelines, and railroad tank cars to the refineries, and from the refineries where the oil is refined to create the many types of fuels that are then transported by pipeline, rail, truck, or tank vessel to the consumers of that oil. Consumption-related spillage comes from manufacturing facilities, nontank vessels that carry oil only as fuel and for machinery, tanker trucks bringing oils to service stations and heating oil tanks, and many miscellaneous sources. The spills occur because of structural failures, operational errors, weather-related events, earthquakes, human errors and negligence, and even vandalism or terrorism.

As shown in Figure 2.1, 72% of spills are 0.003 to 0.03 ton or less. The total amount of these small spills comes to 0.4% of the total spillage. The largest spills (over 30 tons) make up 0.1% of incidents but involve nearly 60% of the total amount spilled. Naturally, the relatively rare large spill incidents get the most public attention owing to their greater impact and visibility, though spill size itself is not a direct measure of damage. Location and oil type are extremely important in determining the degree of environmental and socioeconomic damage.

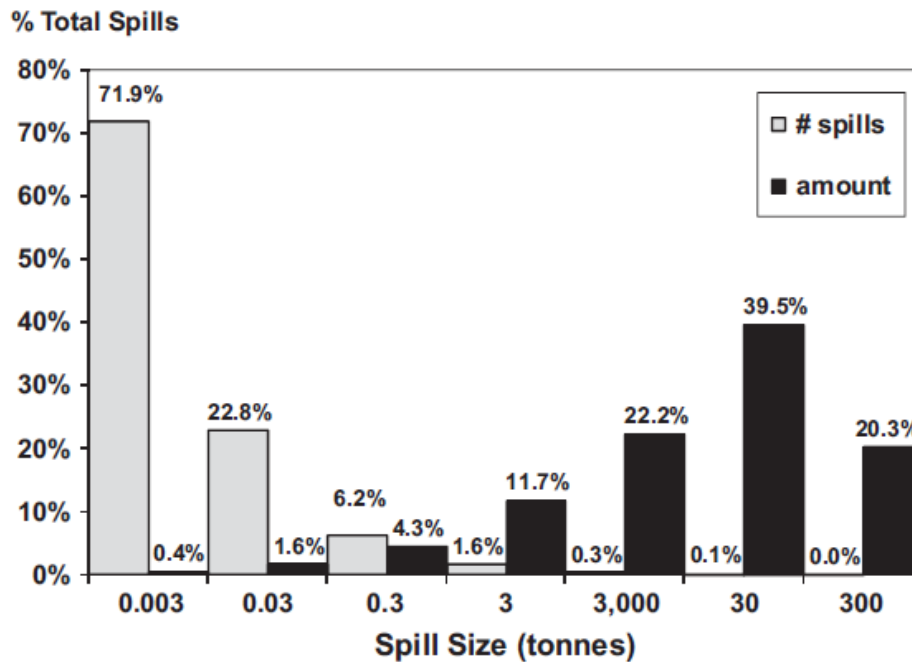


Figure 2.1 Size classes of U.S. marine oil spills, 1990-1999
(ERC data) (Fingas, 2011)

The search for oil reserves offshore is moving into deeper and deeper waters, and crude oil and oil products are being transported across the globe in increasingly larger tankers. As a result, oil spills pose a serious threat to the ecology of the World's oceans. The amount of oil spilled annually worldwide has been estimated at more than 4.5 million tons (ESA).

The biggest contributor to oil pollution in the World's oceans (some 45%) is operational discharges from tankers (i.e. oil dumped during cleaning operations). Approximately 2 million tons of oil are introduced annually by such operations, equivalent to one full-tanker disaster every week. Only 7% of the oil in the sea can be directly attributed to accidents. Land-based sources such as urban waste and industrial discharges, which reach the ocean via rivers, are also a major contributory factor.

After years of study and review of many sources of information the National Research Council (2003) categorized all petroleum input into the sea into four categories: natural seeps, petroleum extraction, petroleum transportation, and petroleum consumption. Table 2.1 summarizes the average, annual releases of petroleum into the environment by source categories during 1990-1999 in gallons and percent per category for the Gulf of Mexico, North America, and Worldwide. Natural seeps dominate all three of the geographic categories. In the Gulf of Mexico during the decade of the 1990s, 82% of the input from coastal and offshore sources was from natural seeps. When only offshore sources are considered, 95% of inputs

came from natural seeps (NRC, 2003). This percentage would obviously be different during the next decade due to the DWH oil spill.

Table 2.1 Average, annual releases (1990-1999) of petroleum by source (best estimates in millions of gallons)
(NRC 2003)

Source	Gulf of Mexico	North America	Worldwide
Natural Seeps	43.1 (82%)	49.6 (63%)	184.7 (83%)
Extraction of Petroleum (platforms, atmospheric deposition, produced waters)	0.8 (2%)	0.9 (1%)	11.7 (5%)
Transportation of Petroleum (Pipeline spills, tanker spills, operational washings, coastal facility spills, atmospheric deposition)	1.3 (2%)	2.8 (4%)	6.3 (3%)
Consumption of Petroleum (land-based, recreational, operational discharges, atmospheric deposition, jettisoned aircraft fuel)	7.1 (14%)	25.9 (33%)	20.2 (9%)
Total	52.3	79.2	222.9

Considerable amount of crude oil is discharged each year from natural seeps, i.e., natural springs from which liquid and gaseous hydrocarbons leak out of the ground. Oil seeps are fed by natural underground accumulations of oil and natural gas. Oil from submarine (and inland subterranean) oil reservoirs comes to the surface each year, as it has for millions of years due to geological processes.

In recent times, the locations of natural seeps have been used for exploration purposes to determine feasible locations for oil extraction. Regional assessments of natural seepage have been conducted in some locations, particularly nearshore in California (Allen et al., 1970; Kvenvolden, 1990; Hornafius et al., 1999; Leifer, 2003), the Indian Ocean (Gupta et al., 1980; Chernova et al., 2001; Venkatesan et al., 2003), and the Gulf of Mexico (MacDonald, 1998).

A comprehensive worldwide assessment of natural seepage is conducted by Wilson et al. (1974). Their work remains the important reference for the recent assessment. Natural seeps are of great magnitude, and was stated to be may be the “single most important source of oil that enters the ocean, exceeding each of the various sources of crude oil that enters the ocean through its exploitation by humankind.” Wilson et al. (1974) estimated that total worldwide natural seepage ranged from 0.2 to 6.0×10^6 tons annually, with the best estimate being 0.6×10^6 tons, based largely on observations of seepage rates off California and western Canada. Estimates of the areas of ocean with natural seeps are shown in Table 2.2.

Table 2.2 Seepage-prone areas of the world’s oceans
(Wilson et al., 1974)

Ocean	Number of 1,000 Square Kilometers		
	High-potential Seepage	Moderate-potential Seepage	Low-potential Seepage
Pacific	1,943	9,285	4,244
Atlantic	1,303	10,363	11,248
Indian	496	7,928	3,010
Arctic	0	5,636	2,456
Southern	0	486	458
Total	3,741	33,697	21,416

In a 2003 National Research Council (NRC) study, a worldwide estimate of natural seepage into the marine environment of between 0.02106 to 2.0106 tons annually was made, with a “best estimate” of 600,000 tons. The 2007 Joint Group of Experts on Scientific Aspects of Marine Protection (GESAMP) study on oil inputs into the marine environment included an estimate of the range of natural seepage as 0.2- 2.0×10^6 tons per year, with a best estimate of 600,000 tons per year (GESAMP,

2007).

2.3 Composition and property

The spills involve many different types of oil ranging from various types of crude oil to a large array of refined products, from heavy persistent fuels to lighter, less persistent, but very toxic lighter fuels. Oil type is important because lighter crudes rapidly lose much of their volume due to evaporation (Fingas, 1996), reducing the volume requiring mitigation, but presenting a sinking risk (Michel and Galt, 1995), for which few mitigation technologies are available. In addition, many light, petroleum polycyclic aromatic hydrocarbons are hazardous to health (Boström et al., 2002), increasing inhalation health risks to response workers and coastal human populations.

Oil acts differently in different environments. First, oil contains many thousands of compounds and all oils contain the same compounds and molecular structures, regardless of their source. Differences among oils (e.g., between the Exxon Valdez oil, and the Deepwater Horizon oil) are caused by differences in quantities of those compounds in the oils. The content of the Deepwater Horizon oil includes nearly 2,000 identifiable compounds.

Second, the quantity of different hydrocarbons determines an oil's chemical and physical properties. For example, an oil that contains lighter, smaller molecules is less viscous. The Deepwater Horizon oil is an extremely light oil, which affects evaporation at the ocean's surface. The structure of the hydrocarbon (e.g., straight-chain, branched, and nonaromatic and aromatic cyclical) also affects how an oil interacts with its environment. Aromatic compounds include benzene and PAHs or PAH homologs, and may include sulfur or heavy metals within the chain. Finally, oil contains a class of residue, asphaltenes, which together form what we call road tar.

Third, most aromatic hydrocarbons in oils are alkyl homologs of "parent" polycyclic compounds, and most studies on the human health effects of oil exposure have involved parent polycyclic compounds (the Environmental Protection Agency's [EPA's] standard oil analytic test, the 8270 GCMS method, detects only the parent compounds). The Deepwater Horizon oil has almost no parent polycyclic compounds, which means that the standard 8270 GCMS method would not be useful.

Lastly, because there are so many compounds present in oil, it is difficult to evaluate toxicity. While the aromatic hydrocarbons are responsible for much of the toxicity, Overton cautioned that they are not the only compounds in oil with potentially toxic effects on human health. Oil also contains a series of saturated compounds, including hydrocarbons, which are called biomarkers. Because biomarkers do not degrade quickly, they can be used to trace oil as it moves through the environment (McCoy et al., 2010).

2.4 Oil spills in North America

In the United States, more than half of the approximately 3 million tons of oil and petroleum products used daily is imported, primarily from Canada, Africa, Saudi Arabia, and other Arabic countries. About 40% of the daily demand in the United States is for automotive gasoline, and about 15% is for diesel fuel used in transportation. About 40% of the energy used in the United States comes from petroleum, 35% from natural gas, and 24% from coal (Fingas, 2011).

Oil and natural gas are the dominant fuels in the U.S. economy, and they provide 62% of the nation's energy and almost 100% of transportation fuels (NRC, 2003). The birth of the oil industry in the U.S. is considered to have begun with the oil discovery and subsequent blowout at Spindle top near Beaumont in coastal southeast Texas in 1901. The first well drilled in the Gulf of Mexico was located one mile offshore near Cameron, Louisiana, in 14 feet of water in 1937. From these slow beginnings and then with development of offshore technology, oil and gas exploration and production expanded across the continental shelf and down the slope of the north western Gulf of Mexico during the next seven decades. Today, about 3,500 exploration and production platforms exist in the north western Gulf, down from nearly 7,000 in total, and including over 25,000 miles of pipeline and approximately 50,000 total wells drilled (multiple wells are drilled from most modern platforms) (Tunnell, 2011).

The United States has experienced a number of significant oil spills. The Argo Merchant (1976) spilled 28,000 tonnes of No 6 fuel oil off the coast of Massachusetts, but natural conditions were favourable and there was relatively little impact. The response of the Mega Borg (1990), which spilled over 16,000 tonnes of oil near Texas, involved containment, recovery and dispersant use. The American Trader (1990) spilled nearly 1,300 tonnes of crude oil off the coast of California and the North Cape (1996) spilled 2,600 tonnes of home-heating oil near Rhode Island. Both of these spills had major responses.

A detailed analysis of oil spillage in the United States, for which there are more accurate data than many other parts of the world, reveals that during the decade of 1998-2007, inland pipelines spilled an average of nearly 11,000 tons annually, with the next largest source being refineries, which spilled 1,700 tons. Inland tanker truck spills amounted to 1,300 tons annually. Tank ships only spilled an average of 500 tons annually during this decade. Nevertheless, the risk for large spills from tank ships, facilities, and offshore oil exploration and production, all of which contain large volumes of oil, remains a concern for contingency planners and spill responders.(Fingas, 2011).

In March 1989, the tank vessel Exxon Valdez struck a reef in Prince William Sound, Alaska, and spilled approximately 11 million gallons of oil, resulting in the largest oil spill in the U.S. history at that time. This incident awakened the nation to how ill-prepared the country was to deal with oil spills in general and especially in cold environments. There was little information available on the affected marine environment and the invertebrate, fish, and wildlife resources in the Sound. Yet

information about existing resources is critical to guide decisions about effective spill response and understand long-term impacts.

As one of numerous reactions to the spill, Congress passed the Oil Pollution Act of 1990 (OPA 90). Within the legislation was a mandate to create the Oil Spill Recovery Institute (OSRI). OSRI was established to serve as a research and technology development organization, charged to provide funding to support oil-spill related research, education, and technology development projects for dealing with oil spills in Arctic and subarctic marine environments. The legislation directs OSRI to improve our understanding of the long-term effects of oil spills on the natural resources of Prince William Sound (PWS) and its adjacent waters, including the environment, the economy, and the lifestyle and well-being of the people who are dependent on them (Title V, Section 5001, Oil Pollution Act of 1990).

The spill from the Macondo well in the Gulf of Mexico is the largest offshore oil spill in U.S. history and among the largest in the world record. The incident is also known as the BP oil spill, the Gulf of Mexico oil spill, the Deepwater Horizon and Mississippi Canyon 252 incident, or the Macondo blowout.

On April 20, 2010, the 9-year dynamically positioned semi-submersible Mobile Offshore Drilling Unit Deepwater Horizon exploded and sank about 77 km off the Louisiana coast in the Gulf of Mexico. The incident cause 11 deaths and 17 injuries.

The location of the spill was 1,500 metres underneath water, with a formation depth of 5,600 metres. The explosion led to a sea-floor oil leak 1 mile beneath the ocean's surface. The gusher's depth has made it difficult to accurately measure how much oil is being discharged, with officials estimating 35,000 to 60,000 barrels a day and some scientists estimating 40,000 to 100,000 barrels per day (MacDonald et al., 2010). Current estimates state that 600,000 tonnes or more of crude oil have spilled into the Gulf of Mexico. The spill lasted for a period of 87 days (Tunnell, 2011), until on July 20, 2010 it was successfully sealed only till on the installation of a new containment cap.

An unprecedented response of 1000s of workers and 100s of boats and ships continued clean-up and assessment into the fall after capping the well in July. The clean-up efforts have been the most demanding on-water response in U.S. history, involving the use of more than 1 million gallons of oil spill dispersants and the deployment of thousands of skimming vessels (Deepwater Horizon Response, 2010; Judson et al., 2010), including local boat operators who assist with containment and response activities using their "vessels of opportunity." Many offshore commercial workers, clean-up workers, and volunteers have subjected themselves to numerous physical hazards (such as chemical exposures, heat stress, and injury) through response activities involving chemical dispersants, booms, and skimmers. Long work days and weeks are common as workers and volunteers combat waves and plumes of oil that continue to threaten their communities, livelihoods, and ways of life.

In addition to the physical stressors, the Deepwater Horizon oil disaster has disrupted delicate social, economic, and psychological balances in communities across the Gulf region. Local fishermen and women in the region are grappling with possibly permanent disruptions to their long-standing livelihoods. Fears associated with contaminated beaches and food continue to dissuade tourists from visiting an area still recovering from the devastation of hurricanes such as Katrina, Rita, and Gustav. Communities question the safety of their most vulnerable populations and worry about the effects that the Gulf oil disaster will have on their immediate and long-term health. The resulting uncertainty about physical, social, and economic health has profound implications for the psychological well-being of individuals in affected communities (McCoy et al., 2010).

Regarding the overall economics of Gulf of Mexico commercial fisheries, fishermen harvested 1.27 billion pounds of shellfish and finfish that earned \$659 million in total landings revenue in 2008 (NMFS, 2010a). The economic multipliers of commercial fishing range from 2X to 3X dockside value, conservatively, to 8X-10X demonstrating the significant impact all along the value chain. It is not just fishermen that are impacted but also the processor, distributor, retail establishments, and restaurants.

In response to economic losses caused by the spill, the Gulf Coast Claims Facility (GCCF) opened in June 2010 “as part of an agreement between the Obama Administration and BP to assist claimants in filing claims for costs and damages incurred as a result of the oil spill stemming from the Deepwater Horizon Incident”. As of 13 December the GCCF had processed over 463,000 claims and paid out about \$2.5 billion to over 166,000 individuals and businesses.

One significant, but difficult to assess, economic sector which the Gulf Coast Claims Facility will have to deal with soon is the fishing industry of the Gulf of Mexico. NOAA Fisheries Service worked in concert with the Food and Drug Administration (FDA), the Environmental Protection Agency (EPA), and Gulf states to determine fishery closures in the northern Gulf of Mexico as a result of the DWH oil spill. This action was “a precautionary measure to ensure public safety and (to) assure consumer confidence in Gulf seafood” (NMFS, 2010b). Closures started on 2 May 2010 in the area around the well blowout and continued to expand through the middle of July, peaking at 84,101 square miles or 34.8% of the Gulf of Mexico U.S. Exclusive Economic Zone (EEZ). Closures then decreased throughout the fall until 15 November when only the area around the MC252 well was closed, an area of 1,041 square miles or 0.4% of the U.S. Gulf EEZ. On 24 November an additional 4,213 square miles were added to the closure for royal red shrimp fishing only, as a result of the discovery of tar balls in some royal red shrimp trawls (NMFS, 2010c).

In Canada, about 12 reported (i.e., spill size or volume more than 4000L, or about 1000 gals) oil spills take place every day, of which only about one of these spills is into navigable waters. These 12 spills amount to about 40 tons of oil or petroleum product. In the United States, there are about 25 spills per day into navigable waters and an estimated 75 spills on land.

Despite the apparently large number of spills, only a small percentage of oil used in the world is actually spilled. There are proportionately more spills into navigable waters in the United States than in Canada because more oil is imported by sea and more fuel is transported by barge. In fact, the largest volume of oil spilled in U.S. waters comes from barges, while the largest number of spills is from vessels other than tankers, bulk carriers, or freighters.

The Canadian petroleum industry has been a major economic driver to North America. The country's oil production ranked seven (2008 figure) globally, manufacturing a daily average of 438,000 m³ (2,750,000 bbl) crude oil, crude bitumen and natural gas condensate. Among them, conventional crude oil accounted for almost one half (45%), and about 283,000 m³/day (1,780,000 bbl/day) was exported to the U.S. (Turner, 2010). There are 22 oil refineries in Canada, 5 of which are classified as large.

Canada uses about 260,000 tons of oil and petroleum products every day. Most domestic oil production in Canada comes from approximately 350,000 oil wells in Alberta and Saskatchewan. Canada imports about 100,000 tons of crude oil or other products per day but exports about 600,000 tons per day, mostly to the United States (Fingas, 2011).

In Atlantic Canada, the blooming of the oil and gas industry on East Coast has led to large numbers of oil spill accidents, threatening health and sustainability of the environment. The MARIS database recorded 1,048 accidents over the period of 1980 to 2005 around South Coast of Newfoundland. Oil spills have released tons of oil to the environment in this area, having caused tremendous contamination problems and becoming a significant environmental concern. In 2004 two large oil spills occurred in the waters near Sable Island off Nova Scotia; one spill released 4,000 litres of diesel and the second spill released 354,000 litres of drilling mud at an exploratory well. In December 2004, about 1070 barrels spilled into the Atlantic Ocean covering an estimated 57 square kilometres within the territory of Newfoundland.

In Canada, most spills take place on land, and this accounts for a high volume of oil spilled. Pipeline spills account for the highest volume of oil spilled. In terms of the actual number of spills, most oil spills happen at petroleum production facilities, wells, production collection facilities, and battery sites. On water, the greatest volume of oil spilled comes from marine or refinery terminals, although the largest number of spills is from the same source as in the United States – vessels other than tankers, bulk carriers, or freighters.

The most appropriate major spill for the Gulf of Mexico is the Ixtoc I spill. This platform blowout in the southern Gulf of Mexico, Bay of Campeche, 50 miles north of Ciudad del Carmen, Campeche, was very similar in many ways to the Deepwater Horizon oil spill, but it also had distinctive differences. The Ixtoc spill began on 3 June 1979 and ended on 23 March 1980, lasting almost 10 months and releasing about 140,000 million gallons. The burning platform sank several days after the blowout, and similar clean up strategies (burning, dispersant, booms, and

skimmers), as well as containment strategies (top kill, junk shot, top hat called the sombrero, and relief wells) were utilized (Jernelöv and Lindén, 1981). Besides extending for a much longer period of time than the DWH oil spill, the other main differences were the water depth, 170 feet for Ixtoc versus 5000 feet for DWH and the use of dispersants at great depth.

After 60 days of oil release into the southern Gulf and drifting on westward and northward moving currents, the oil reached Texas beaches and coated them with moderate to heavy oiling for over 150 miles north of the Rio Grande during August and September 1979 (ERCO, 1982; Hooper, 1981). The clean-up strategy in Texas was to let oil hit the outer barrier island beaches but boom off all tidal inlets to prevent oil entering the sensitive estuaries and lagoons of the South Texas coast. For the most part, this strategy worked well.

Unfortunately, as with most major spills, there were no long-term, ecosystem studies to monitor the affect of the spill in either Texas or Mexico. Short-term studies in Texas revealed impact and recovery of shorebirds (Chapman 1979, 1981) and beach biota (Tunnell et al., 1981; Kindinger, 1981) after 1 and 2-3 years, respectively. Besides some minor oiling of shorelines along jettied inlets and shorelines just inside inlets, no major estuarine impacts to habitats or species were reported. Offshore, one study compared the Ixtoc oil spill and Burmah Agate (a tanker spill off Galveston in 1979) to the large multi-year South Texas Outer Continental Shelf study completed several years prior to both spills and found no effects related to the spills in the outer shelf area (Lewbel, 1985).

The more recent event, the Deepwater Horizon oil spill released over 200 million gallons of oil into the northern Gulf of Mexico for almost three months. Compared to the Ixtoc I oil spill, the Deepwater Horizon oil spill affected a much smaller area of the Gulf (Figure 2.2). The Deepwater Horizon spill occurred during late spring and early summer when climatic conditions and sea conditions are generally calm in the northeastern Gulf near the well site, whereas the Ixtoc spill occurred from early summer to the following spring through all seasons of the year, including numerous winter fronts and several tropical storms. The Deepwater Horizon spill oiled a shoreline area of less than 400 linear miles, and the Ixtoc spill oiled over 1500 linear miles of the entire western and southern Gulf. This oiling of an area of less than 5% of the entire Gulf during the Deepwater Horizon spill is significant for the recovery process, since many northern Gulf species have a much wider distribution than the affected area, and therefore the ability to help recolonize impacted areas by prolific spawners with widely dispersed planktonic eggs and larvae.

Ecologically the Deepwater Horizon spill occurred in a very sensitive area of the Gulf, which includes the highly productive coastal wetlands and marshes of the Mississippi Delta. These salt and brackish marshes are a number 10 on the ESI scale, being sensitive to oiling and difficult to clean up. In fact, the usual clean-up strategy for marshes is to leave them alone and let natural cleaning process proceed, as any clean up activity tends to push oil deep into the sediments by clean-up crews and machinery, making recovery take much longer. In addition to these sensitive

marshes, other highly productive, critical habitats in the Fertile Crescent shallow waters include oyster reefs and seagrass meadows. These highly productive and biodiverse habitats serve as feeding grounds and nursery grounds for many nearshore species. By comparison, regarding the Ixtoc oil spill, the fine-grained sand beaches of the western and southern Gulf are a number 3 on the ESI scale, so they are not as sensitive, and they can recover more quickly. These fine-grained sand beaches are found on almost continuous barrier islands and peninsulas west of the Mississippi Delta and provide natural barriers (or natural booms) for the more sensitive estuarine and lagoonal habitats inshore of them. In the northern Gulf a more open coast prevails with smaller and discontinuous barrier islands offshore, thus allowing oil to potentially reach sensitive inshore environments.

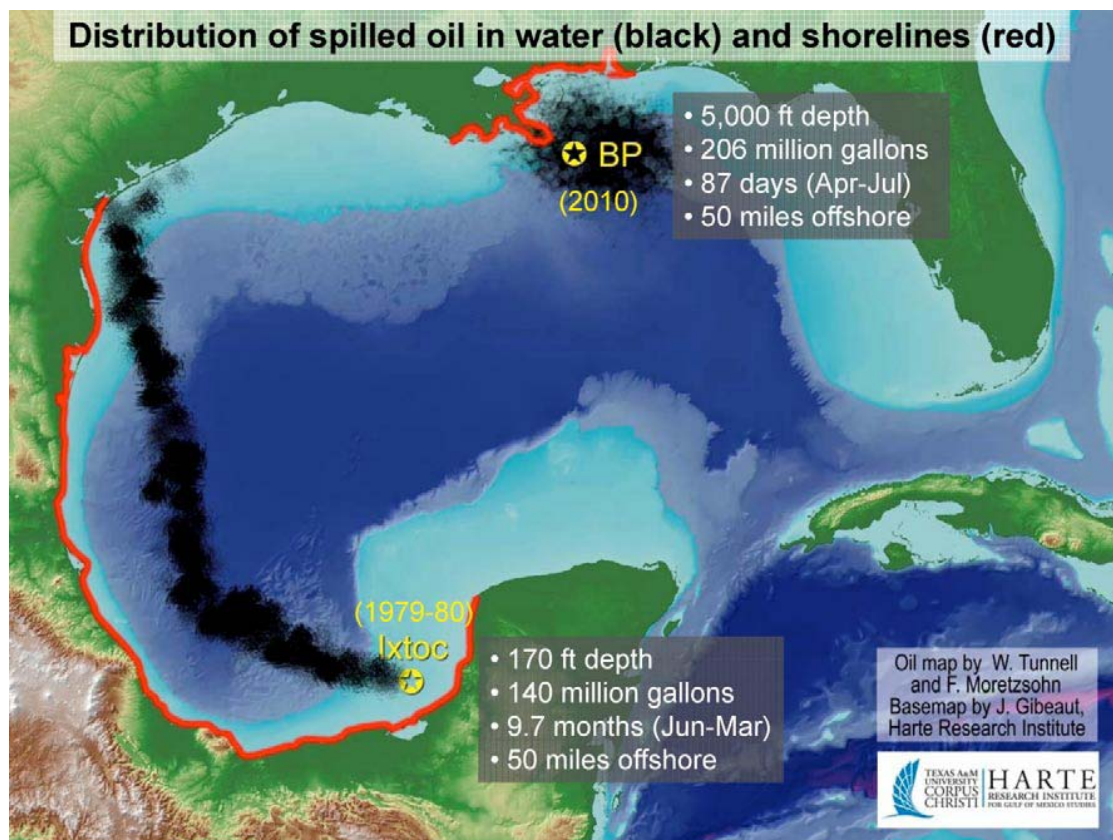


Figure 2.2 Location and distribution of spilled oil and oiled shorelines caused by the BP DWH oil spill and the Ixtoc I oil spill

2.5 Oil spills outside North America

When the tanker Torrey Canyon spilled 130,000 tons of crude oil off the western coast of the UK in March 1967, killing 15,000 seabirds and oiling nearly 300 kilometers of English and French coastline, there was a large public outcry. The

environmental damage from this spill was multiplied by the use of highly toxic first-generation dispersant chemicals in the response.

The Torrey Canyon spill was not the first oil tanker spill by any means. A large number of oil tankers were torpedoed and sunk during World War II. During the first six months of 1942 alone, a total of 484,200 tons of oil were released from torpedoed tankers within 90 kilometers of the eastern U.S. coast (Campbell et al., 1977). This came to about one tanker spill of about 20,000 tons per week over six months. Clean-up efforts consisted of burning incidental to the torpedoing and minimal cosmetic actions on swimming beaches. While the occurrence of these incidents during wartime may explain the relatively low concern about environmental damage from the spilled oil, there was, arguably, a general lesser awareness of environmental protection in these times as well.

The Torrey Canyon spill in 1967 was notable in that when it occurred, it is the largest spill to date. The tanker's capacity had recently been increased to hold 130,000 tons of oil cargo. Subsequently, there were at least five significantly larger worst-case discharge (complete cargo loss) tanker spills, as well as several other large spills associated with oil wells and pipelines. Following on the 1967 Torrey Canyon incident, the 1969 Union Alpha Well 21 blowout off Santa Barbara, California, which released 14,300 tons of crude oil, is often credited with being the impetus for the environmental movement in the United States, as well as for the establishment of the federal Environmental Protection Agency (EPA) (Easton, 1999). The wreck and spill of the tanker Torrey Canyon in southern England in 1967 and the blowout of a Santa Barbara, California, platform in 1969 ushered in the modern era of oil spill concern and awareness, prompting planning for oil spill response, clean up, contingency plans, and studies of major oil spills (Tunnell, 2011).

In the 1970s, other significant oil spills around the world brought greater attention to the problem on an international scale –the Arrow (Canada, 1970), the tanker Metula (Chile in 1974), the tanker Urquiola (Spain in 1977), the Ekofisk blowout (Norway in 1977), the tanker Amoco Cadiz (France in 1978), the largest tanker spill of all time, Atlantic Empress (Trinidad and Tobago/Barbados in 1979), and the largest nonwar-related spill in history – the Ixtoc I well blowout (Gulf of Mexico in 1979) (Hayes, 1999). The largest oil spills in history are listed in Table 2.3.

Table 2.3 Largest oil spills in history worldwide
environmental research consulting (ERC data)

(Fingus, 2011)

Date	Source Name	Location	Tons
10-Mar-1991	700 oil wellsy	Kuwait	71,428,571
20-Jan-1991	Min al Ahmadi Terminalyz	Kuwait	857,143
3-Aug-2000	oil wells	Russia	700,000
3-Jun-1979	Ixtoc I well	Mexico	476,190
1-Feb-1991	Bahra oil fieldsy	Iraq	377,537

2-Mar-1990	oil well	Uzbekistan	299,320
19-Jul-1979	T/V Atlantic Empressx	Trinidad/ Tobago	286,354
25-Oct-1994	Kharyaga-Usinsk Pipeline	Russia	285,714
4-Feb-1983	No. 3 Well (Nowruz)	Iran	272,109
6-Aug-1983	T/V Castillo de Bellver	South Africa	267,007
16-Mar-1978	T/V Amoco Cadiz	France	233,565
10-Nov-1988	T/V Odyssey	Canada	146,599
11-Apr-1991	T/V Haven	Italy	144,000
1-Aug-1980	D-103 concession well	Libya	142,857
6-Jan-2001	pipeline	Nigeria	142,857
19-Jan-1991	T/V Al Qadasiyahyz	Kuwait	139,690
19-Jan-1991	T/V Hileeney	Kuwait	139,690
18-Mar-1967	T/V Torrey Canyon	United Kingdom	129,857
19-Dec-1972	T/V Sea Star	Oman	128,891
23-Feb-1980	T/V Irenes Serenade	Greece	124,490
19-Jan-1991	T/V Al-Mulanabbiyz	Kuwait	117,239
7-Dec-1971	T/V Texaco Denmark	Belgium	107,143
19-Jan-1991	T/V Tariq Ibn Ziyadyz	Kuwait	106,325
20-Aug-1981	storage tanks	Kuwait	106,003
26-Jan-1991	Min al Bakar Terminalyz	Kuwait	100,000

T/V: “tank vessel”, refers to tank ships or tankers
 Ended in January 2010

The Piper Alpha rig explosion and fire (United Kingdom, 1988) lost 165 lives. Soon afterwards, the 1989 tanker Exxon Valdez spill in Alaska is perhaps the most notorious spill incident, though it is by no means the largest. The spillage of over 37,000 tons of Alaskan crude oil into what was considered to be a “pristine” location, Prince William Sound, precipitated the most expensive and the lengthiest spill response and damage settlements in history. Its repercussions were felt worldwide, resulting in the passage of significant spill prevention and liability legislation in the United States – the Oil Pollution Act of 1990 (OPA 90) – as well as international conventions on spill prevention that included such measures as the requirement for double-hulls on tankers by 2015 and increased financial liability. The significant financial consequences for tanker owners and operators as a result of the Exxon Valdez spill and the spiller liability inherent in subsequent regulations brought the consequences for spills to an unprecedented level. The financial risk associated with large spills may have had as much impact on spill prevention as any actual preventive measures, such as double-hulls on tankers.

Worldwide oil spillage rates have decreased dramatically since the 1960s and 1970s, from about 635,000 tons annually to about 300,000 tons per year from all sources, not counting the anomalous intentional spillage associated with the 1991 Gulf War, which amounted to over 82 million tons on land and at sea. By the 1980s, a global 40% reduction was estimated since the decade 1988-1997. Spillage reduced

another 20% by the 1990s. The largest sources of oil spills in the last two decades have been related to oil transportation by tank ships (tankers) or through pipelines (Fingas, 2011). The significant decrease of oil spill occurrence was due to the implementation and enforcement of prevention measures and more responsible operations on the part of the shipping and oil industries (Etkin, 2001, 2002; NRC, 2003; GESAMP, 2007). These reductions are more remarkable considering the increases in production, shipping, and handling of oil during this time period.

There have been a number of studies aimed at estimating the cost of large oil spills. For example, COGLA, 1985 assessed the costs of 100 significant spills and attempted to make correlations between cost and various parameters such as level of preparedness, intensity of clean-up, and amount of shoreline oiled. Other studies such as Etkin, 2005, 2010, and API, 2010 attempted to calculate a “dollar-per-barrels spilled” for various types of spills for the purpose of estimating the value of different preventive measures. A recent review documents the costs of various spills in recent years (Della Mea, 2010). Examples of some developed countries are showed in Table 2.4 below. Spills in less-developed countries have unit manpower costs that are much lower than in Canada, and may also have lower clean-up standards.

Table 2.4 Costs of several notable spills in recent history

(source: Turner, 2010)

Incident	Location	Year	Spill volume, tonnes	Payments to claimants, US \$ million	Payments 2010 CND \$ million
Sea Empress	U.K.	1996	73,000	47	80
Nakhodka	Japan	1997	6,200	167	297
Erika	France	1999	20,000	138	258
Prestige	Spain, France, Portugal	2002	64,000	133	244
<i>Includes only response costs that were reimbursed; other sources report total response costs as much as 50% greater.</i>					

However, these costs pale in comparison to the two highest profile events in U.S. waters, the Exxon Valdez incident in Alaska in 1989, which had reported clean-up costs on the order of \$2 billion and a similar amount in terms of damage claims, and the recent Macondo incident in the Gulf of Mexico, which had estimated clean-up costs on the order of \$9 billion, and may have damage claims of triple that amount. Except for the Macondo incident, all of the others described here were

tanker accidents. One obvious difference with the response to the Macondo blowout has been the expense related to source control. Whereas there are costs related to salvage in most tanker incidents, none of them had the same level of vessel commitment, in numbers or time, as in the attempts to contain oil at the wellhead and drill two independent relief-wells, as has been the case in the Macondo incident. For example, each of the two relief-wells is likely to cost on the order of \$100 million to complete.

On the other hand, response costs for the Montara blowout (Australia, 2009) were reported to be on the order of \$5.3 million for clean-up, and \$170 million total including well-control. The Montara well was uncontrolled for 74 days; reports on the total spill volume were not published in the official inquiry documents, and varied widely in other sources between 30,000 and 150,000 barrels. The relatively low costs for this incident can likely be attributed to: the oil was highly dispersible and the main spill-response was dispersant application, the fact that there were very limited shoreline effects attributed to the spill.

Oil spill disasters have resulted in tragic impact to human, environment, ecology, and economy. It is therefore imperative to conduct a comprehensive re-evaluation of the capability of oil spill prevention, response, contaminant and clean-up, and a thorough scrutiny of regulations and their enforcement so as to avoid a similar incident in future.

2.6 Oil spills in Newfoundland and Labrador

Newfoundland and Labrador (NL)'s offshore oil operation has a relatively short history of 15 years since the first commercial production was commenced in Hibernia platform in November 1997 (Turner, 2010). The second field in Terra Nova started production in 2002.

Newfoundland and Labrador (NL) produces about 270,000 barrels of crude oil, from three active offshore oil fields which are Hibernia, Terra Nova, and White Rose, representing 10 percent of Canada's total crude oil production. It is estimated that about 100 million barrels of oil were produced in the three active oilfields of Newfoundland in 2010 (C-NLOPB, 2011). Oil spills in NL offshore happen more often than environmental assessments predicted. While the oil spill becomes problematic, it is more risky of the lack of response on the issue (Terry, 2008). Since 1997, it is estimated that roughly 2,703 barrels of drilling fluids and other hydrocarbons have been spilled into the ocean through the about 340 spills reported from NL's offshore (Terry, 2008). In 2004, about 1,040 barrels of crude oil were spilled at Terra Nova, followed by a penalty of \$290,000 (C-NLOPB, 2007). In 2004, approximately 96.6 m³ of synthetic based mud was spilled at the surface at White Rose. Husky Energy pleaded guilty to two of three counts in connection with this spill, with a penalty of \$50,000 comprised of a fine of \$10,000 for each count, and \$30,000 to the Environmental Damages Fund (C-NLOPB, 2008).

Oil rig disasters are not restricted to spills or blowouts, as the people of Newfoundland and Labrador are all too painfully aware. On the night of 14 – 15 February 1982, the Ocean Ranger, a semisubmersible drill rig, capsized and sank in a fierce storm in the Hibernia oil field, approximately 315 kilometers off the coast. All 84 crew members were lost. Subsequent inquiries found that the rig sank after seawater entered its ballast control room through a broken porthole, causing an electrical malfunction in the ballast panel controlling the rig's stability. The disaster resulted in regulatory changes focusing on training and safety practices and procedures offshore. These changes were not specifically related to well control or drilling practices (Angus and Mitchell, 2010).

According to the Chairman and CEO of the C-NLOPB (Max Ruelokke, 2010), since the beginning of production of oil in that region, only “some 1,100 barrels of crude have been spilled in our offshore area, which is approximately 1 barrel per 1 million produced. There have been no blowouts in our offshore area.”

The biggest offshore oil spill in Canadian history occurred in November 2004 when a total of 1,000 barrels were discharged from the Terra Nova offshore oil production vessel (C-NLOPE, 2004; CBC News, 2010). In comparison, the Gulf of Mexico incident released between 20,000 and 40,000 barrels a day. That equates to more in a single day than the combination of all the spills that have occurred at offshore Newfoundland and Labrador projects in ten years. “Obviously, we would prefer to have no injuries or spills, but we believe the record for our offshore area is quite respectable (Max Ruelokke, 2010).”

It should also be noted, that unlike what is happening in the Gulf of Mexico, the committee was advised that an oil slick originating from a Newfoundland and Labrador offshore blowout would likely not affect Canadian shorelines. A Husky Energy representative attributed this possible scenario to the Labrador Current. The company (Paul McClosky 2010) evaluated several scenarios and observed that “in all cases, the models indicated that oil should head out into the open ocean.” However, the waters on the continental shelf off the coasts of Newfoundland and Labrador and Nova Scotia support seabird and marine life populations that would be vulnerable to oil spills in the open ocean (Ian 2010)

2.7 Summary

As the major energy source worldwide, petroleum products have been ever increasingly manufactured and consumed, so is the risk involved. Despite significant progress in reducing spillage through a variety of technological and regulatory prevention measures along with better industry practices, the risk of significant oil spills remains. On the daily basis, hundreds to thousands of spills are likely to occur worldwide in many different types of environments, on land, at sea, and in inland freshwater systems. The spills involve many different types of oil ranging from various types of crude oil to a large array of refined products, from heavy persistent fuels to lighter, less persistent, but very toxic lighter fuels.

Multiple sources of spillage are involved, such as from tankers, offshore platforms, drilling rigs and wells, as well as spills of refined petroleum products and their by-products. These spills occur because of structural failures, operational errors, weather-related events, earthquakes, human errors and negligence, and even vandalism or terrorism. The biggest contributor to oil pollution in the World's oceans (some 45%) is operational discharges from tankers. The amount of oil spills from natural seeps is recorded much more than from petroleum extraction, transportation and consumption. Natural seeps are considered as of great magnitude, and the single most important source of oil that enters ocean. An amount of 0.6×10^6 tonnes of worldwide natural seepage is estimated.

Oil spills in most occurrences (72%) are with small scales; the overall amount of these small spills accounts for only less than 1% of the total spillage. The largest spills (over 30 tonnes) rarely occur (0.1% of incidents) yet involve nearly 60% of the total amount spilled. Over the history, some international oil spills have captured public attention due to their catastrophic impact on environment, ecology, economy, and human health. In this report, some large international spill cases over the history were summarized, as well as two catastrophic cases: the Exxon Valdez oil spill in 1989 and the recent Deepwater Horizon oil spill in 2010.

CHAPTER 3

IMPACTS OF OFFSHORE OIL SPILLS

Offshore oil spills are of tremendous concern due to the enormous economic loss and the harm to ecological systems, public health, society and community they may cause. The catastrophic Deepwater Horizon oil spill occurred on April 20, 2010 threatened over \$5.5 billion fishing and tourism industrial economic entities and more than 200,000 employment opportunities (Hagerty and Ramseur, 2010); killed millions of seabirds and billions of fish eggs (Corn and Copeland, 2010); and caused a dramatic population decline and shift of microorganisms, phytoplankton and other flora (Widger et al., 2011). According to the survey of Columbia University's National Center for Disaster Preparedness, 40% of the Gulf coastal residents reported that they had experienced physical health problem related to the spill, 20% of Gulf Coast residents reported a drop in income, and 25% thought they might have to move away from the Gulf (CUNCDP, 2010). During the long run of oil and gas exploitation, the adverse impacts of oil spill have been documented in various aspects including economy, ecology and environment, public health and society/community.

3.1 Economic impacts

The total economic impact of oil spill can be breakdown into socioeconomic losses, cleanup costs, environmental damages, research costs and other costs (Liu and Wirtz 2006). These costs can either be assigned with monetary values in a real economic world, or estimated through modeling which has been the primary tool to estimate environmental damages (Liu and Wirtz 2006).

3.1.1 Socioeconomic losses

The immediate damages of oil spills were primarily on the economic activities around the blowout region and the direct economic loss of disrupted oil and gas exploitation. For the offshore oil spills and the ship-source oil-pollution, the prominent affected industries have been the commercial and recreational fisheries and coastal tourism. The socioeconomic losses of Deepwater horizon oil spills, Prestige oil spills have been well-documented in the literature. In the Gulf of Mexico, the commercial fisheries industry was estimated with dockside value of \$659 million in 2008 (NMFS, 2008). This industry as well as the related processor, wholesale and retailed businesses supported over 200,000 jobs with related income impacts of \$5.5 billion (NMFS, 2008). In terms of recreational fisheries, recreational anglers contributed \$12 billion on equipment and trips in 2008 and supported businesses including charters, bait and tackle shops, restaurants and hotels (NMFS, 2008). On the other hand, the tourist industry accommodated 21.9 million visitors in 2009 and contributed to 620,000 jobs and corresponding income impact of \$6 billion (Ache, 2008). Upon the Deepwater Horizon blowout, National Oceanic and Atmospheric Administration (NOAA, 2012), had closed parts of the Gulf to both commercial and recreational fishing till 15 November, 2010. In June, 2010, 88,522 square miles which accounted for 36.6% of the federally managed waters of the Gulf

Exclusive Economic Zone had been closed. On the costal line, portions of Louisiana, Alabama, Mississippi and Florida state waters had also been closed. Fishermen had filed claims with BP for economic compensation. Seafood industry was also greatly affected by the consumer’s concerns of seafood safety. Booking and trips for recreational fishing charters were decreased, and cancellations of spot fishing tournaments had been announced (Hagerty, 2010). After the Prestige oil spill in the Galicia, Spain, 2002, an estimated decrease of 34,000 tonnes and 65 million euros for the aquaculture and coastal fishing was concluded along with 52 million euros for compensation of affected fishermen and people related to the fishing activity (Garza-Gil et al., 2006). The Prestige oil spills also greatly affected Galicia tourism; the incomes decreased 134 million euros, the domestic excursions and visits from other countries go down notably by 19% and 20%, respectively. The short and long term socioeconomic costs of the Prestige oil spill were estimated with assessment models as 633.58 million euros and 6734.4 million euros, respectively (Liu and Wirtz, 2006).

3.1.2 Environmental contamination and cleanup

Based on historical data of oil spill cleaning cost, important factors driving the costs included oil type, proximity to shoreline, location, cleanup methodology, and spill size (Etkin 2000). After normalization to 1999 US dollar, it is estimated that cost per unit oil spill cleanup of No.2 diesel fuel<light crude<crude<heavy crude<No. 6 fuel<No.5 fuel<No. 4 fuel. Spills of more persistent products require expensive spill response operations, and generally, fuel required more expensive treatment than crude (Etkin, 2000). Studies have also concluded that shoreline length oiled (Etkin, 2000), spill size (Etkin, 1999) were positively correlated with the cleaning cost, while the distance (Etkin, 1998b) from the shoreline had negative effect. On the other hand, the cleanup methods have been estimated with the sequence of natural attenuation (\$1,286.00/tonne)<*in situ* burning(\$3,127.87/tonne)<dispersants(\$5,633.78)<mechanical (\$9,611.97/tonne)<manual (23,403.45/tonne) (Etkin, 1998a). The cleaning and restoration of some oil spills was summarized in **Table 3.1**.

Table 3.1 Cleaning and restoration in some oil spills (source: Garza-Gil et al., 2006)

Oil spills	Type	Volume (1000 tonnes)	Cost(\$M or euros)	Costper tonnes(\$ or euros)
Amocco Cadiz (1978)	Crude	223	134	650
Exxon Valdez (1989)	Crude	35	3100	70,454
Erika (1999)	Fuel	20	124	6200
Prestige (2002)	Fuel	77	559	10,666

3.1.3 Ecological damage and restoration

Environmental damage cannot be directly measured from economic world; therefore, economic modeling tools have been applied to measure them in a monetary way. The environmental impacts reflected on economic loss was primarily attributed to the decrease of services of the natural source after the incident, and according to the study, in the Prestige accident, the environmental damages cost conservatively 633.58 million euros (Liu and Wirtz, 2006).

3.1.4 Evaluation of economic impact of oil spills

A study of the costs of 360 oil spills between 1990-1999 by the international of P& I Clubs has been conducted, and conclude the main factors influencing the cost of spills are type of oil, physical, biological and economic characteristics of the spill location, weather and sea conditions, amount spilled and rate of spillage, time of the year, effectiveness of clean-up as well as complex interactions between these factors(White and Molloy, 2003).

3.1.5 Liability and compensation

In US, the liability and compensation of oil spills are defined by Oil Pollution Act of 1990 (OPA) liability provisions. Under these provisions, responsible parties including owners/operators and lessees are liable for both oil spill removal cost as well as a range of other costs, including injuries to natural resources; loss of real personal property; loss of subsistence use of natural resources, lost government revenues resulting from destruction of property or natural resource injury; lost profits and earnings resulting from property loss or natural resource injury; and costs of providing extra public services during or after spill response (OPA, 1990). Accordingly, the 1989 Exxon Valdez spill tallied approximately \$5 billion in today's dollars, and BP announced \$20 billion to pay for the economic damages (Hagerty, 2010). To supplement OPA Compensation, the Oil Spill Liability Trust Fund (OSLTF) which is financed by a per-barrel tax on crude oil received at U.S. refineries and on petroleum products imported into US for consumption is established to respond oil spills and recover damages for private parties (Hagerty 2010). For the oil spills from tankers the 1992 International Oil Pollution Compensation (IOPC) Fund provide financial compensation for oil pollution damage in its 105 Member States, and it is financed by contributions of entities that received oil by sea transport. **Table 3.2** summarized costs of several notable spills in recent history.

Table 3.2 Costs of several notable spills in recent history(Source: Turner, 2010)

Incident	Location	Year	Spill volume, tonnes	Payments to claimants, US\$ million ¹	Payments 2010 CDN \$ million ²
Sea Empress	U.K.	1996	73,000	47	80
Nakhodka	Japan	1997	6,200	167	297
Erika	France	1999	20,000	138	258
Prestige	Europe	2002	64,000	133	244

¹Includes only response costs that were reimbursed; other sources report total response costs as much as 50% greater.

²Amount in US dollars converted to Canadian at exchange rate prevailing at time of incident, and brought forward to 2010 using Canadian CPI data.

Current Canadian laws cap a company's potential liability for damages from a spill at \$40-million in Arctic waters and \$30-million off Eastern Canada. The Polluter-Pays-Principle is a key element of good environmental practice in Australia. The company in charge of the Montara well, which blew out in August 2009, accepted responsibility for reimbursing the Australian Government for the costs of the clean-up, limited environmental monitoring and rehabilitation. However, the current Australian law places no specific liability on the owners of oil wells to pay for the clean-up or environmental damage caused by spills. Companies are only legally required to have insurance to cover the costs of complying with directions relating to the clean-up or other remediation of the effects of the escape of petroleum. The Australian Government has relied on the goodwill of the company in the Montara incident to recover costs. In Norway, regulations state that the licensee is liable for pollution damage without regard to fault. The regulations place no limit on the potential liabilities with regards clean-up costs or environmental damage caused by spills. There is a stated exception to this, that if the pollution were determined to be an inevitable event of nature, or due to an act of war, exercise of public authority or a similar force majeure event, then the liability may be reduced to the extent it is reasonable.

The United Kingdom has a strict liability regime in the form of the Offshore Pollution Liability Agreement. All offshore operators currently active in exploration and production on the U.K. Continental Shelf are party to a voluntary oil pollution compensation scheme known as Offshore Pollution Liability Association Ltd. (OPOL). OPOL has been extended to cover facilities in other offshore areas of North West Europe and has the support of the U.K. and other Governments. It is accepted as representing the committed response of the oil industry in dealing with compensation claims arising from offshore oil pollution incidents from exploration and production facilities. OPOL Limits of Liability have been increased over the intervening years to, at the time of the Macondo spill, US\$120 million per incident. In mid-August, this limit was raised to US\$250 million, based on an assessment of potential third-party costs of an oil-spill in modeled spill scenarios. The Oil-spill Advisory Group of OPOL has also commissioned the modeling of additional spill

scenarios with the aim of providing a more comprehensive picture of potential oil-spill costs.

Generally, the liability and compensation funds have been shown to cover only a fraction of the estimated real damages in some cases. The accumulated amount of the estimated losses for Galicia due to the Prestige oil spill (762 million euros) was 5 times the limits of applicable environmental responsibility (180 million euros)(Garza-Gil et al., 2006).

3.2 Environmental impacts

3.2.1 Impact on seabirds

After the Exxon Valdez oil spill (1989), 36,115 dead seabirds were recovered from beaches and processed at morgues. Most of 1,888 live oiled seabirds brought to rehabilitation centers also died and about 3,260 oiled carcasses were never delivered to morgues. Of these 41,263 carcasses accounted for, Piatt and Ford (1996) estimated that only 30,000 were killed by oil population. They also conducted the study to estimate the impact with uncertainty analysis, and made the final conclusion that about 250,000 seabirds were killed by Exxon Valdez oil spill.

For the Sea Empress oil spill, the waters of Welsh coast around the impacted area are of outstanding international importance for breeding seabirds, wintering sea-duck, and waterfowl. Oiled birds, both live and dead, were collected along the whole coastline affected. By June 1996, 7000 birds of 36 species had been collected, 85% of which came ashore between February 24 and March 4, 1996, when most bulk oil was on the sea. The species most affected was the common scoter, which comprised two-thirds of the birds recorded (4600). Most of the remainder was auks, mainly guillemots (1600) and razorbills (340). The wintering population of common scoter was badly affected, with 10,000 fewer birds in 1997 than in 1996 (SEEEC, 1998).

For the Braer oil spill, Five species of seabirds comprised 89% of the 1768 birds found oiled as a result of the incident: shags, black guillemots, kittiwakes, long-tailed ducks, and eider ducks. In the subsequent year, reduced breeding numbers were apparent for shag and black guillemot, but increased numbers were seen in affected colonies during 1994e1995. No effects on foraging behavior were seen in four species of seabirds (kittiwakes, Arctic terns, shags, and guillemots) despite feeding in oiled areas (Davis and Topping, 1997).The oil spill did not have a major impact on the abundance of young sandeels, food for the chicks of Arctic terns and kittiwakes.

During 1991 Gulf War oil spill, an estimated 30,000 seabirds were killed, and breeding success in 1992 and 1993 severely declined; however, seabird colonies appeared to recover by 1995 (Symens and Alsuhaibany, 1996; Symens and Werner, 1996).

After the Tanker SOLAR 1 oil spill in Philippines, the pollution by the oil from the Torrey Canyon was found to have little biological effect other than the death of more than 30,000 seabirds (Bourne et al., 1967). In a sample of 1223 dead birds of eight different species collected on UK coasts, almost 98% were guillemots and razorbills. These species are particularly vulnerable to spilled oil, as was also seen during the recent UK incident involving the container ship MSC Napoli (Law, 2008). The main bird mortality caused by the Torrey Canyon involved local British populations, especially the larger auks, including disproportionately high numbers of young birds that are more migratory. Some sub-adult shags (birds of the cormorant family) seeking nesting sites were also killed (Bourne et al. 1967).

3.2.2 Impact on fish and shellfishes

Due to the Exxon Valdez oil spill, After the Braer oil spill (1993), a fisheries Exclusion Zone was established to prevent contaminated fish and shellfish from entering the human food chain. In support of this effort, and because of the high value and vulnerability of fish and shellfish to contamination by oil and polycyclic aromatic hydro-carbons (PAHs) as a result of the large quantity of oil (ca. 72,000 tons) dispersed into the water column, a major monitoring program was undertaken (Davis and Topping, 1997). Fish and shellfish were collected both from fish markets (for reference samples collected outside the Exclusion Zone) and from research vessels and hired fishing vessels (within the Exclusion Zone). The first samples were collected around January 13-17, 1993. In these samples both hydrocarbon (aliphatic hydrocarbons and PAHs) composition and concentration and the level of petroleum-associated taint in edible flesh were assessed, the latter using a trained sensory assessment panel. Full details of the procedures used are given elsewhere (Davies and Topping, 1997; Davis et al., 2002). Sensory assessment is a relatively cheap and rapid method of analyzing a large number of samples; several thousand samples were analyzed in the first few months following the Braer spill. A highly trained sensory panel can produce consistent data that can be readily used to select samples for more detailed, instrumental analysis. All species sampled during January 1993 were found, by gas chromatography-mass spectroscopy (GC-MS), to contain elevated concentrations of PAHs. In wild fish, concentrations fell rapidly from a maximum of 2650mg/kg wet weight to reference concentrations (less than 40mg/kg wet weight) when there was also an absence of taint. The fishery was reopened during April 1993. Concluding on appropriate reference or background concentrations for PAH in fish is fundamental, for this provides clear criteria for removing harvesting restrictions. In the case of the Braer, the absence of any petrogenic taint was also a condition for lifting restrictions. Low levels of contamination of free-living finfish by PAH was also a feature of the Sea Empress spill (Law and Kelly, 2004), primarily as a result of the accumulation of two- and three-ring PAH (naphthalenes and phenanthrenes) from the dissolved phase via the gills. Such contamination is rapidly lost as the dissolved concentrations fall. Crabs and lobsters retained significant levels of contamination for a longer period, on the basis of both sensory and instrumental analysis. Restrictions on the collection and

sale of crustaceans other than *Nephrops norvegicus* (Norway lobsters) were removed in September 1994, 20 months after the spill (Davies and Topping, 1997). As for fish, an absence of petrogenic taint was a prerequisite of removal of a harvesting ban, and PAH concentrations were required to be within the established reference concentration range. Bivalve mollusks (mussels and scallops) accumulated high concentrations (greater than 20,000mg/kg wet weight) of two- to six-ring PAHs, including those that are of carcinogenic potential and of concern in the human food chain (Law et al., 2002). Lower concentrations were seen in whelks, probably because they are carnivores rather than filter-feeders, as filter-feeders can ingest dispersed oil droplets directly (Law and Kelly, 2004). Restrictions were removed for all mollusks except mussels in February 1995, two years after the spill (Davies and Topping, 1997). Long-term monitoring of PAH contamination in mussels, using both sensory assessment and GC-MS, was continued as a result (Webster et al., 1997), but in 1996 concentrations were still higher than the reference concentrations, although no taint could be detected. Parallel studies in sediments in which PAH profiling was undertaken using GC-MS indicated that the primary source of PAH in the majority of Shetland Island sediments sampled was pyrogenic rather than petrogenic (i.e., from combustion sources rather than oil), and that concentrations within the Exclusion Zone were not significantly higher than those in sediments from outside the zone (Webster et al., 2000). Considerable additional investigation was required into why concentrations in mussels were so variable. When the primary source of contamination (the oil spill) is no longer a significant source of PAHs, and PAH concentrations are close to reference values, potential local, minor sources of PAHs should be investigated, as should the impact of seasonality. In this context, there is a need to establish winter and summer reference concentrations for mussels. The final fishery restrictions, for mussels and Norway lobster, were lifted seven years after the spill. Fisheries are an important part of Shetland's economy, and the value of the commercial fish and shell fisheries affected by the spill was around £22 million in 1993.

During the Sea Empress oil spill, there were no reported mortalities of commercial fish or crustacean species as a result of the spill. Large numbers of dead or moribund shellfish (mostly bivalve mollusks) were, however, washed ashore during the weeks following the spill (SEEEC, 1998). None of these involved the major, commercially exploited stocks (mostly cockles and mussels) in estuarine areas (particularly the Three Rivers area and the Burry Inlet. These incidents involved a number of species (including cockles, clams, and razorshells (Rutt et al., 1998) and occurred within the area of bulk oil contamination.

3.2.3 Impact on benthos

The effects of oil spills on benthic organisms may be especially important because of the multiple ecological process and ecosystem functions that these organisms support (Mendelssohn et al., 2012). The primary productivity of benthic microalgae may rival that of macrophytes, and benthic microalgae serve as the

principal food resource for much of the wetland food web. As ecological engineers, infauna bioturbate and aerate sediments, facilitate the decomposition of detritus, and enhance flux of nutrients between sediments and the water column. They also serve as food for nekton (fishes and other natant organisms) foraging on flooded wetlands. Epifauna (e.g. the marsh periwinkle) may contribute to trophic cascades that regulated macrophyte abundance, and reef-building suspension feeders (mussels and oysters) create nursery habitat for many species. The biomass, species composition, and availability of benthos therefore affect higher trophic levels in food web that include humans (Mendelsohn et al., 2012).

In the Exxon oil spill, a field survey of 31 streams found significantly higher pink salmon egg mortality in oiled than in unoiled streams in 1989-91 (Bue et al., 1993). Coded wire tag data indicate that juvenile growth rates were significantly lower in moderately oiled hatchery areas than in lightly oiled areas in 1989, although low water temperatures confounded oiling (Willette et al., 1994). Other studies also showed that significant higher Dolly Varden fish (Hepler et al., 1993; Marty et al., 1993), Herring (Biggs and Baker, 1993; Funk, 1994), shrimp (Armstrong et al., 1995; Donaldson and Ackley, 1990) and snail (Hignsmith et al., 1995; Houghton et al., 1993) mortality in oiled than unoiled stream.

In order to investigate the impact of the Braer oil spill on benthos, 12 intertidal sites were studied, both those sites affected by the oil and those selected as reference sites (Davies and Topping, 1997). Effects on rocky shores close to the wreck site were more evident than in the sediments. Limpet populations were absent from the mid-lower shores, leading to a consequent bloom of algae that persisted for some months. No effects were observed in sub-tidal rocky areas exposed at low water. Two offshore locations were also studied, at which deposition of oil had taken place. Only minor impacts on community diversity were observed, although amphipods were absent from the most heavily contaminated sites in 1993. From studies conducted after the Sea Empress spill, amphipods seem to be particularly vulnerable to dispersed oil in the water column (Law and Kelly, 2004). Recovery of the amphipod fauna was evident in that instance after two years, as confirmed by a subsequent survey two years later (Nikitik and Robinson, 2003). In the case of the Braer, recovery was underway but incomplete in 1994 (Davies and Topping, 1997). No gross impacts were observed.

Studies of the seabed benthic communities showed little impact from the Sea Empress oil spill except for marked reductions in the number of amphipods in areas to the north of the grounding site, within Milford Haven (Law and Kelly, 2004; Levell, 1996). The amphipods, which are particularly vulnerable to oil, were likely affected by naturally dispersed oil being carried into Milford Haven on flooding tides rather than chemically dispersed oil, as oil was chemically treated some miles from shore as the tide ebbed. The entrance to Milford Haven is extremely turbulent, and so oil released into the flooding tides would disperse very effectively. Recovery of the amphipod fauna was evident in a survey undertaken in 1998 and continuing in a later survey in 2000 (Nikitik and Robinson, 2003).

The benthos has experienced a broad range of effects from the DWH spill, and these effects probably varied, depending on many factors. Because of their high biomass and ecosystem-engineering qualities, large epifauna, such as fiddler crabs, oysters, periwinkles, and ribbed mussels, have a high potential to alter marsh ecological function. Fiddler crabs are sensitive to the toxic effects of oil, and therefore, declines in abundance could cause indirect effects that are significant but difficult to predict. The marsh periwinkle (*Littoraria irrorata*) has a significant grazing impact on *Spartina* (Silliman et al., 2005). Toxic effects on *L. irrorata* would presumably decrease grazing pressure on *Spartina* and may aid its post spill recovery. However, oil toxicity expressed on *Geukensia demissa* (the ribbed mussel) may reduce *Spartina* production, because mussels increase soil nitrogen content (Bertness, 1984). Oysters are the principal benthic suspension feeder in the northern Gulf of Mexico and appear to be sensitive to oil-particularly to oil suspended in the water by dispersants. They may also have suffered from the effects of reduced salinity after freshwater diversions were opened to increase outflow from coastal bays in an attempt to prevent the entry of oil into marshes. Oyster reefs provide important habitat for many estuarine species, and therefore, the indirect effects of oyster toxicity could be substantial. Benthic infauna in Mississippi River Delta marshes is typically composed of small-surface deposit-macrofauna (mostly small annelids) and meiofauna (Mostly nematodes and copepods) (Carman et al., 1997) that are consumed in high numbers by juvenile fishes and by crustaceans, such as shrimp. Oil-induced changes in species composition in Louisiana will likely not greatly affect the body size of infauna, and therefore predation rates by nekton may be less affected than in other wetlands.

3.2.4 Impact on wetland vegetation

Wetland vegetation is the ecosystem component providing the foundation for wetland structure and function on which many important ecosystem services rely. Vegetation responses to petroleum hydrocarbons and vegetation's capacity to recover are dependent on a variety of factors both intrinsic to the plant species and specific to the spill event. Because spills occur under different chemical, environmental, and biotic conditions, impacts and recovery trajectories can vary greatly and can be difficult to predict. The primary determinants of vegetation responses to petroleum hydrocarbons are (1) toxicity of the oil, which is itself dependent on the types of oil, the amount of weathering, and the extent of plant coverage; (2) the oil's amount of contact with the penetration of the soil; (3) plant species composition; (4) oiling frequency; (5) the season of the spill; and (6) cleanup activities (Lin and Mendelsohn, 1996; Hester and Mendelsohn, 2000; Pezeshki et al., 2000).

The type of oil is a primary determinant of toxicity. Heavy crude oils, such as San Joaquin or Venezuela crude, which are composed of small concentrations of low molecular weight alkanes and aromatics, have a small amount of direct toxicity to plants, whereas light crudes, such as South Louisiana weight hydrocarbons, can

cause necrosis and plant mortality on contact. Of course, even highly toxic refined products such as diesel, if they are weathered enough, will eventually lose toxicity, but the less toxic residuals can still coat vegetation. This condition prevents photosynthesis, thereby impairing the assimilation of carbon used for growth and transpiration, which promotes evaporative cooling. The frequency of repetitive oiling of vegetation is also an important determinant of the ultimate injury; repetitive oiling depletes the underground nutrient reserves used to generate new shoots after successive re-oilings. The time of the year in which an oil spill occurs also influences the spill's impacts on plants. Spills during colder periods, when plants have a lower metabolism or are dormant, have a reduced impact relative to oil exposure during warmer seasons (Alexander and Webb, 1985). However, arguably the most important determinant of severity is whether the oil penetrates the soil and comes into contact with nutrient-absorbing roots and shoot-regenerating rhizomes; this scenario can cause plant death. Perennial marsh plants, which regenerate new aboveground shoots each spring, usually recover from organs more often results in plant death. Species specific difference in responses to oil can be dramatic (Lin and Mendelsohn, 1996). Oil cleanup is another important controller of oil spill impacts. Manual removal of oil by spill response personnel can break plant shoots, which may do more harm to the vegetation than the oil itself, or they may push oil farther into the soil (Hoff et al., 1993; Hester and Mendelsohn, 2000). Therefore, first responders to oil spills try to minimize such damaging impacts.

The extent of recovery of marsh vegetation after an acute oil spill impact can be just as variable as the initial effect of the spill on vegetation. In situations in which the oil has an impact only on aboveground shoots and leaves, recovery can be relatively rapid, occurring the following growing season or earlier, depending on the presence of viable propagules, the prevalence of residual oil, the extent of shoreline erosion, and the impacts of the cleanup (Hester and Mendelsohn, 2000). However, when oil penetrates the soil and the initial mortality of the vegetation is extensive, recovery to reference conditions may take 3-4 years (Hester and Mendelsohn, 2000) or even longer (Bergen et al., 2000; Michel et al., 2009). In extreme cases, recovery may never occur if certain intrusive remediation actions are performed (e.g. soil removal, as in the *Amoco Cadiz* spill; Baca et al., 1987; Gilfillan et al., 1995), or if erosion due to wave energy or subsidence is accelerated after plant mortality. In contrast, some remediation actions, such as *in situ* burning, can provide post-spill conditions that enable initial recovery within days or weeks (Baustian et al., 2010). Therefore, although a number of factors influence the degree of impact and the speed of recovery from oiling, vegetation recovery is more the rule than the exception.

During the Deepwater Horizon oil spill, marsh shorelines and generally not the marsh interior were primarily exposed to the weathered oil, a situation that limited the extent of environmental damage. Nonetheless, approximately 430 miles of marsh shorelines were oiled (Zengel and Michel, 2011). Of those marsh shorelines that were oiled, 41% (176 miles) were either heavily or moderately oiled (Zengel and Michel, 2011). The primary marsh types affected were salt marshes

dominated by *Spartina alterniflora* and *Juncus roemerianus*; mangroves, dominated by the black mangrove (*Avicennia germinans*), which were located on small islands and shorelines and as scattered stands within salt marshes; and low to intermediate salinity marshes, dominated by *Phragmites australis*, the common reed, along the margin of the Mississippi River Bird foot Delta. Although few quantitative data are yet available on the extent of vegetation impacts, recent findings for the salt marshes in the Bay Jimmy area of northern Barataria Bay, Louisiana documented variable impacts depending on oiling intensity (Lin and Mendelssohn, 2012). Along heavily oiled shorelines, near complete mortality of the two dominant species, *S. alterniflora* and *J. roemerianus*, occurred. In contrast, moderate oiling had no significant effect on *Spartina*, despite significantly lowering live aboveground biomass and stem density of *Juncus*. Since the spill, some recovery has been noted for oiled marshes (Mendelssohn et al., 2011). For example, in the oiled delta marshes at the mouth of the Mississippi River, *P. australis* produced new shoots from oiled nodes on the stems, and *S. alterniflora* regenerated from rhizomes along moderately and some heavily oiled shorelines throughout Louisiana. However, as of the fall of 2011, many of the most heavily oiled shorelines had minimal to no recovery, and only time will tell whether these shorelines will re-vegetate naturally before shoreline erosion occurs.

3.3 Public health impacts

When a big spill occurs there is usually a large group of volunteers, in general local inhabitants, who mobilize and take part in the cleanup work to minimize the impact of the spill on the natural and economic resources and recover the coastal environment as soon as possible. These individuals constitute an exposed population whose health may be potentially affected by the noxious properties of the oil.

Nevertheless, there are only a few studies focused on the repercussions of oil exposure for human health. Most of them are related to acute effects and psychological symptoms

3.3.1 Effects caused by transference to the food chain

Amat-Bronnert et al. (2007) performed an in vitro study in two human cell lines, one from hepatoma and another one from bronchial epithelium, treated with an Erika fuel extract. DNA adducts performed by 32 P-post labelling method were only detected in hepatoma cells, indicating biotransformation via cytochrome P450 (CYP) 1A2 and 1B1 since the two cell lines do not possess the same metabolic system (hepatoma cells exhibit a wide spectrum of metabolic enzymes while bronchial cells do not). Moreover, western blot and densitometry quantification showed that exposure to the fuel extract induced some metabolizing enzymes such as CYP 1A2, cyclooxygenase 2 and 5-lipoxygenase; the latter two are involved in

carcinogenic processes. In epithelial bronchial cells induction of leucotriene B₄, a mediator of inflammation, was revealed by immunoassay. These results acquire special importance with regard to human health, since inhalation is one of the most representative ways of absorbing fuel compounds. Lemiere et al. (2005) carried out a study to determine the potential genotoxic risk for consumers of marine food contaminated with polycyclic aromatic hydrocarbons (PAH) coming from oil spills. Mussels (*Mytilus* sp.) contaminated with Erika oil were collected and provided daily to rats over periods of 2 and 4 weeks. The DNA damage was measured by the single-cell gel electrophoresis (comet) assay in hepatic, bone marrow and blood cells. While no evidence of genotoxicity was observed in the peripheral blood samples, significant increases in DNA damage were observed in the liver and the bone marrow of rats ($P < 0.001$). The intensity of the DNA damage increased with the PAH contamination level of the mussels. Therefore, this study demonstrated that oil-contaminated food can cause genotoxic damage in consumers. Also, it showed that mussels, often present in the human diet especially in coastal producer regions, carry pollutants in a bioavailable form when contaminated with oil.

A similar study in rats fed with Erika oil-contaminated mussels (*Mytilus edulis*) was performed by Chatyet al. (2008). Rats were fed for 2 days and CYP 1A1 mRNA expression and ethoxyresorufin-O-deethylase (EROD) catalytic activity were analyzed by RT-PCR and a fluorimetric method, respectively. Results obtained showed the transient induction of CYP 1A1 mRNA and EROD activity, which reached a maximum after 12 h, returning to basal levels within 36 h. The studies presented in this section show evidence for the bioaccumulation of oil compounds and their transference to the food chain in oil-contaminated marine food, and demonstrate the induction of DNA damage by the products generated by metabolic enzyme activity transforming many polluting agents into even more toxic intermediaries. In this regard, Bro-Rasmussen (1996) indicated that toxic chemicals at low concentrations will not immediately kill humans; however, depending on their potential to bioconcentrate when climbing the food chain, persistent chemicals may create a human hazard in the case of chronic ingestion. For this reason, *in vitro* and *in vivo* studies that consider not only bioaccumulation ability, but also the time that the pollutants stay in the organisms and the transference rate through the different links of the food chain, must be performed, and also studies on the optimal way to decontaminate oil-exposed organisms to make them safe for human consumption.

3.3.2 Acute toxic and psychological effects

The first oil spill for which studies on the effects on human health are collected in the literature is the one from Exxon Valdez. Although a variety of studies exist on the ecological impact of this spill, only a few consider the psychological, psychiatric and social effects.

Palinkaset al. (1992) assessed the levels of depressive symptomatology between two groups, one of indigenous people (N=188) and another one of Euro-Americans (N=371), all of them residents in 13 communities of Alaska (11 in the

region directly exposed to the oil spill itself and two control communities). The results of these authors suggested that cultural differences played an important role in the perception of the psychological damage produced by this disaster, which was related to the cleaning work in which the people were involved and also the damage to fishing grounds, the main sustenance of these communities. The group of Euro-Americans showed a certain moderating effect of the damage in relation to familiar support; however, this factor did not significantly influence in the indigenous groups. These results emphasize the role of cultural differences in the perception of and capacity to overcome the psychological impact. Later, the same authors (Palinkaset al., 1993) as a result of this same disaster examined the relationship between exposure and subsequent cleanup efforts and the prevalence of generalized anxiety disorder, post-traumatic stress disorder (PTSD) and depressive symptoms in 13 communities of Alaska. They performed a community survey of 599 men and women approximately 1 year after the spill. Prevalence of 20.2 and 9.4% were found for the generalized anxiety disorder and PTSD, respectively. Also, the prevalence of depression scale scores above 16 and 18 was 16.6 and 14.2%, respectively. For all the parameters analyzed, exposed individuals showed scores several times higher than unexposed individuals. Women were particularly vulnerable to the effects of exposure to the oil spill and cleanup activities on the prevalence of generalized anxiety disorder ($b=0.22, P<0.0001$; odds ratio=1.43, 95% CI 1.23–1.67), PTSD ($b=0.19, P<0.001$; odds ratio=1.40, 95% CI=1.15–1.69) and CES-D Scale scores of 18 and above ($b=0.17, P<0.001$; odds ratio=1.35, 95% CI=1.13–1.60). The authors suggest, on the basis of their results, improving the mental health care of disaster victims, particularly in primary care settings. Gill and Picou (1998) monitored the impact of Exxon Valdez spill on the affected populations by means of a 4-year (1989–1992) longitudinal study in which they applied a survey on social disruption and psychological stress, using random-sampling strategies, personal interviews and control communities. Data obtained revealed the chronic nature of stress. Out-migration expectations and desires increased from 1989 to 1991. Social disruption was reported by a high proportion of residents in 1989, but had declined to just over half in 1991. High levels of event-related psychological stress were found in 1989 and 1990 but they diminished in the following two years. Finally, Palinkaset al. (2004) confirmed the prevalence of PTSD associated with ethnic differences. They reported high levels of social disruption one year after this disaster, in both ethnic groups (indigenous Alaskan and Euro-Americans). However, low level family support, participation in spill cleanup activities and a decline in subsistence activities were significantly associated with PTSD in indigenous Alaskan, but not in Euro-Americans.

Campbell et al. (1993) performed a cross-sectional study in which a population of individuals exposed to MV Braer oil spill ($N=420$) was compared with a control group ($N=92$), from Hillswick, 95 km north of the incident. They compiled information on demographic details, smoking and alcohol consumption, perception of health, peak expiratory flow, hematology, liver and renal function tests, and blood and urine toxicology. Their results showed that, during the first and second day after the spill, the population reported mainly headaches, irritation of the throat and

itchy eyes. The authors did not find significant differences between both groups for any of the biological markers. Taking these results together, only anecdotal reports of certain acute symptoms could be confirmed. Later, the same authors reported longer-term effects in the same populations (344 exposed individuals and 77 controls; Campbell et al., 1994). Among exposed people, 7% perceived their health to be poor compared with none of the controls ($\chi^2=8.05$, $df=3$, $P<0.05$). Comparison of the symptoms of exposed people in the 2 weeks before with their presence immediately after the incident showed more tiredness and fever, and fewer throat, skin and eye irritations, and headaches (odds ratio=1.86, 95% CI 1.19–2.92). The mean general health questionnaire score of the exposed subjects was significantly greater than that of the controls. The high rate of non-responders among individuals selected to participate in this study was reported (59 of the 215 non-responders in the first phase of the study and 16 of the 86 non-responders in the second phase were surveyed). The main reasons for non-responding was not feeling that their health had been affected, not interested in the study or did not think the study was useful (Foster et al., 1995). Crum (1993) performed a cross-sectional study evaluating the peak expiratory flow rate in two groups of children aged 5–12 years who were resident within 5 km of the Braer shipwreck. The first measure was carried out three days after the accident in 44 children, and a second one in 56 children between 9 and 12 days after the oil spill. The main results showed that the children's peak expiratory flow rates were within the normal range in both parts of the study, and no deterioration was seen over the study period, even in the children known to have asthma. No significant difference was observed between the two sets of values ($P=0.502$, Student's *t* test for paired samples).

In the wake of the Sea Empress oil spill, Lyonset et al. (1999) investigated the acute health effects (self-reported physical and psychological symptoms) in the residents of the vicinities of the affected area (Milford Haven, southwest Wales). They designed a retrospective cohort study that included 539 exposed and 550 controls. Results obtained, after adjustment by age, sex and smoking status, allowed the conclusion that the people living in the exposed areas presented high levels of anxiety and depression scores, worse mental health and self-reported headache (odds ratio=2.35, 95%CI 1.56–3.55), sore eyes (odds ratio=1.96, 95% CI 1.06–3.62) and sore throat (odds ratio=1.70, 95% CI 1.12–2.60). These last three symptoms were expected from the known toxicological effects of oil, so the authors suggested a direct health effect in the exposed population. On the basis that exposure to a complex emergency has a substantial psychological component, Gallacher et al. (2007) performed work in 794 exposed individuals and 791 controls in which anxiety, depression and symptom reporting were used as measures of the health impact. The main results indicated that perceived risk was associated with raised anxiety and non-toxicologically related symptom reporting (odds ratio=2.28, 95% CI 1.57–3.31, $P<0.001$), whereas physical exposure to oil was only associated with toxicologically related symptom reporting. The authors concluded that psychological exposure was a substantially more sensitive measure of health impact than physical exposure in relation to psychological outcomes.

Morita et al. (1999), as a result of the Nakhodka oil spill, conducted a study in 282 people (men and women) who joined in cleanup work. Interviews on health status and determinations of several hydrocarbon metabolites in urine were carried out. Their results were similar to those from Campbell et al. (1993), showing that people suffered mainly from pains in the lumbar region and legs, headaches and irritation of eyes and throat. The multivariate logistic regression model was applied to clarify the risk factors of having at least one symptom with several relevant variables. Results showed that being of female gender, the number of working days on cleanup activities, direct exposure to oil and history of hypertension and low back pain were significant risk factors for the development of symptoms ($P < 0.05$). In the urine analyses, only three individuals showed higher levels of hippuric acid ($> 1.0 \text{ mg l}^{-1}$) that had returned to normality four months later. In this study the use of personal air samplers by the cleanup workers was remarkable. They allowed the determination of the concentrations of carcinogenic benzene, toluene and xylene in the environmental air, and their results showed that these levels were lower than the occupational acceptable limits (10 ppm for benzene, 100 ppm for toluene and 100 ppm for xylene). The highest concentration of suspended particles on any given day was 0.088 mg m^{-3} , also below the occupational acceptable limit (2 mg m^{-3}). Erika Schvoerer et al. (2000) presented a cross-sectional investigation on human health risk assessment as a result of the Erika oil spill in 3669 interviewed people, who included cleaning workers and volunteers. Their results indicated that 7.5% of the individuals experienced some type of wound and 53% some health problem (30% lumbar pain, 22% migraine, 16% dermatitis). They reported in a smaller degree ocular irritation (9%), respiratory problems (7%) and nausea (6%). The duration of the cleaning work was identified as a risk factor. Baars (2002) evaluated the health risk for people involved in the cleaning activities after the Erika oil spill and also for tourists, with an emphasis on the carcinogenic properties of the oil, on the basis of the known toxicological properties of the oil components and assumptions on the levels of exposure during the performance of different activities. In assessing toxic risks the actual exposure levels were compared with limit values taken from the literature; in assessing carcinogenic risk the actual exposure levels were compared with the $1:10^4$ lifetime excess risk of developing tumors. The outcome indicated that the risks for the general population were limited. For people who had been in bare-handed contact with the oil there was increased risk of developing skin irritation and dermatitis, but these effects were in general reversible, and also that of developing skin tumors, which was very limited due to the short contact time with the oil. Doret et al. (2003) reported an assessment of human health risk after decontamination of beaches polluted by the Erika oil. They determined the 16 PAH selected by the US EPA in samples of sand, water and the surface of rocks from 36 cleaned-polluted beaches and seven control beaches, and contemplated seven possible scenarios of exposure for people using the beaches in tourist activities (children, adults and pregnant women) or working activities. The life-long excess risk for skin cancer and for all other cancers was about 10^{-5} in scenarios including contact with the polluted rocks. The authors concluded that exposure was mainly associated with polluted water among children and with contaminated rocks for

adults, and that, despite uncertainties, decontaminated beaches did not entail any significant health risks and could be opened to the public.

As a result of the disaster of the tanker Prestige, densely populated coastal regions of Spain (Galicia, Asturias, Cantabria and the Basque country), as well as the neighboring French coasts, with intense activity of extraction of marine resources and tourism, were affected. Several studies were performed after this accident in order to evaluate the possible human health effects. Suarez et al. (2005) evaluated the conditions of exposure and the acute health effects in individuals who participated in the cleanup works in the regions of Asturias and Cantabria (Spain), and the association between these and the type of work. Four hundred individuals from each region were interviewed. Collected data included information on the work performed, use of protection devices and acute symptoms. Bird cleaners accounted for the highest prevalence of lesions (19%, $P < 0.001$), including neurovegetative disorders (11.2%, $P = 0.169$) and low back pain (3.1%, $P = 0.281$). Working periods longer than 20 days in highly polluted areas were associated with increased risk of injury in all workers. A specific analysis restricted to seamen only found a strong and significant association with having worked for more than 3 days (odds ratio=14.30 and 11.02 for categories of 3–20 days and over 20 days, respectively) and having torn or not worn the protective suit (odds ratio=1.20 and 7.79, respectively), but no severe disorders were identified among individuals analyzed. The same authors reported another study examining the association between use of protective devices, frequency of acute health problems and health-protection information received by 799 exposed individuals, classified according to the tasks performed (Carrasco et al., 2006). These authors observed a significant excess risk of itchy eyes (odds ratio=2.89; 95%CI 1.21–6.90), nausea/vomiting/dizziness (odds ratio=2.25; 95% CI 1.17–4.32) and throat and respiratory problems (odds ratio=2.30; 95% CI 1.15–4.61) among uninformed subjects. Furthermore, there was a noteworthy significant excess risk of headaches (odds ratio=3.86; 95% CI 1.74–8.54) and respiratory problems (odds ratio=2.43; 95% CI 1.02–5.79) among uninformed paid workers. Seamen, the group most exposed to the spilled oil, were the worst informed and registered the highest frequency of toxicological problems. Therefore, the authors confirmed the results obtained in their previous study and found a significant association between proper health-protection briefing and use of protective devices and lower frequency of health problems. Zocket al. (2007) evaluated the prevalence of lower respiratory tract symptoms (LRTS) more than a year after Prestige accident in 6780 fishermen who had participated in the cleanup labors (response rate 76%), through questionnaires that included qualitative and quantitative information. Their results showed that LRTS was more prevalent in cleanup workers (odds ratio=1.73; 95% CI 1.54–1.94), and that the risk of LRTS increased in relation to the number of exposed days, exposed hours per day and number of activities carried out (linear trend, $P < 0.0001$). The excess risk of LRTS decreased with elapsed time since last exposure (odds ratio=2.33, 1.69 and 1.24 for less than 14 months, 14–20months, and more than 20months, respectively), although it was still significant when more than 20 months had elapsed. Carrasco et al. (2007) performed a new study on the effects of the Prestige oil spill on health-

related quality of life (HRQoL) and mental health in the affected population, approximately 18 months after this disaster, using several questionnaires. The main results showed coastal residents as having a lower likelihood of registering suboptimal HRQoL values in physical functioning (odds ratio =0.69; 95% CI 0.54–0.89) and bodily pain (odds ratio=0.74; 95%CI 0.62–0.91), and a higher frequency of suboptimal scores in mental health (odds ratio =1.28; 95% CI 1.02–1.58). The authors concluded that, almost one and a half years after the accident, worse HRQoL and mental health levels were not in evidence among subjects exposed to the spilled oil. Nevertheless, a slight impact on the mental health of residents in the affected areas was suggested by some of the scales applied. Similar results were obtained by Sabucedo et al. (2009), who evaluated the psychological impact of Prestige oil spill. They carried out a descriptive study that involved 938 men and women from 23 localities throughout the Galician coast. Half of them were fishermen or workers related to the extraction of fishing resources, and the other half were not linked to these activities. Questionnaires on different psychological and psycho-social factors were filled in at the time of the accident and one year after. The results showed that the affected subjects had received a good deal of social support and were satisfied with the economic aid received. In addition, affected individuals with high support and satisfaction scores were currently in a better situation than those affected with low scores, and even better than those not affected.

Janjua et al. (2006), following the Tasman Spirit ship wreck, conducted a study which included an exposed group composed of adults of both genders living on the affected coastline (N=216) and two control groups living 2 km (N=83) and 20 km (N=101), respectively, away from the indicated area. Surveys on acute symptoms related to eyes, respiratory tract, skin and nervous system, as well as consultations of allergies, tobacco consumption and perceptions on the effect on their health and anxiety about their health effects were performed. Their results showed moderate-to-strong associations (prevalence odds ratios ranging from 2.3 to 37.0) between the exposed group and the symptoms, which decreased with the distance from the spill site, and multiple linear regression model revealed strong relationship of exposure status with the symptoms score (b=8.24, 95%CI 6.37–10.12). Khurshid et al. (2008) presented a short-term study in people who were working or living in the vicinity of Karachi beach. Hematological and biochemical parameters were determined, and liver and renal function tests were carried out. They also took seawater and sand samples and analyzed them for hydrocarbon/organic contents. The results only showed slight rises in the levels of lymphocytes and eosinophiles. The authors recommended performing follow-up studies after oil spills taking samples every 3 months for 3–5 years, noting respiratory disorders and any changes in the skin. Finally, Meo et al. (2008) assessed, by means of spirometry, lung function and followed up the progression after one year in 20 subjects exposed to this oil spill and 31 controls. Subjects exposed to polluted air had significant reductions in lung function compared with their matched controls (Pranging from 0.001 to 0.02 for the different lung function parameters). The reported impairment was reversible and lung function parameters were improved when the subjects were withdrawn from the polluted air

environment. In summary, studies performed after Exxon Valdez spill only accounted for psychological effects in the exposed populations. For all the other accidents, there are also studies on acute toxic effects, and moreover, for the Erika oil spill there are two works on potential toxicological risk assessment, both concluding that exposure to pollutants contained in the oil during common activities did not entail any significant health risk. Data obtained in most of these studies indicated that technological disasters that involve oil spills have acute physical consequences that diminish with time and are mainly reversible, and psycho-logical consequences and continuing disruptive and stress-provoking consequences for resident communities. The results also suggested that conflicting definitions of long-term effects and recovery of the natural environment contributed to community stress.

3.3.3 Genotoxicity and endocrine toxicity

Colelet al. (1997) evaluated the possible genotoxicity as a consequence of the Braer tanker oil spill. They used blood samples to assess the primary damage in the DNA (DNA adducts in the mononuclear cell fraction by a modified ³²P-post labeling method and mutations at the hprt locus in T lymphocytes). These authors did not obtain any evidence of genotoxicity for either end point, but they proposed several issues to be taken into account in the design of biomonitoring studies after oil spills.

Laffonet al. (2006) conducted a study to determine the possible genotoxic damage associated with the exposure to Prestige oil, in 34 volunteers, who worked in autopsies and cleaning of oil-contaminated birds, and 35 controls. Environmental concentrations of volatile organic compounds (VOC) in the working room were determined. Genotoxicity was evaluated by means of micronucleus (MN) test and comet assay, and the possible influence of several DNA repair genetic polymorphisms was also analyzed. Their results showed significantly higher DNA damage ($P < 0.01$), but not cytogenetic damage, in relation to the exposure time ($r = 0.376$, $P < 0.05$), and also certain exposure-genotype interactions. Pérez-Cadahía and colleagues performed a study with the objective of evaluating the genotoxicity and endocrine toxicity related to exposure to Prestige oil during the different cleaning labors. Exposed individuals were classified into three groups: manual volunteers, hired manual workers and hired workers using high-pressure water machines. The environmental exposure levels of VOC were determined and different biological parameters were measured. Their results were published in different papers. In an initial stage (Pérez-Cadahía et al., 2006, 2007), a relatively small population (68 total exposed vs 42 controls) was analyzed. The data obtained indicated that the highest levels of VOC were observed in the volunteer environment and that exposure to Prestige oil induced genotoxic damage (tests applied: sister chromatid exchanges (SCE), MN test and comet assay), the comet assay being the most sensitive test to detect it, and alterations in hormonal status (prolactin and cortisol plasma concentrations, significant decreases with $P < 0.01$). Also, gender, age and tobacco smoking influenced the levels of genetic damage, while the effect of

using protective devices (clothes and mask) was less noticeable than expected. Later, they enlarged the study with the aim of checking the validity of their previous data, including 180 exposed subjects and 60 controls. Their results showed significant increases in the levels of blood heavy metals (aluminum, nickel and lead) and DNA damage, and alterations in the endocrine status of the exposed populations (significantly higher prolactin plasma concentrations, $P < 0.01$; Pérez-Cadahía et al., 2008a). They also found general increases in MN frequency and decreases in the proliferation index in the individuals with longer times of exposure (Pérez-Cadahía et al., 2008b). Moreover, significant influence of several genetic polymorphisms in metabolizing enzymes and DNA repair proteins was observed. In addition, their previous results showing the absence of effect of using protective devices were confirmed.

Finally, the same authors (Pérez-Cadahía et al., 2008c) investigated the relationship between blood levels of heavy metals and genotoxic or endocrine parameters in the individuals exposed to Prestige oil. Cortisol plasma concentration appeared to be the most sensitive parameter to the effects of metal exposure, since it was significantly influenced by blood concentrations of aluminum, nickel (both inversely) and cadmium (positively), and jointly by aluminum and nickel. On this basis, the authors suggested plasma levels of cortisol as a potentially relevant biomarker to assess the effects of exposure to heavy metals. Taking into account the known genotoxic, cancer-provoking and endocrine disrupting properties of many compounds contained in the spilled oils, it seems surprising that only for two oil spills (Braer and Prestige) are there studies contemplating these consequences for human health in exposed individuals. The results obtained in most of these studies provide evidence of genotoxicity and alterations in the hormonal status related to the exposure. The only work with negative results (Colet et al., 1997) comprised a relatively small population (26 exposed vs 9 controls), and nothing is specified on the participation of the exposed individuals in the cleanup tasks; only their status as residents in the polluted area is mentioned. It seems probable that direct participation in the cleanup work involved a higher exposure to the oil toxic compounds than that experienced by zone inhabitants who did not participate in the cleaning.

3.3.4 Summary and recommendation for studies on public health impacts

Until now there have been 38 large oil spills, but only for seven of them have studies on the repercussions of the exposure to spilled oils on human health been performed. Most of these investigations correspond to cross-sectional epidemiological studies that analyze acute physical effects or psychological consequences in the affected people. Some of them do not include a matched control population, which makes the information provided confusing and difficult to interpret. A smaller number of studies are *in vitro* or *in vivo* approaches aiming to investigate the effects at the cellular level and the ability of the oil compounds to be

transferred into the food chain and induce damage in consumers; others are focused on biological markers indicative of genotoxicity and/or endocrine toxicity.

On the occasion of the Prestige oil spill, Porta and Castaño-Vinyals (2003) recommended performing epidemiological studies of exposure to the spilled oil on the medium- and long-term impact on human health. In addition to a first transversal stage, they recommend the monitoring of the exposed populations in a second longitudinal stage. This would allow (i) determination of whether the biomarkers of internal dose, of biologically effective dose and of early biological response remain stable with time or undergo variations; (ii) determination of certain factors influencing the mentioned biomarkers; and (iii) analysis of the levels of biomarkers or any other factor associated with the appearance of a particular illness, subclinical effects or interesting alterations (physiological, genotoxic, etc.). Some studies compare the evaluated or estimated exposure levels with occupational acceptable exposure limits, or use these limits to calculate the potential toxicological risk. Nevertheless, this comparison is not entirely correct, since the occupational limits are usually defined for exposures of 8 h/day during a whole working life, i.e. considering a chronic exposure. Exposure to spilled oils takes place over several days or some months at the most, involving time periods much shorter than occupational exposures.

In summary, most of the studies collected in this review provide evidence on the relationship between exposure to spilled oils and the appearance of acute physical, psychological, genotoxic and endocrine effects in the exposed individuals. Considering the relatively high frequency of this kind of environmental disaster, it seems necessary to establish detailed intervention protocols that include some mechanisms to detect and control the possible harmful health effects that exposure can induce, including performing the immediate collection of biological samples from the beginning of the cleanup work, in order to establish the levels of individual internal exposure effects at the acute and chronic level, especially those related to genotoxicity. This will permit not only determination of the risk that exposure may involve, but also evaluation of whether protective devices used by the individuals in each case adequately fulfilled their function, or on the contrary they did not exert the required protection and therefore require to revision of material characteristics and improved briefing sessions on their correct use.

3.4 Social and community impacts

The sociocultural and psychological impacts of the Exxon valdez oil spill were examined by Lawrence et al., (1993) in a population-based study of 594 men and women living in 13 Alaskan communities approximately one year after the spill occurred. A progressive "dose-response" relationship was found between exposure to the oil spill and the subsequent cleanup efforts and the following variables: reported declines in traditional social relations with family members, friends, neighbors and coworkers; a decline in subsistence production and distribution activities; perceived increases in the amount of and problems associated with

drinking, drug abuse, and domestic violence; a decline in perceived health status and an increase in the number of medical conditions verified by a physician; and increased post-spill rates of generalized anxiety disorder, post-traumatic stress disorder, and depression. Alaskan Natives, women, and 18-44 year olds in the high- and low-exposed groups were particularly at risk for the three psychiatric disorders following the oil spill. Their results suggest that the oil spill's impact on the psychosocial environment was as significant as its impact on the physical environment.

The results also have important theoretical and pragmatic implications for the understanding and mitigation of adverse impacts of long-term processes of sociocultural change. Picou et al., (1990) surveyed the people of Cordova as to how the spill changed their lives. Cordova on Prince William Sound is isolated from other settlements by mountains, glaciers and the sea. The single road to the rest of Alaska was destroyed in the 1964 earthquake. The economy of Cordova is dominated by the fishing industry. Cordova fishermen hold 55% of the salmon and 44% of herring licenses of the licenses of the Prince William Sound area. The town people have a history of subsistence practices stemming directly from a Native-Alaskan heritage. About 20% of the residents of Cordova are Native-Alaskans.

Although the oil spill did not reach the Cordova beaches, it impacted critical fishing grounds used local fishermen. Two towns were selected for the disaster assessment, one that was directly affected by the spill, Cordova, and a control town, Petersburg, that was not affected by the spill. The research design included the collection of data in a stratified random sample of households, an ethnographic sample of native Alaskans, and a random telephone survey of the inhabitants. Four questions were asked of residents in Cordova and Petersburg, namely, have you noticed any changes in the way your family gets along together; have you made any changes in the plans for the future; have other family members changed their future plans; have things changed for you at work. The results indicate that spill had a significantly greater social disruption in Cordova than in the Petersburg area. These disruptions included family relations and future plans of the community members.

The four researchers who conducted this study felt that the general uncertainty that characterized Cordova residents was directly related to the threat posed by the spill for the future economic viability in the community. In another of their survey which aimed at measuring post-traumatic stress disorders, significant different responses were also observed between residents of Cordova and Petersburg. The majority of the residents of Cordova had such intrusive recollections of the spill such as inadvertent thoughts, unexpected negative pictures and thoughts that would result in an emotionally upset. Other contrasts in the emotions between the residents of the two communities included stress behavior in Cordova in the avoidance and recollection of the traumatic aspects of the spill.

3.5 Impacts of oil spills in Newfoundland and Labrador

3.5.1 Economic impact of oil spill in NL

The S.L. Ross Environmental Research Limited, NL (2007) conducted a comprehensive impact assessment study of the South Coast of NL. The studied area has key hazards related to oil spills as summarized in **Table 3.3**. The problems associated with icing, fog, wind are not usual in other places.

Their approach was to analyze the economic consequences on three key industries: wild fisheries and fish processing, aquaculture, and tourism. Oil spill cleanup costs are also estimated and included in the final total of economic effects.

In terms of wild fisheries and fish processing, Atlantic cod, scallops, lobster, and snowcrab represent 65 per cent of the quantity and 87 per cent of the value of the Newfoundland fishery.

Table 3.3 Summary of key hazards in the south coast of NL (source: The S.L. Ross Environmental Research Limited, 2007)

Sub-area	Weather and sea conditions	General traffic conditions	Navigational Hazards
Cape Ray to Burin Peninsula	Generally ice-free in winter but freezing spray is common	Considerable passing traffic, en route to ports in the St. Lawrence River and beyond Ferry traffic to/from port aux Basques	Port aux Basques: Narrow entrance. Shoaling and exposed rocks. Difficult berthing in heavy weather
Placentia Bay	Swell from south can travel well within bay. Southerly winds can produce widespread fog	Tankers to/from Come by Chance refinery and Whiffen Head Transshipment terminal	Rocks and Shoals line defined traffic lines. Lanes narrow and merge to a single lane
Cape St. Mary's to Cape Race	Rough seas can be funneled into St. Mary's Bay and Trepassy Bay. Strong tidal currents nearshore. Concentration effect of cape can produce local speeds up to 25 knots greater than elsewhere. Icebergs in area March to July	Area of traffic convergence including tankers transiting to Placentia Bay, and transatlantic routings heading for Cabot Strait	Several marked rocks and shoals along defined traffic routes.
Cape Race to Cape St. Francis	Unlimited exposure to the east, large swells common. Pack ice through late winter month; icebergs in spring and early summer	Area of traffic convergence: vessels entering St. John's traffic along coast. Considerable fishing activity in area	Limited Maneuverability in narrow entrance to St. John's.

The main effect on fisheries in the event of a spill will be the closure of the fishery while a slick persists in a given area, and the closure of fish processing plants due to the interruption in supply. Other effects could include oiling of gear, and a loss of market confidence due to the possibility of tainting.

The estimation of economic loss includes several assumptions that would make the calculation conservative, that is, the losses may not actually be as great as estimated. For example, fishers are assumed to not recoup any losses during closures by attaining higher catch rates afterwards, or that they may be alternatively employed during a closure.

Aquaculture operations in Newfoundland are concentrated in the area of Bay d'Espoir to Fortune Bay, with a value of \$34.6 million salmonid and blue mussel production in 2007. Placentia Bay blue mussel production represents an additional valued of \$1.4 million. Aquaculture sites are located in inshore areas, so would be affected by spills that persist and reach shoreline areas. The economic assessments include gear damage, lost sales of product, and lost value of primary processing. It is assumed that if harvesting is lost for part of the year it is not made up later.

Newfoundland's tourism industry brings in an estimated \$800 million per year industry in Newfoundland. It is noted that one of the main attractions of the province is the interaction with the natural environment, much of it marine-based. The effects of a spill on tourism may be difficult to quantify in that tourists' perceptions of damage may reduce their travel to an area affected by a spill, although this can be mitigated somewhat by public information efforts. The approach taken here is to estimate the loss of revenue of key tourism activities in each Hazard Zone if affected by "very large" and larger spill sizes for a period of 30 days in each case. Seasonality is not varied, although it is acknowledged that spills in summer would likely have a greater effect since that is high tourist season. In sum, the economic impact of preventative spill scenarios range from 64.2 to 484,713 and from 102 to 665,029 in thousands of CND, for medium-persistence oil and high-persistence oil, respectively along the south coastal line. When times these impact with probability, the risk of economic loss was calculated. It was observed that for inner Placentia Bay, outer Placentia Bay, Placentia Bay South, the risk due to tanker spills predominates because of the exposure created by the refinery and terminal at the head of Placentia Bay, and the tanker traffic originating in or passing through these zones. The risk associated with vessel fuel spill is much the same in the studied area except Cabot Strait, where it is approximately 3 times greater than the other region. This is due mainly to the high consequence in the event of a spill, related to the high value aquaculture operations in Cabot Strait.

3.5.2 Liability for damages caused in NL

Companies drilling in Canada's offshore areas are responsible for preventing, mitigating and managing any oil spills from their operations. They are liable for cleaning up a spill and for paying for third party losses or damages (Canadian Oil

and Gas Operations Act). Third party damages are claims for specified damage, loss and injury from people or groups other than the offshore operator. It is important to note there is a distinction between a company's financial responsibility to clean up a spill and for its legal liability to pay any third party losses or damages. The responsibility to clean up a spill is unlimited; there is no cap on the money an operator must spend on this. The Canada Oil and Gas Operations Act and the Atlantic Accords require that those responsible for a spill take all reasonable measures to contain and clean up the spill. If such measures are not being taken, the legislation empowers the offshore regulators to direct the management of the spill response (Angus and Mitchell, 2007).

Offshore operators face an escalating scale of financial responsibility for damages and losses. To begin with, the two Atlantic offshore petroleum Boards require anyone drilling to have in place a \$30 million absolute liability fund (Canada-Newfoundland Oil and Gas Spills and Debris Liability Regulations). North of 60 degrees latitude, this fund must be \$40 million. If there is a spill that results in damage or loss, the operator must pay, whether they are at fault or not. The next step of financial responsibility is an additional \$70 million Civil Liability Fund; however, it requires proof of fault or negligence on the part of the drilling company or operator (C-NSOPB and C-NLOPB, 2000). The third level in an operator's financial responsibility aims at demonstrating their capacity to meet any financial liability that may occur in conducting drilling program. The operator can be required to provide evidence to the Boards that they have a minimum of \$250 million to fund well control, well safety and spill clean-up expenses. The amount set by the regulators depends on the particular circumstances of a drilling operation and ensures that the company can pay damages of at least that amount (Mark Corey, 2010). Third-party claims require proof of fault or negligence on the part of the operator, and if the company has been negligent or is at fault, there is no limit to their liability.

3.5.3 Environmental impact of oil spills in NL

The S.L. Ross Environmental Research Limited, NL (2007) also conducted the environmental impact assessment of the south coast of NL. The approach used was to identify a short list of Valued Ecosystem Components (VEC's). These are species or habitats of special significance by virtue of their particular aesthetic, cultural or economic value to a region. Within this broad definition, other factors include relative abundance of a species, its vulnerability to oil exposure, its importance within the ecosystem, and its commercial importance. For each of the VEC's, the potential consequences were estimated for spills ranging from small to exceptionally large. In most cases a quantitative estimation was made both in terms of total numbers of a species and as a percentage of the regional and broader population. Nearshore and shallow waters are important for spawning and early stages of several important fish species, and could be vulnerable to spilled oil depending on the timing of the spill. Seabirds are the VEC most vulnerable to the

effects of oiling; the identified species all come into contact with the sea surface, and potentially oil from a spill. Murres and black guillemots are particularly vulnerable as they fly infrequently, spending the majority of their time on the sea surface. The environment risk assessment results showed that the recovery time of studied species varied from 1 year to 11 years when facing vessel fuel or tanker cargo oil spills at different locations.

3.6 Summary

Offshore oil spills can cause enormous economic loss and harm to ecological systems, public health, society and community. The total economic impacts, including socioeconomic loss, cleanup costs, environmental damages, research costs and other costs were reviewed. These costs were either assigned with monetary values or estimated through modeling techniques. In terms of socioeconomic loss, it mainly referred as the interruption of commercial, recreational fisheries and coastal tourisms. For cleaning and restoration costs, they are vary depend on the oil type, proximity to shoreline, location, cleanup methodology, and the spill size. In the aspects of environmental damage related cost, as it cannot be directly measured from economic world, they were estimated with modeling tools. In summary, factors that determine the costs of oil spills include type of oil, physical, biological and economic characteristics of the spill location, weather and sea conditions, amount spilled and rate of spillage, time of the year, effectiveness of clean-up as well as complex interactions among these factors. The economic impacts of oil spills to some extent can be directly reflected on the total amount of liability and compensational funds which were regulated according to the law of each country.

The environmental impacts of offshore oil spills have mainly been reviewed in terms of mortality and community deterioration of seabirds, fish, shellfishes, benthos and wetland vegetation. It has been found that oil spills have not only immediate impact on the environment, but also long-term effects on the above mentioned ecosystems. The public health impacts from offshore oil spills were reviewed in terms of effects caused by transference to the food chain, epidemiological studies on acute toxic and psychological effects, and studies on long term genotoxicity and endorine toxicity. The reviewed studies provided evidence on the relationship between exposure to spilled oils and the appearance of acute physical, psychological, genotoxic and endocrine effects in the exposed individuals. The social and community effects from offshore oil spills have been studied in terms of surveys between affected communities and controlled communities. The increased post-spill rates of generalized anxiety disorder, post-traumatic stress disorder, and depression were concluded. Besides, intrusive recollections of the spill such as adverted thoughts, unexpected negative pictures and thoughts that would result in an emotionally upset have been observed in affected communities.

In Newfoundland and Labrador, impacts of oil spills have been reviewed in terms of economic impact, liability for damages and environmental effects. The

economic and environmental impacts were mainly estimated from the assessment using modeling techniques and focus on the south coast of NL where oil transportation predominates. Companies drilling in NL are responsible for preventing, mitigating and managing any oil spills from their operations. The Canada Oil and Gas Operations Act and the Atlantic Accords provide regulatory supervision in terms of a blowout.

Limited considerations regarding the economic impacts due to the damage of environment observed. The liability and compensation funds also made decisions on the assumptions that environment can eventually restore itself after the spills, while this was proven to be inappropriate and may cause underestimation of the impacts.

In terms of environmental effects of oil spills, limited studies conducted long-term monitoring of affect ecological systems after the spills. However, the long-term impacts may be more critical as the evidences for the regulatory decision-making considering the oil spills.

Considering the relatively high frequency of this kind of environmental disaster, it seems necessary to establish detailed intervention protocols that include some mechanisms to detect and control the possible harmful health effects that exposure can induce, including performing the immediate collection of biological samples from the beginning of the cleanup work, in order to establish the levels of individual internal exposure effects at the acute and chronic level, especially those related to genotoxicity. This will permit not only determination of the risk that exposure may involve, but also evaluation of whether protective devices used by the individuals in each case adequately fulfilled their function, or on the contrary they did not exert the required protection and therefore require to revision of material characteristics and improved briefing sessions on their correct use.

Very limited efforts were paid on the sociocultural and psychological impacts of oil spills which require further studies to reveal a more comprehensive picture on how the impacted community suffered from the spills and provide information to the social service system to improve their works with the affected communities.

CHAPTER 4

POLICIES AND REGULATIONS

4.1 Existing policies and regulations for offshore oil spill

4.1.1 Worldwide

International Maritime Organization is the United Nations' Specialized agency responsible for safety and security of shipping and the prevention of marine pollution by ships.

The International Convention for the Prevention of Pollution from Ships (MARPOL) is the main international convention covering prevention of pollution of the marine environment by ships from operational or accidental causes. The Convention includes regulations aimed at preventing and minimizing pollution from ships - both accidental pollution and that from routine operations - and currently includes six technical Annexes (IMO, 1997). Regulations for the Prevention of Pollution by Oil are one of the technical Annexes related to oil spill. The annex covers prevention of pollution by oil from operational measures as well as from accidental discharges. For example, it is mandatory for new oil tankers to have double hulls and brought in a phase-in schedule for existing tankers to fit double hulls.

In 1989, IMO is called up and established an International Convention on Oil Pollution Preparedness, Response and Co-operation (OPRC). It requires the parties of it should establish measures for dealing with pollution incidents, either nationally or in co-operation with other countries. Ships are required to carry a shipboard oil pollution emergency plan. Operators of offshore units under the jurisdiction of Parties are also required to have oil pollution emergency plans or similar arrangements which must be coordinated with national systems for responding promptly and effectively to oil pollution incidents. Ships are required to report incidents of pollution to coastal authorities and the convention details the actions that are then to be taken. The Convention calls for the establishment of stockpiles of oil spill combating equipment, the holding of oil spill combating exercises and the development of detailed plans for dealing with pollution incidents. Parties to the convention are required to provide assistance to others in the event of a pollution emergency and provision is made for the reimbursement of any assistance provided. The convention provides for IMO to play an important coordinating role (IMO, 1990).

IMO was also given the task of establishing a system for providing compensation to those who had suffered financially as a result of pollution. Two treaties were adopted, in 1969 and 1971, which enabled victims of oil pollution to obtain compensation much more simply and quickly than had been possible before. Both treaties were amended in 1992, and again in 2000, to increase the limits of compensation payable to victims of pollution. A number of other legal conventions have been developed since, most of which concern liability and compensation issues (IMO, 2012). Additionally, International Convention on the Establishment of an

International Fund for Compensation for Oil Pollution Damage (FUND) is established to provide compensation for pollution damage to the extent that the protection afforded by the 1969 Civil Liability Convention is inadequate; give relief to ship owners in respect of the additional financial burden imposed on them by the 1969 Civil Liability Convention; and give effect to the related purposes set out in the Convention (IMO, 1971).

4.1.2 United Kingdom

The United Kingdom's response strategy revolves around the National Contingency Plan for Marine Pollution from Shipping and Offshore Installations. The Maritime and Coastguard Agency (MCA) is responsible for major oil-spill preparedness, with regional operations managers. Responses are based on regional operations and central support (Turner, 2010).

The U.K.'s response policy employs the Tiered Response system. Ports, harbors and oil-handling facilities are required to have oil-spill response contingency plans and are required to be able to handle up to a Tier 2 spill in their jurisdiction. Offshore installations have similar requirements for spills up to the Tier 3 level. The MCA has produced guidelines and advice on developing contingency plans. Major response policy allows natural dispersion unless sensitive ecosystems are under threat. A Net Environmental Benefit Analysis is used to determine if dispersants are used as a primary response. Only approved dispersants may be used (Turner, 2010).

The MCA has access to several aircraft and stockpiles of dispersants and 14 airfields around the country. The independent Nautical Institute is responsible for the accreditation of oil-response training whereas private companies provide most of the training. The Government funds the National Contingency Plan, but recovery costs are paid for by the polluter (Turner, 2010).

The U.K. is party to many international conventions and agreements.

4.1.3 Norway

In Norway, the Petroleum Safety Authority (PSA) is the regulatory authority for technical and operational safety for the Norwegian Offshore Area. The PSA's regulatory role covers all phases of operations, from planning and design through construction and operation to removal of facilities. The PSA has been designated the authority to promulgate regulations, supervise compliance and follow-up to ensure that operators and their contractors maintain acceptable standards of health, environmental protection, and safety and emergency preparedness.

The National Oil-spill Contingency System (NOSCS) delegates specific responsibilities to federal and municipal Governments along with private industry. All response plans and agencies are standardized and coordinated through the

NOSCS. In the event of a major oil-spill, the NOSCS would operate as a single integrated response organization (Norwegian Coastal Administration).

The Norwegian Coastal Administration (NCA) is in charge of the NOSCS and, as such, is responsible for coordinating the municipal and federal Government's oil-spill response preparedness as well as private industry preparedness. It is led by a Director General who reports to the Norwegian Minister of Fisheries. The NCA is also responsible for monitoring incidents and, if necessary, they can assist or take control if the responsible party is in a situation beyond their capability or are performing unsatisfactorily. The spills for which they are responsible include those from ships, major spills from unidentified sources and any other spills not handled by private or municipal preparedness agencies. They coordinate all levels of response agencies in case of a major oil-spill and there are agreements with other Governmental and private agencies regarding assistance with personnel and equipment (Norwegian Coastal Administration).

The respective operators are responsible for spills from offshore installation. On behalf of and in cooperation with operators, the Norwegian Clean Seas Association for Operating Companies (NOFO) implements and coordinates all industry oil spill responses. NOFO, a cooperation of all 16 companies operating on the Norwegian Shelf, states its main objectives are to establish and maintain oil-spill emergency preparedness and to coordinate and communicate relevant oil-spill contingency issues between members and regulating authorities.

Norway's response policy focuses on containing and recovering oil as close to the spill as possible. There are many oil barriers, as part of the response plan, that attempt to prevent spilled oil from reaching the shore. The contingency system is highly developed with Government and industry response equipment stockpiles distributed throughout the country. Funding for oil-spill response preparedness has been given priority status in the national Norwegian budget, allowing for improved response equipment, training and exercises (Turner, 2010).

Norway is party to many international conventions and agreements.

4.1.4 Australia

Australia's response strategy revolves around the National Plan to Combat Pollution of the Sea by Oil and Other Noxious and Hazardous Substance (the National Plan). The Australian Maritime Safety Authority (AMSA) is responsible for major response preparedness whereas the Australian Marine Oil-spill Centre (AMOSC) is the major industry organization involved.

Australia's response policy applies both Net Environmental Benefit Analysis and the Tiered Response approach. There are national and state/territorial contingency plans in place as well as plans developed by industry and ports for smaller spills.

There is response equipment, managed by either Government or industry, at various locations around Australia. Local ports and oil-handling companies have Tier 1 response equipment whereas larger regional and national stockpiles are used for larger spills. Both the AMSA and AMOSC offer training courses at levels ranging from oil-spill operations to upper management. The National Plan is funded primarily on a potential-Polluter-Pays-Principle, whereas regional Governments as well as industry and ports also provide funding. Research and development is part of the national plan but before any new response measures are accepted and introduced into the National Plan they must be extensively proven in the field, be non-invasive and they must not create any additional problems (Turner, 2010).

Australia is party to many international conventions and agreements.

4.1.5 United States

In the U.S., oil spills in their respective histories have played a large role in the regulatory structure and response policy. Earth Day was created in 1970 because of the Santa Barbara spill, and the Clean Water Act was passed in 1972 in part because of these spills. The first oil spill training school in the U.S., the National Spill Control School (NSCS) at Texas A&M University-Corpus Christi, was developed as the first oil spill training facility in the U.S. in the mid-1970s because of these first major spills, and it remains active today. The NSCS was later named as the resource training program for the Oil Pollution Act of 1990.

When the Exxon Valdez tanker ran aground in 1989 and spilled almost 11 million gallons of oil into the pristine environment of Prince William Sound, Alaska, another new era began in dealing with oil spills in the sea. In 1990 the U.S. Oil Pollution Act was passed, and a new structure was established in the U.S. for dealing with oil spills and the payment for recovery of damaged environments and economies (Natural Resource Damage Assessment program or NRDA) by the responsible party. Until the DWH oil spill, the Exxon Valdez spill was the largest and most significant in U.S. history. Beyond the ecological damage, the Exxon Valdez disaster caused a fundamental change in the way the U.S. public viewed oil, oil transportation, and the oil industry (NRC 2003). Despite continuing heavy use of fossil fuels by society, "big oil" was suddenly seen as a necessary evil, and something that had to be feared and mistrusted. This reaction was quick and significant (NRC 2003).

The governing framework for oil spills in the United States is a combination of federal, state and international authorities. Within this framework, several federal agencies have the authority to implement oil spill regulations. The framework and primary federal funding process (the Oil Spill Liability Trust Fund) used to respond to oil spills. In 1990, the U.S. congress established the Oil Pollution Act (OPA). It is the first comprehensive law to specifically address oil pollution to waterways and coastlines of the U. S. The act was consolidated the existing federal oil spill laws under one program. The law expanded the liability provisions within the Clean

Water Act (CWA) and created new requirements regarding oil spill prevention and response. Key OPA provisions are included (Ramseur, J.L. 2012):

Spill Response Authority: OPA Section 4201 amended Section 311(c) of the CWA to provide the President (delegated to the U.S. Coast Guard or EPA) with authority to perform cleanup immediately using federal resources, monitor the response efforts of the spiller, or direct the spiller's cleanup activities. The federal government—specifically the On-Scene Coordinator (OSC) for spills in the Coast Guard's jurisdiction—determines the level of cleanup required. Although the federal government must consult with designated trustees of natural resources and the governor of the state affected by the spill, the decision that cleanup is completed and can be ended rests with the federal government. States may require further work, but without the support of federal funding.

National Contingency Plan (NCP): The 1990 law established a multi-layered planning and response system to improve preparedness and response to spills in marine environments. Among other things, the act also required the President to establish procedures and standards (as part of the NCP) for responding to worst-case oil spill scenarios.

Tank Vessel and Facility Response Plans: As a component of the enhanced NCP, OPA amended the CWA to require that U.S. tank vessels, offshore facilities, and certain onshore facilities prepare and submit oil spill response plans to the relevant federal agency. In general, vessels and facilities are prohibited from handling, storing, or transporting oil if they do not have a plan approved by (or submitted to) the appropriate agency. The plans should, among other things, identify how the owner or operator of a vessel or facility would respond to a worst-case scenario spill. Every vessels must have a plan and procedures to call upon—typically through a contractual relationship—the necessary equipment and personnel for responding to a worst-case spill. In 2004, an amendment was enacted requiring non-tank vessels (i.e., ships carrying oil for their own fuel use) over 400 gross tons to prepare and submit a vessel response plan.

Double-Hull Design for vessels: The act required new vessels carrying oil and operating in U.S. waters to have double hulls. However, OPA provided certain exceptions, depending on the size of the vessel (e.g., less than 5,000 gross tons) and its particular use (e.g., lightering). For older vessels, OPA established a staggered retrofitting schedule, based on vessel age and size. As of January 2010, single-hull vessels (with several exceptions, some of which expire in 2015) cannot operate in U.S. waters.

Liability Issues: OPA unified the liability provisions of existing oil spill statutes, creating a freestanding liability regime. Responsible parties are liable for any discharge of oil (or threat of discharge) from a vessel or facility to navigable waters, adjoining shorelines, or the exclusive economic zone of the United States (i.e., 200 nautical miles beyond the shore). The range of liable damages includes injury to natural resources, loss of personal property (and resultant economic losses), loss of subsistence use of natural resources, loss revenues resulting from

destruction of property or natural resource injury, loss profits and earning capacity resulting from property injury or natural resource injury, and costs of providing extra public services during or after spill response. OPA set liability limits (or caps) for cleanup costs and other damages. Until 2009, liability limits for vessels were based on vessel carrying capacity, generally \$2,000 per gross ton for double-hulled vessels and \$3,200 for single-hulled vessels. Offshore facility liability is unlimited for removal costs but capped at \$75 million for other costs and damages; onshore facility and deepwater port liability is limited to \$350 million.

The Oil Spill Liability Trust Fund (OSLTF): OPA provided the statutory authorization necessary to put the fund in motion. Through OPA, Congress transferred balances from other federal liability funds⁸⁴ into the OSLTF.

Financial Responsibility: OPA requires that vessels and offshore facilities maintain evidence of financial responsibility (e.g., insurance). The Coast Guard's National Pollution Funds Center (NPFC) implements the financial responsibility provisions for vessels; the Bureau of Ocean Energy Management, Regulation, and Enforcement (formerly the Minerals Management Service, MMS) implements this requirement for offshore facilities. The current levels of financial responsibility are related to the current liability limits for various sources (e.g., vessels, offshore facilities) of potential oil spills.

Other federal laws contain provisions that related to oil spill: The Clean Water Act (CWA) was the primary federal statute governing oil spills prior to OPA and many provisions continue to apply; the Outer Continental Shelf Lands Act (OCSLA) provided the foundation for regulations that are implemented by the Bureau of Ocean Energy Management, Regulation, and Enforcement (formerly the Minerals Management Service, MMS); and the Hazardous Liquid Pipeline Act and the Pipeline Safety Improvement Act authority the Department of Transportation to regulate various issues regarding oil spills from pipelines (Vann, 2011).

4.1.6 Canada

Between 1991 and 1993, the Canadian Coast Guard (CCG) and Environment Canada exercised considerable planning with consultation with the private sector, on the development of the two main elements of a private-sector funded response capability for ship-source spills.

The Canada Shipping Act (CSA) had to be amended to create the legislative framework in order to make the industry Government relationship work. In August 1995, the regulations were approved by the Minister of Fisheries and Oceans allowing the CSA amendments to be proclaimed. At about this time, responsibility for managing the newly-founded National Oil Spill Preparedness and Response Regime was transferred to Transport Canada.

Canada's Marine Oil-spill Preparedness and Response Regime is based on the Polluter-Pays-Principle. Transport Canada is the lead federal regulatory agency

responsible for the regime and is built on a partnership between Government and industry. Transport Canada sets the guidelines and regulatory structure for preparedness and response to marine oil-spills. The guiding principles for the regime are (Turner, 2010):

- Effective and responsive legislation
- Potential polluters pay for preparedness
- Polluter pays for reasonable response costs
- Based on partnership with industry
- Comprehensive contingency plans and
- Mutual agreements with neighbors

Environmental Response Systems is responsible for the development and administration of policies, regulations, and programs that protect the marine environment, mitigate the impact on the environment of marine pollution incidents and to ensure the safety of the general public. It works with other federal agencies and departments including Fisheries and Oceans Canada, the Canadian Coast Guard, and Environment Canada.

Canada also participates in joint activities with the United States and has established a formal Canada –U.S. Joint Marine Pollution Contingency Plan. The regime is governed by the following legislation and International Conventions: Canada Shipping Act, Dangerous Chemicals and Noxious Substances Regulations, Oil-pollution Prevention Regulations, Pollutant-discharge Reporting Regulations, Response Organization and Oil-handling Facilities Regulations, Arctic Waters Pollution Prevention Act, Oceans Act, Fisheries Act, International Convention for the Prevention of Pollution from Ships (MARPOL73/78), International Convention on Oil-pollution Preparedness, Response and Cooperation (OPRC 90), International Oil-pollution Compensation Fund, Civil Liability Convention, and the Salvage Convention.

4.1.7 Newfoundland and Labrador

The C-NLOPB (Canada-Newfoundland and Labrador Offshore Petroleum Board) is the joint federal-provincial regulating body authorized to oversee all aspects of the province's offshore petroleum industry. Their mandate is to interpret and apply the provisions of the Atlantic Accord and the Atlantic Accord Implementation Acts to all activities of operators in the Newfoundland and Labrador Offshore Area and to oversee operator compliance with those statutory provisions (C-NLOPB, 2010).

The C-NLOPB regulatory mandate covers four areas: safety, environmental protection, resource management and industrial benefits. Its role in the implementation of this mandate is to facilitate the exploration and development of the petroleum resources such that it conforms to the legislated statutory provisions. This includes worker safety, environmental protection and safety, effective

management of land tenure, maximum hydrocarbon recovery and value and Canada/Newfoundland and Labrador benefits(C-NLOPB, 2010). Prioritization of the mandates is not within the legislation, but the C-NLOPB has taken the initiative to ensure worker safety and environmental protection take precedence.

Safety within the offshore is accomplished through strict oversight into all operator safety procedures. This includes verifying operators have effective safety plans, performing audits and inspections to ensure operators follow these safety plans and all applicable statutory requirements, and ensuring through compliance actions that digressions from approved plans and applicable statutory requirements are corrected (C-NLOPB, 2010).

Environmental protection is an essential element of the Board's mandate. The C-NLOPB's objectives also verify that operators assess and provide for all effects of the environment on the safety of their operation. Operators must also provide detailed environmental assessments in agreement with Canadian regulations concerning the impact of their operations on the environment. In addition, plans must provide for mitigation measures where appropriate. The C-NLOPB will also verify, through compliance actions, that operators abide by their environmental plans (C-NLOPB, 2010).

The final objectives of the C-NLOPB deal with resource management and Government benefits. The Board regulates exploratory licenses, significant discovery licenses and production licenses for the entire Newfoundland and Labrador offshore. This administration of land tenure is performed in an effective and efficient manner. The Board oversees all production activities to ensure maximum recovery and effective oilfield practice. This includes production monitoring and plan approvals. The Board also expands the knowledge base of the Newfoundland and Labrador offshore via the acquisition of data from exploratory and production activities. Finally, the Board verifies that operators have approved Canada/Newfoundland and Labrador Benefits Plans addressing their statutory obligations (C-NLOPB, 2010).

The C-NLOPB is regulatory oversight of Operator activity. As a result, the Board does not have the responsibility of worker and environmental safety, nor establishment or administration of royalties or taxes for any offshore activity. The Board does not promote industry.

The Atlantic Accord legislation defines a Chief Safety Officer with broad powers and responsibilities for worker safety, as well as a Chief Conservation Officer with powers over resource management. The legislation stipulates that an order made by the Chief Safety Officer cannot be overruled by the Board, and it prevails over a decision of the Chief Conservation Officer. In short, the Atlantic Accord legislation provides that in matters of safety versus resource management and production, safety is paramount. The Board provides required data and information to Government.

The Board regulates that individual drilling programs must have their own two-tiered process. First, authorization of the overall drilling program must be

achieved through an Operators Authorization. Second, a well approval for an individual well must be obtained in the form of an Approval to Drill a Well as part of the drilling program application. Relevant regulatory approvals within the context of the operations authorization include a Project-Specific Environmental Assessment, a Certificate of Fitness, an Operator's Declaration of Fitness, a Letter of Compliance from Transport Canada, Safety Plans, an Environmental Protection Plan and Contingency Plans. The Approval to Drill a Well must provide detailed information regarding the planned drilling program. The Board provides guidelines for drilling and production, which focus on critical matters with respect to well-control and blowout prevention. The guidelines reflect high standards and modern thinking in the areas of drilling, cementing and well-control matters. These guidelines can be updated to incorporate lessons learned to improve upon the current standard. In addition to the approval process, the C-NLOPB provides additional levels of oversight as required by the Atlantic Accord Implementation Act. Oversight is accomplished through auditing, compliance monitoring, scheduled inspections and investigations (Turner, 2010).

Offshore oil and gas operators are required by law to develop spill-response plans as part of their approval and permitting process. The operator's emergency-response plan is a detailed plan that guides the actions of workers and contractors if an emergency occurs. Such plans require that workers have the proper training enabling them to make the right decisions and take the right actions when they have to react to an emergency. Emergency-response plans also identify sources of extra support, specialized expertise and resources that may be needed for an emergency. As well, this approach ensures that companies quickly notify the proper Government agencies and advise fishing vessels in the area of an incident (Turner, 2010).

4.2 Challenges in Harsh Environments

The challenges from oil spill response policies are that stimulating cooperation and debate on key HSE challenges in petroleum-related activities. A spill that due to its severity, size, location, actual or potential impact on the public health and welfare or the environment, or the necessary response effort, is so complex that it requires extraordinary coordination of international, federal, state, local, and responsible party resources to contain and clean up the discharge.

The complex factors including environmental challenges and jurisdictional conflicts impeded the implementing of oil spill policies. Environmental challenges are present as a result of operations in deeper waters and in the harsh environment (e.g. arctic area). The complexity of the industry dictates that it must be implemented on a more rapid time scale than traditionally exercised to achieve the successful development and application of technologies. As we continue to move forward, new technologies and new strategies will be required. As a result, there is a challenge finding a way to ensure that reasonable measures are being taken to

mitigate risks such that incidents are unlikely to occur, and then if one does occur, there is a method of response-plan. If not, there is a danger that safety interests may not be addressed adequately. A response gap analysis involved the response operating limits of spill response systems for a set of environmental factors, such as wind, sea state, sea ice, visibility, etc., and an analysis of the frequency, duration, and timing of conditions that would preclude a response in a particular location must be conducted prior to the regulations (WWF, 2007).

On the other hand, the prescriptive nature of the regulations had created increased administrative challenges and costs that affected regulatory efficiency and effectiveness. Regulators observed increased numbers of requests from companies to use new or cost-effective technologies and processes not reflected in the regulations. The flexibility to develop more efficient and effective regulatory processes was limited by the existing regulations, which contained prescriptive and detailed information requirements specifically regarding the number of copies and timing of applications and specific reference to authorized activities. Further, while not currently exercised, the Acts allow authority to be given to the Boards, through regulation, to deal with certain production matters by way of an order (Canada Gazette, 2009).

The improvements of the Regulations will, like drilling and production activities, resolve regulatory duplication, move from a prescriptive to a goal-oriented style, incorporate a management systems approach, facilitate regulatory process improvements and reduce the administrative burden.

4.3 Summary

The oil industry and regulatory authorities of United Nation, The United Kingdom, Norway, Australia, The United States, and Canada including Province of Newfoundland and Labrador have made series of laws, regulations and policies to ensure the safe and environmentally sound activities related to oil spill prevention and response. These commitments demand preparedness and continuous improvement throughout every phase of exploration and production where oil is produced, transported, stored or marketed. Prevention is considered as the most critical area in all jurisdictions, with considerable efforts being placed to ensure the risk of a spill is as low as reasonably possible. In addition to prevention, oil-spill response is also of the upmost importance. All regulatory regimes under study acknowledge that the speed and effectiveness of a response operation can be greatly enhanced through the improved planning, training and coordination of a response system. In addition, International Maritime Organization (IMO) of United Nation has the responsibility of coordinating different countries, including the assistance of international actions. Moreover, extraordinary coordination of international, federal, state and local resources is required for a spill. The developments of oil industry generate newer and more complex environmental and industry challenges, resulting in both the cumbersome legislation and implement processes and unclear

effectiveness of the regulations. The existing regulations can limit the flexibility of developing a more efficient and effective regulatory system. As a result, a response gap analysis, more advanced regulations and more effective cooperation are recommended.

CHAPTER 5

STRATEGIES FOR OFFSHORE OIL SPILL

MANAGEMENT

5. 1 Management strategies in United Kingdom

UK offshore operators are required to have Oil Pollution Emergency Plans (OPEPs), the details of which have to be approved by DECC as required by the Offshore Installations (Emergency Pollution Control) Regulations 2002 (Government of United Kingdom, 2002), and the Merchant Shipping (Oil Pollution and Preparedness, response Co-operation Convention) Regulations 1998 (Government of United Kingdom, 1998). The plans are reviewed by DECC, the Maritime and Coastguard Agency (MCA) and relevant environmental consultees, such as the Marine Management Organization (or relevant devolved authority), the Joint Nature Conservation Committee (JNCC) and the relevant inshore statutory nature conservation body (for example, Natural England).

OPEPs set out the arrangements for responding to oil spill incidents that have the potential to cause marine pollution. They aim to prevent such pollution and reduce or minimize its effects should it occur. OPEPs are risk assessments that are relevant to a specific field or installation. The plans focus on the worst-case scenario; following the Gulf of Mexico incident, operators are now required to carry out additional modeling for deepwater drilling installations, including an extended assessment of oil spill beaching predictions (DECC, 2010).

OPEPs use computer models to determine the likely movement of any spilled oil and the environmental sensitivities of the location. Predicting the wind direction and sea-current patterns are critical to the accuracy of such models and the subsequent response. For instance, in the West of Shetland, prevailing westerly winds would generally direct an oil spill towards the Shetland shoreline, so in the case of an oil slick the response would move immediately to coastal protection. It is acknowledged by DECC that the computer model used industry-wide (OSIS) has limitations with regard to predicting long term spill and deepwater effects. The Oil Spill Response and Advisory Group (OSPRAG) are undertaking a review of this model (DECC, 2010).

Depending on the nature of the spill, the response can range from monitoring slick behavior, through to the use of chemical dispersants along with physical containment (the use of booms and skimmers) and recovery of the oil. To ensure the OPEP is, and remains, fit-for-purpose operators are obliged to hold a personnel and equipment exercise every five years with the MCA. Under the International Convention on Oil Pollution Preparedness, Response and Co-operation Convention 1990, adopted by the UK in 1994, all operators must test their OPEP offshore with every shift at least once a year (DECC, 2010).

The MCA maintain stockpiles of counter pollution equipment at various sites throughout the UK, with oil spotting and dispersant spraying aircraft located in

Inverness and Coventry. If this equipment is required, control of the incident will pass to the MCA and the Secretary of States' Representative for Maritime Salvage and Intervention, SOSREP, who represents DECC in relation to offshore installations and the Department for Transport in relation to shipping. Oil spill response is divided into three categories depending on the amount of oil spilled (MMO, 2012):

- Tier 1—100 tonnes or 740 barrels—a small sized spill that will employ local resources;
- Tier 2—500 tonnes or 3,700 barrels—a medium spill requiring regional assistance; and
- Tier 3—10,000 tonnes or 74,000 barrels—activates the National Contingency Plan.

For comparison, it is estimated that approximately 4.9 million barrels of oil leaked into the Gulf of Mexico. The National Contingency Plan (NCP) is one of the measures the UK has taken to meet its obligations under the United Nations Convention on the Law of the Sea (UNCLOS), setting out the circumstances in which the MCA's national assets are deployed. The NCP supports and underpins an operator's required Oil Pollution Emergency Plan (OPEP), the details of which have to be approved by DECC. These include installation-specific risk assessments that model the likely path of an oil spill and environmental sensitivities. The date for testing OPEPs, NCPs and the powers of SOSREP has been brought forward from 2013 to spring 2011.

The role of the Secretary of States' Representative for Maritime Salvage and Intervention (SOSREP) was created in 1999 as part of the Government's response to Lord Donaldson of Lymington's review of the grounding of the Sea Empress oil tanker at the entrance to Milford Haven in 1996, which spilt around 70,000 tonnes of oil (over 500,000 barrels). SOSREP represents the Secretary of State for the Department of Energy and Climate Change in relation to offshore installations, and the Secretary of State for the Department for Transport in relation to ships and tankers. SOSREP is empowered to make crucial decisions, often under time pressure, without recourse to a higher authority, where such decisions are in the "overriding UK public interest" (HSE, 2010).

Legislation requires that every five years each operator must conduct an exercise to test a facility's Oil Pollution Emergency Plan (OPEP) with the involvement of SOSREP. The Maritime and Coastguard Agency (MCA) maintain stockpiles of counter pollution equipment at various sites throughout the UK, and have remote sensing and dispersant spraying aircraft located in Inverness and Coventry. If this equipment is required, control of the incident will pass to the MCA and SOSREP. SOSREP automatically becomes involved in any incident where there is a significant threat of significant pollution, known as the "trigger point" for intervention. The key responsibilities of SOSREP include: acting at the earliest point

during a shipping or offshore incident to assess the risk to safety, to prompt the end of any such incident and to ensure that increasing risk is evaluated and appropriate measures taken to prevent or respond to escalation; monitoring all response measures to significant incidents involving shipping and the offshore industry; if necessary, exercising ultimate control by implementing the powers of intervention, acting in the overriding interests of the UK and its environment; and reviewing all activities after significant incidents and exercises (Maritime and Coastguard Agency,2009).

5.2 Management strategies in Austria

On activation of the National Plan, the IC or the MPC may submit a request to AMSA for personnel from other states/NT to assist with the incident response, for example to fill positions in the Incident Control Centre or incident response team. A request should be made initially through the AMSA Duty Officer via the Emergency Response Centre on 1800 641 792 or 02 6230 6811. This request must be followed by written confirmation within three hours of the verbal request. During extended responses AMSA may appoint an officer to coordinate inter-state deployments and will advise the IC and the MPC accordingly (Flinder Ports, 2012).

The following information is to be provided when making such a request:

- roles or skills required, for example Planning Officer, Aerial Observer
- number of personnel required to fill each role
- contact name, address, and time of where personnel are to initially report
- brief overview of the work to be undertaken.

Suitable personnel will be selected by AMSA from the National Response Team (NRT) or the National Response Support Team (NRST), unless special circumstances exist. This procedure does not apply to the activation of NRT and NRST personnel from within the State/NT where the incident has occurred. In such circumstances, the relevant combat or statutory agency is responsible for activation in accordance with applicable contingency plans or state/NT arrangements (Flinder Ports, 2012).

The maximum release period is 10 days (including travel time) as per the National Response Team Policy, unless both AMSA and the NRT/NRST member's organization reach a separate agreement. Where an extension on deployment is being sought, the requesting agency is to provide details on how the health and safety of the individual/s is to be managed. Personnel will remain in the employ of their own agency and all entitlements in relation to their contract of employment remain unchanged.

AMSA, as manager of the National Plan, has developed and jointly funded with the Australian Institute of Petroleum (AIP) through its Geelong-based Australian Marine Oil Spill Centre (AMOSC), a Fixed Wing Aerial Dispersant

Capability (FWADC) for oil spills in the marine environment. Based on the concept of utilizing large agricultural fixed wing aircraft to apply oil spill dispersants, the FWADC is designed to complement dispersant spraying arrangements using helicopters, which are typically confined to close inshore work. Under the contract arrangements six aircraft are strategically located to provide full coverage of the Australian coastline. The aircraft are located in (TMR, 2011):

- Ballarat, Victoria
- Adelaide, South Australia
- Ballidu, Western Australia
- Batchelor, Northern Territory
- Emerald, Queensland
- Moree, New South Wales.

Activation of the FWADC is through the AMSA Duty Officer. Each aircraft is available to depart within four hours of activation, twenty- four hours per day, seven days per week. AMSA will also activate an Airbase Manager and loading crew to manage the aircraft and loading of dispersant into the aircraft.

The statutory agency has relevant legislative authority and is responsible for the overall conduct of the incident response, and for the institution of legal proceedings (Government of Australia, 2005).

- Maritime Safety Queensland is the statutory agency for all areas of Queensland Coastal Waters, except those waters contained within the GB RWHA that are within the scope of QCCAP.
- AMSA is the statutory agency for all areas outside of Queensland 'Coastal Waters', except those waters contained within the GBRWHA that are within the scope of QCCAP.
- The Great Barrier Reef Marine Park Authority (GBRMPA) is the statutory agency for all areas within the Great Barrier Reef Marine Park.
- DERM is the statutory agency for land-sourced oil spills in Queensland.

Furthermore, the following agencies are responsible for leading and coordinating the incident response (Government of Australia, 2005):

- Maritime Safety Queensland is the combat agency for all incidents within the scope of QCCAP except from those that occur at oil or chemical terminals.
- The relevant oil company or chemical terminal operator is responsible for responding to marine pollution incidents at terminals. The oil industries' response arrangements are described in the Australian Marine Oil Spill (AMOS) Plan and are covered under the mutual aid arrangements of the AMOSC. The chemical industries' response arrangements are described in the Plastics and Chemicals Industries Association (PACIA) Chemsafe Emergency Management Program

- arrangements.
- DERM is responsible for the management of oil pollution from land-based sources from non-devolved environmentally relevant activities into Queensland waters. Under a Memorandum of Understanding, Maritime Safety Queensland will assist DERM in managing land-sourced oil spills by providing experienced officers and the necessary infrastructure and resources.
 - Councils are responsible for devolved land-based spills or dumping for: non-licensed premises where clean-up costs are less than \$5,000, and for ERA/FCL registered premises regardless of clean-up costs. All other land-based spill situations are the responsibility of DERM.

5.3 Management strategies for offshore oil spill oil spill in Norway

The Norwegian Oil Spill Preparedness is based on chapter 6 in The Pollution Control Act of 13 March 1981 (Government of Norway, 1981). The Act is based on the Polluter Pays Principle and states the responsibilities and obligations of the industry, the municipalities and the government with regard to acute pollution incidents. The Pollution Control Act states that the National Contingency System is divided into private (industry), municipal and governmental contingency areas with specific responsibilities. In Norway, all contingency plans and organizations are standardized and co-ordinated. Hence, in the event of a major national emergency, the national contingency system will work as a single integrated response organization (Sydnes and Sydnes, 2011).

Industrial plants that can cause significant oil pollution are obliged to establish an adequate level of preparedness. The Climate and Pollution Agency sets requirements and supervises contingency measures against oil and chemical contamination. These requirements primarily apply to operators on the Norwegian Continental Shelf, the crude oil terminals, and the refineries and companies distributing oil products as well as major industrial companies. The requirements are stated in the regulations relating HES (Health, Environment and Safety) on the Norwegian continental shelf (Bjerkemo, 2010).

In Norway the approx. 430 municipalities are divided into 34 inter municipal preparedness areas; each with its own approved contingency plan. The local authorities are responsible for dealing with minor acute spills that may occur within the municipality due to normal activity, which are not covered by the polluter's private contingency arrangements. The local authorities, the fire departments, the port authorities etc. all collaborate on municipal preparedness. In addition, the municipalities have an obligation to assist the government in the event of a major oil pollution action (Sydnes and Sydnes, 2011).

The Norwegian Coastal Administration (NCA) is a Governmental agency under the Ministry of Fisheries and Coastal Affairs. The main tasks are to safeguard

and develop the coastline for all users. The Norwegian Coastal Administration shall contribute to secure vessel traffic and good accessibility along the coast as well as a good, national preparedness against acute pollution. The Norwegian Coastal Administration is responsible for organizing and maintaining the governmental oil spill response preparedness and for coordinating the governmental, the municipal and the private industry's preparedness in national contingency system against acute pollution. This also involves controlling and monitoring any response operations undertaken by the industry or the municipalities' major spills from unidentified sources. Additionally, the NCA can provide resources to response-operations under private or municipal management. If the party responsible for carrying out the response-measures does not master the task, the NCA will assist, and (possibly) take over the management of the operation if so required. The NCA is responsible for coordinating private, municipal and Governmental preparedness into a national emergency response system (EPPR, 2012).

In incidents involving vessels in distress, the Main Rescue Coordination Centers have the responsibility for saving lives. NCA will have the responsibility for any clean-up operations of oil at sea and emergency-offloading measures on behalf of the ship owner. Norwegian Maritime Directorate (NMD) has the responsibility to intervene with the owners and ensure the safety of the vessels. NCA and NMD therefore have developed a close co-operation with regard to operations aimed at vessels in distress. On Director General Level an agreement between NCA and The Petroleum Safety Agency has been established. The aim of this agreement is to have a forum for co-ordination and decision-making during response operations involving large oil spills from the petroleum activities. Examples of such operations are blowouts and other large spills from the production facilities offshore. In addition, NCA has an agreement with the Norwegian Coast Guard and the Armed Forces regarding assistance with personnel and equipment. This agreement is the foundation for putting oil spill response equipment permanently on board 8 Coast Guard vessels. There are also other agreements with different governmental bodies such as Civil Defence, National Metrological Centre etc. (Vik, 2005).

5.4 Management strategies in America

Due to the well-publicized Exxon Valdez and BP Oil Spill Disaster in the Gulf of Mexico, including many other lesser-known but just as devastating oil spills, as well as terrorist attacks, sabotage and kidnappings – the oil and gas industry as a whole has suffered a huge "black-eye" and now faces an uphill battle for credibility with environmental groups, governmental regulators, insurance companies and most importantly with its various investors and owners who are critical to maintaining accessibility to the huge amounts of capital that will be necessary for future exploration activities. The environmental and financial impacts of marine oil spills, both large and small, are well known within the oil and gas industry. The potential impact, economic or otherwise, of a terrorist attack or act of sabotage is less understood but no less important to industry and it has now become critical to

have the airborne remote sensing capabilities not only available but also deployed in each specific geographic area where current and/ or future off -shore exploration and production activities are in-play (Long, 2012).

Environmental rules and regulations and strict operating procedures have been imposed to prevent oil spills, but these measures cannot completely eliminate the risk. What is needed is to have an overarching and all-encompassing Marine Oil Spill Response and Contingency Action Plan (OSRCAP) in-place, which when properly employed is the most all-inclusive method of offshore security, spill detection and tracking, disaster management, damage mitigation and the deployment of rapid and effective counter-terrorism measures and clean -up efforts. In the event of an oil spill or attack, information about the threat or the size and extent of the spill is critical to assist the oil and gas industry in contingency planning and this will only be available when the proper OSRCAP assets are in -place and used proactively (Long, 2012).

The Department of the Interior (DOI) and industry have implemented many of the Commission's recommendations to improve safety and environmental protection. In addition to issuing a Workplace Rule on Safety and Environmental Management Systems and a new Drilling Safety Rule in October 2010 (BOEMRE 2010), the Department of Interior has taken several steps to implement the Commission's recommendations. A key one has been the separation of the leasing and environmental review functions from the regulatory activities.

Another has been to appoint a chief scientist to head the environmental division. The Department is also working on additions to the two rules already issued and is including additional safety conditions in the notices it periodically issues to lessees. Although the two new bureaus - the Bureau of Ocean Energy Management (BOEM), and the Bureau of Safety and Environmental Enforcement (BSEE) —are not completely independent, as the Commission urged, the Department provided strong budgetary and operational rationales for the decision to structure these two new entities as it did.

The Department of the Interior is moving towards a risk management based regulatory approach, similar to the United Kingdom's "safety case", as the Commission recommended. This shift will take time and will have to be molded to the cultural and legal characteristics of the U.S. regulatory system, but continue to believe that it will be more effective than a strictly prescriptive approach. This does not, however, obviate the need for DOI's adoption of important safety rules, such as those governing well design and the design and construction of blowout preventers (Peterson and Fensling, 2012).

Industry has responded to one of the Commission's most important recommendations by establishing a new Center for Offshore Safety. This new Center holds promise of helping to ensure that the firms involved in offshore drilling perform at the top of their game. As a similar organization, the Institute of Nuclear Power Operations (INPO) helped achieve in the nuclear power industry, such an entity can be extremely effective in promoting the adoption of safety improvements

and environmental protection. Several major oil companies also have undertaken important initiatives to improve their safety and environmental protection practices, and are supporting significant improvements through various international organizations.

Although the Oil Spill Commission Action project were informed that they were under development, there are no regulations strengthening practices and procedures under the National Environmental Policy Act (NEPA) have been formally proposed, as the Commission recommended, to improve the quality of the reviews during the planning, leasing, exploration and development stages. Environmental groups assert that the Environmental Assessments being prepared on exploration plans continue to provide little site-specific analysis, and that BOEM continues to link “or tier” them back to inadequate Environmental Impact Statements prepared before the Macondo well blowout (OSCA, 2012).

Although the Council on Environmental Quality (CEQ) and DOI have modified their approach to Environmental Assessments and worst case oil spills in some areas, new procedures need to be adopted to assure an improved level of environmental analysis, transparency and consistency. The Commission also recommended that Congress amend applicable law to give the National Oceanic and Atmospheric Administration (NOAA), one of the federal government’s leading scientific agencies, a formal consultative role during the development of offshore leasing plans and sales. Congress has not acted on this recommendation, but the Department of the Interior and NOAA have signed a comprehensive cooperative agreement that assures NOAA a significant role in planning and permitting.

Although BOEM has increased funding for its environmental studies program, additional action is needed to establish a robust interagency research program to better define and monitor environmental conditions in new lease areas. Several companies operating in Alaska have signed an agreement with NOAA to share all the environmental information they collect. This is a useful partnership between industry and government but a comprehensive government-designed and implemented research program is essential to assure good decisions by the public agencies.

It is unfortunate that two years after the worst oil spill in U.S. history, Congress has yet to take action to bolster the government’s program for managing offshore activities. In the last session of Congress, in 2010, the House of Representatives did pass legislation, HR 3534, that incorporated many changes the Commission subsequently incorporated in its final report, but the Senate took no action. In the current session neither branch of Congress has acted upon legislation that would implement the Commission’s recommendations. Indeed, the House has passed several bills (for example, HR 1229, 1230, and 1231) containing provisions, such as requirements that extensive offshore areas be leased without adequate review, that actually run contrary to what the Commission concluded was essential for safe, prudent, responsible development of offshore oil resources.

According to the Bureau of Ocean Energy Management, Regulation, and

Enforcement (BOEMRE), all offshore oil and gas facility owners or operators must submit an oil spill contingency plan for approval prior to beginning any exploration, development or production activities. These plans must describe in detail what actions will be taken in the event of a spill to control, contain and recover the oil from the environment. Response activities are described in the worst-case discharge scenario which includes identification of equipment, personnel and support services required to cleanup a facility's worst case discharge. The Alaska Region verifies that the company has sufficient response resources either through company owned or contracted assets such as an Oil Spill Removal Organization (OSRO). Additionally these plans must include spill trajectories to identify where currents and wind will most likely carry the oil and identification of environmentally sensitive areas that could come in contact with the spill and protective actions to be taken to limit the oil's impact (BOEMRE 2010).

5.5 Management strategies in Canada

In June 2010, Transport Canada released a plan and a policy for preparedness and response in relation to Canada's Marine Oil Spill Preparedness and Response Regime. We found that Transport Canada's plan outlines roles and responsibilities of all parties in the event of a marine incident, including Transport Canada, the Canadian Coast Guard, Environment Canada, private sector certified response organizations, ships, and oil-handling facilities. The plan's purpose is to establish the national preparedness capacity of Canada's Marine Oil Spill Preparedness and Response Regime. However, the plan does not contain information on the state and expected levels of the preparedness relative to risks, or on mechanisms to ensure an adequate response, and therefore the plan does not fulfill its own purpose, which is to establish Canada's national preparedness capacity (Vaughan, 2010).

The Canadian Coast Guard's emergency management plan (called the Marine Spills Contingency Plan) dates back to 1998. Since the release of this plan, significant legislative and administrative changes have occurred that are not reflected in the plan. For example, in December 2003, several sections of the Canada Shipping Act, 2001, including some policy and all regulatory responsibilities for pollution prevention, were transferred from Fisheries and Oceans Canada to Transport Canada. Other changes include revisions to the Canada Shipping Act in 2001 and the enactment of the Emergency Management Act in 2007 (Ministry of the Environment, 2012).

Coast Guard's plan defines the scope and framework within which it will operate to ensure a response to marine pollution incidents. However, it does not contain an up-to-date response model and related procedures that would be used to manage the Coast Guard's response to a major incident. Nor does the plan mention Public Safety Canada, which could play an important coordinating role in the event of a significant incident. The various Coast Guard regions have also prepared

emergency management plans. Some of these plans have been recently updated (Quebec in 2009 and Central and Arctic in 2008), while the remaining plans date back to 2004 or earlier (Newfoundland and Labrador, 2004; Maritimes, 2004; and Pacific, 2001). These plans are based on the Canadian Coast Guard's 1998 plan, but because they have been updated at different times, they are not consistent across regions (Fisheries and Oceans Canada, 2010).

Given the Canadian Coast Guard's role as the lead responder to ship-source oil spills, the lack of an up-to-date national emergency management plan and model for responding to a major incident presents risks to the Coast Guard's ability to effectively coordinate and oversee a response to a major incident. The Coast Guard recognizes that its plan needs updating and is developing a National Environmental Response Strategy that is expected to be in place by March 2011. The strategy is to be followed by the development of a national response policy and plan for directing its efforts, including those related to a major incident (Fisheries and Oceans Canada, 2010).

Environment Canada's main responsibility is to providing advice received from Regional Environmental Emergencies Teams and by providing expert advice on potential risks and ecologically sensitive areas as well as key physical, biological, and cultural resources. The Department's environmental emergencies plan was released in 1999 and has not been updated since. The Department's regional emergency plans and plans for Regional Environmental Emergencies Teams vary by region in their format and content, and in the date they were last updated (Ministry of the Environment, 2012).

Emergency management plans are evolving documents; as such, they require regular reviewing and updating to take into account policy; legislative, organizational, and technological changes; and experience and lessons learned from responding to incidents and conducting exercises. Environment Canada is the federal authority for providing environmental advice during a oil or chemical spill. The Department is responsible for establishing and coordinating multi-stakeholder Regional Environmental Emergencies Teams (REET) composed of representatives from the federal, provincial, and territorial governments; industry; and other organizations in a region, such as Aboriginal groups. During a marine pollution incident, Environment Canada would support those involved by providing expert environmental advice directly, or through the Regional Environmental Emergencies Teams, particularly with respect to environmental priorities, resources at risk, and the most appropriate cleanup countermeasures. It would also provide advice on ways to reduce the impact on the environment, modeling of spill trajectories, marine weather warnings and forecasts, and the location of wildlife and sensitive ecosystems (Environment Canada, 1999).

Pollution prevention includes any activity geared toward eliminating or reducing oil and chemical spills, which includes the enactment and enforcement of relevant legislation and regulations. Regulations under the Canada Shipping Act, 2001 and the Arctic Waters Pollution Prevention Act set discharge limits for a variety of marine pollutants and require Canadian and foreign ships in Canadian

waters to meet specified construction, equipment, reporting, and operational standards in order to prevent and control pollution. Likewise, the Migratory Birds Convention Act, 1994 prohibits discharges from vessels into waters frequented by migratory birds, while the Fisheries Act prohibits the deposit of deleterious or harmful substances into waters frequented by fish. Transport Canada and Environment Canada are responsible for ensuring that spills from ships are prevented by promoting and enforcing compliance with actions such as ship inspections and prosecution of offenders.

Marine services can help improve the safety of marine transportation and prevent accidents and subsequent spills. For example, within the Canadian Coast Guard, Marine Communications and Traffic Services broadcasts information such as weather bulletins and ice information and regulates vessel traffic movement, which can reduce the probability of ships being involved in accidents. Another example of prevention is the requirement (since 1 January 2010) that tankers greater than 5,000 gross tonnes have a double hull, as per the International Maritime Organization's International Convention for the Prevention of Pollution from Ships. This design is considered to be more effective than single hull tankers in preventing pollution in the event of accidental grounding or collision.

Despite pollution prevention efforts, oil spills may occur. Internationally, aerial surveillance is widely adopted and considered to be an effective method for detecting oil spills. Transport Canada operates the National Aerial Surveillance Program for detecting oil spills at sea. Through partnership with Environment Canada's Canadian Ice Service, Transport Canada has created a Marine Aerial Reconnaissance Team. Since 2006, new technology allows Transport Canada's three surveillance aircraft to cover a much broader area than before, day or night, and in more challenging weather conditions (Minister of Transport, 2009).

Having emergency management plans in place, informed by an up-to-date knowledge of risks regarding offshore oil spills and supported by training, exercises, and appropriate spill response equipment, are important aspects of being prepared to respond to oil and chemical spills. When a spill does occur, it is important to respond appropriately to minimize environmental and socio-economic impacts. Response activities can include containment and recovery of the pollutant, shoreline cleanup, and wildlife recovery, and can involve local communities, provincial governments, and international cooperation efforts. The specific response should be appropriate to the location, size, and nature of the incident. If necessary, environmental response equipment of certified response organizations and the Canadian Coast Guard may be transferred from across the country to respond to a marine pollution event, including oil spills from ships (Government of British Columbia, 2002).

In the case of any spill, the offshore operator is in charge and must activate its response plan. Operators have a tiered response program, with each tier providing equipment and resources appropriate to the size of the spill. Small, Tier One, spills can be dealt with immediately by the operator itself onsite, while others would require further outside assistance, in addition to the operator's on-site

resources and assets.

Meanwhile, the responsible government agency, C-NLOPB or C-NSOPB, acts in a monitoring role. It does, however, have the authority to supersede the operator if it determines that the response is inadequate. This situation was described by the CEO of the C-NSOPB in testimony before the committee. Depending on the significance of the spill, the role would range from monitoring the operator's activities to giving direction to the operator or in the most severe or extreme cases to managing the spill response. The tiered response system forms cascade. Tier Two responses will incorporate on-site equipment and resources from a Tier One response. A Tier Three response will bring additional resources on top of the assets and personnel mobilized during Tier Two.

If the oil spill is of a greater magnitude and cannot be immediately contained by equipment on site, offshore operators mobilize a Tier Two response. As all Atlantic offshore oil and gas projects have a contract with ECRC to provide assistance with oil spill cleanup responses, this organization is brought in at this stage. The offshore operators need to purchase their equipment, including state-of-the-art Norwegian skimmers and booms. These are held for them by ECRC. Other operators on the Grand Banks also have equipment that can provide mutual aid. That is the equipment referred to in Tier Two along with the equipment that ECRC has (David and Mitchell, 2010).

When ECRC responds to a spill, it works as a contractor for the offshore operator, who has oversight and final say on whatever oil spill response plans are: ECRC's role in a spill is to provide operational management, which includes spill management and planning. There would be an emergency phase and in the background we would be preparing a longer-term response plan. That response plan would be developed in conjunction with government agencies as well as the responsible party (the offshore operator). The responsible party, in cooperation with the lead agency, would sign off on that plan and we would continue with the response (David and Mitchell, 2010).

A severe oil spill or simultaneous small spills that exceed regional resource capacity trigger the Tier Three response plan. This is the ultimate step in the tiered response and therefore signifies critical situation, such as a blowout. All available resources are pooled to assist in the containment. Offshore operators such as ExxonMobil are international corporations that can bring in equipment and expertise from abroad. They have a team of people who are trained every year in global response and going around to various locations to train for tabletop type scenarios. They have knowledge, contacts and access to resources virtually around the world that Exxon Mobil can call in at their disposal if need be. That would be the third tier of response (David and Mitchell, 2010).

Representatives from Chevron and Husky Energy who also appeared before the committee provided similar descriptions of their global emergency response capabilities. As for ECRC, their plan response escalation includes the following: At that point, Tier One and Tier Two will still be deployed. They will also call upon

additional resources to assist in the effort. This will potentially include mobilization of Coast Guard resources, additional ECRC resources from other places in Canada, and international support. They have a contract with Oil Spill Response Limited, OSRL, which is based in Southampton in the United Kingdom. They can deploy significant resources, including a couple of Hercules aircraft to fly in additional equipment (David and Mitchell, 2010).

5.6 Management strategies in Newfoundland and Labrador

The Canada-Newfoundland and Labrador Offshore Petroleum Board (C-NLOPB) is responsible for regulating the offshore petroleum industry. The C-NLOPB reports to the ministers responsible for energy in the federal government and the government of Newfoundland and Labrador. The responsibilities of C-NLOPB are broad and include (Burley, 2008):

- Administering a rights issuance and land tenure system,
- Ensuring that activities are conducted in a safe, environmentally prudent manner,
- Assessing and ensuring conservation of petroleum resources, and
- Promoting industrial and employment benefits.

Under its mandate, the C-NLOPB works with other agencies, both federal and provincial, and accomplishes this through Memoranda of Understanding (MOUs). MOUs have been negotiated with the departments responsible for environment, fisheries and transportation. The MOU with the environment departments recognizes the Regional Environmental Emergency Team (REET).

The definition of “spill” is a discharge, emission or escape of petroleum other than one authorized by legislative authorities. C-NLOPB has a relatively narrow jurisdiction. However, the C-NLOPB is the lead agency for drilling and production currently taking place at three sites on the Grand Banks and for exploratory drilling units when on site. The C-NLOPB is a resource agency in other cases, e.g., for supply vessels and shuttle tankers. The response regime is similar to that of the CSA and is based on the “polluter pays” principle. The polluter is responsible for the cleanup. The C-NLOPB can intervene if the operator response is not satisfactory. Contingency plans must be developed and filed with the C-NLOPB (Burley, 2008).

The oil spill response planning elements are typical for this type of response. Tier 1 is in the field; Tier 2 is in provincial waters; and Tier 3 is national or international. The operator’s plan is the basis for the specific command and control structure and communication procedures, identifies resource requirements and has provisions for personnel training. Resource-sharing provisions are in place among the operators (Grattan, 2008).

The Division also administers the federal/provincial Disaster Financial Assistance Program to compensate for losses in events such as floods. It is not an insurance program but an assistance program that provides funding to help people

live at a reasonable or safe standard. The Director of the Division is also responsible for the province's Emergency Measures Organization (EMO). EMO works with representatives at the municipal level. It also has stakeholders in the federal and provincial governments, the not-for-profit sector and other interested parties. EMO recognizes that small communities are challenged to do emergency planning because they have limited resources. They will have to develop partnerships with organizations that have access to the necessary resources. Communications is the key to the successful activation of an emergency response plan. Most plans will be based on engaging communities and stakeholders. Local volunteer fire departments are not necessarily ready to respond to an oil spill. They need specialized emergency planning and resources. Partnerships should be built with those who have knowledge of oil spills. Most communities will respond to the extent of their capability. Emergency situations can be managed. Key components include determining who has the jurisdiction, providing training and exercises, and establishing effective communications (Hollett, 2008).

Environment Canada's role in oil spill response is to work with other agencies to provide technical advice. It does not have operational responsibility, except when a federal incident occurs. The primary mechanism that Environment Canada uses to fulfill its role and provide expertise on environmental sensitivities is through the Regional Environmental Emergency Team (REET). In Atlantic Canada, REET is chaired by Environment Canada and acts as the principal adviser to Transport Canada, the Canadian Coast Guard and the C-NLOPB. It provides coordinated advice to lead agencies in emergencies, participates in exercises, is active in both civil and pollution emergencies, and participates in both planning and response modes. REET relies on partners to provide the response effort with the resources required. The benefits of REET are that it (Percy, 2008):

- offers a focus for advice provided to the lead agency in a spill,
- provides a forum for consensus building and dispute resolution,
- helps set priorities in a cleanup,
- minimizes environmental damage through pre-planning efforts, and
- maximizes the use of limited regional resources.

The Canadian Association of Petroleum Producers (CAPP) offers the perspective of companies engaged in the oil and gas industry. There are 150 members in CAPP with 500,000 employees in this industry across Canada. There are three projects in active production on the Grand Banks: Hibernia, Terra Nova and White Rose. Another field, the Hebron Project, is under consideration. The focus of the industry is on prevention of oil spills. Prevention is the most effective way to avoid damage. All aspects of project design and operations incorporate a philosophy of prevention first, and mitigation of environmental impacts should a spill occur. The systems are designed to prevent releases into the environment. Policies and procedures, training and equipment are all designed to reduce the probability of a spill and minimize the effects if one should occur. The offshore operators and regulatory agencies work together in six key areas (Williams, 2008).

- Mutual aid — Mutual aid is a requirement in the C-NLOPB safety plan guidelines. In the plans, there must be evidence of sharing of resources between operators. There is an MOU between CAPP and the C-NLOPB respecting mutual aid, specifically emergency response assistance. The mutual aid provisions can be activated if there is an incident or if one is imminent. The industry has access to Canadian Coast Guard spill response equipment if needed. There can be access to international resources.
- Response organizations and training — There is a common response organization, Eastern Canada Response Corporation (ECRC). Training is available through ECRC, Oil Spill Response Limited (OSRL), the Canadian Coast Guard and local companies such as Cormorant Limited.
- Oil spill response plans — Each company has its own response plan.
- Standard equipment and procedures — Operators require equipment suitable for the offshore operating environment of the Grand Banks. Typical equipment includes surveillance and tracking through aircraft and track in buoys, Brecobird scaring devices and sorbent booms. The operators have among them five Single Side Sweep (SVSS) oil containment and recovery systems.
- Seabird programs — There are populations of seabirds on the Grand Banks that have been identified as at risk in the event of a major oil spill. The operators support a seabird monitoring program.
- Annual oil spill response exercise— There is an annual exercise involving all stakeholders in the industry. This exercise tests the plans and identifies areas for improvement.

5.7 Challenges in the Harsh Environments in Offshore Newfoundland and Labrador

Since Newfoundland and Labrador locates in the north region with a harsh environment which poses unique challenges for spill response. Existing management techniques will have limitation when applied in offshore NL.

The presence or absence of ice is a large factor in the ability to respond to a spill, but it is not the only environmental factor affecting spill response. Temperature affects the consistency of oil and the speed at which it degrades. Winds and the resulting wave action are another factor. High energy from wind and waves can help oil to disperse naturally, but this energy also breaks up a thick slick into multiple thinner slicks, which are more difficult to address. Also, in broken ice, waves are less effective at naturally dispersing oil (Buist *et al.*, 2008).

Weather, including wind and wave activity, also affects responder access to an oiled area and whether recovery strategies such as boom and skimmers will work. Adverse weather conditions prevented responders from collecting oil from the wellhead, employing mechanical recovery methods, and conducting in situ burns at times during the Deepwater Horizon response. Seasonally short days and

the prevalence of fog and storms also limit the amount of time when response is feasible. Sea state may be calmer in the NL offshore than in the Gulf, as the sea ice has a muffling effect on waves. However, the water may grow turbulent over time as the summer ice melts and wave activity increases (Rainville and Woodgate, 2009). The amount of time when responders are simply unable to work is known as the response gap, and it is based on, among other things, adverse weather conditions. Furthermore, it was noted that temperature alone would be a significant limitation. All non-emergency work stops when temperatures reach below -45 degrees Fahrenheit (Cleveland, 2010).

Wave conditions mostly affect the type of booms to be used as oil spill countermeasure. The sizes and strengths of booms are designed and used dependent on different wave conditions. On implementation, the wave condition for the effective function of well-designed, constructed and maintained offshore-type booms are defined as a boom-water relative velocity under 0.4m/s and the wave height of less than about 2 meters. If exceeding this limit of wave environment, booms cannot effectively contain oil for the subsequent skimmer recovery. It was indicated that favourable wave conditions for spill containment may occur from late spring until early fall (Turner, 2010).

The most advance oil spill response will be rendered ineffective when the visibility is less than 1km or at night, due to the difficulties of directing response operation from the air.

Although it may be possible to recover oil already collected and contained in a boom, spray one last oil slick with dispersants or complete an in-situ burning of oil in a fire boom at dusk, it is not possible with the state of the art technique to continue offshore oil clean-up operations at night. In NL, although the relatively long daylight in summer (17 hours in June) is favourable for response enforcement, its short winter daylight time (7 hours in December) limits the function.

The presence of ice will also affect a spill-response operation, necessitating a change in strategies and techniques. And consistent long-term funding is needed for developing and improving response options for dealing with accidental oil spills in ice-covered waters.

Spill response operations in ice and open water are fundamentally different. These variances must be recognized when determining the most appropriate strategy for dealing with oil in specific ice conditions and seasons, including freeze-up, winter, and break-up. Both the waters of the Labrador Shelf and west Newfoundland can experience considerable amounts of ice during the winter months. Although the presence of ice precludes efficient mechanical recovery techniques, spilled oil can still be removed effectively from ice-covered waters using other techniques, such as in-situ burning, oil-mineral aggregate application, and dispersant application, the latter two techniques followed by mixing with propeller wash using ice-strengthened vessels. However, because of the vastly different ice environments and oil-in-ice situations, over-reliance on a single type of response

will likely result in inefficient, ineffective clean-up after an actual spill (U.S. Arctic Research Commission, 2004).

Successful spill response hinges on more than the immediate availability of the best technology. Several important non-technical issues raised during the course of this project should also be considered when planning spill response programs and operations: (1) Encouragement of more flexible regulations so that all possible response tools can be considered for use from the outset of a response.(2) Development of long-term education and public outreach programs to explain the advantages and disadvantages of different response strategies. (3) Application of biological sciences as part of net environmental benefit analysis to assess the relative merits of different response strategies.

In conclusion, it is important to study spill incidents from the past to learn how the oil has affected the environment, what clean-up techniques work, and what improvements can be made, as well as to identify the gaps in technology.

5.8 Summary

Most of oil spills are accidental, so no one can know when, where, or how they will occur. Spills can happen on land or in water, at any time of day or night, and in any weather condition. Preventing oil spills is the best strategy for avoiding potential damage to human health and the environment. However, once a spill occurs, the best approach for containing and controlling the spill is to respond quickly and in a well-organized manner. A response will be quick and organized if response measures have been planned ahead of time.

A management strategy/contingency plan is a set of instructions that outlines the steps that should be taken before, during, and after an emergency. A contingency plan looks at all the possibilities of what could go wrong and contingent upon actual events, including the contacts, resource lists, and strategies to assist in the response to the spill. The oil spill management strategy/contingency plan helps to minimize potential danger to human health and the environment by ensuring a timely and coordinated response. Well-designed local, state, regional, and national contingency plans can assist response personnel in their efforts to contain and clean up oil spills by providing information that the response teams will need before, during, and after spills occur. Developing and exercising the plan provides opportunities for the response community to work together as a team and develop the interpersonal relationships that can mean so much to the smooth functioning of a response.

The management of offshore oil spill may appear complicated because it provides many details about the numerous steps required to prepare for and respond to spills. It also covers many different spill scenarios and addresses many different situations that may arise during or after a spill. Despite its complexity, a well-designed contingency plan should be easy to follow. Although they are different in many respects, contingency plans usually include hazard identification, vulnerability analysis, risk assessment, and response actions.

Some management strategy or contingency plans are designed to deal with oil spills that might occur at specific places, such as oil storage or refining facilities. Others are designed to address spills that might occur anywhere within a large geographic region. Therefore, the management of offshore oil spill in each country usually includes three levels: local, regional, national, and the levels are usually denoted as Tier 1, Tier 2, and Tier 3.

Every facility that stores or refines oil products, whether owned by a private company or operated by a government agency, is required to develop a plan for dealing with an accidental release of oil on its property. For each industry sector (storage facilities, marine transfer facilities and vessels, pipelines, and offshore facilities) are intentionally as standardized as possible. This improves the ability of government, industry and responders to prepare for events and implement an effective response. However, areas for improvement were apparent. Specific suggestions are made to improve 1) the speed with which the response can be “ramped up,” including modular response strategies in areas such as area contingency plans and vessels of opportunity 2) spill response plan content and structure, 3) the role of regulatory agencies, and 4) training and exercises for large spill events. In conclusion, it is important to study spill incidents from the past to learn how the oil has affected the environment, what clean-up techniques work, and what improvements can be made, as well as to identify the gaps in technology.

Regional contingency plans describe the area covered by the plan; describe the responsibilities of an owner or operator and of government agencies in removing, mitigating, or preventing a discharge; and list all equipment, dispersants, or other mitigating substances and devices available to an owner or operator and government agencies to ensure effective and immediate removal, mitigation, or prevention of a discharge.

The national contingency plans ensure that the resources and expertise of the federal government would be available for those relatively rare, but very serious, oil spills that require a national response. This plan was designed primarily to assist with coordinating the various national agencies that are responsible for dealing with oil spill emergencies.

Because the approaches and methods for responding to oil spills are constantly evolving and each oil spill provides an opportunity to learn how to better prepare for future incidents, contingency plans are also constantly evolving and improving—ensuring increased protection for human health and the environment from these accidents.

Since Newfoundland and Labrador locates in the north region with a harsh environment which poses unique challenges for spill response. Existing management techniques will have limitation when applied in offshore NL. The presence or absence of ice is a large factor in the ability to respond to a spill, but it is not the only environmental factor affecting spill response. Temperature affects the consistency of oil and the speed at which it degrades. Winds and the resulting wave action are another factor. High energy from wind and waves can help oil to disperse

naturally, but this energy also breaks up a thick slick into multiple thinner slicks, which are more difficult to address. Also, in broken ice, waves are less effective at naturally dispersing oil.

Spill response operations in ice and open water are fundamentally different. These variances must be recognized when determining the most appropriate strategy for dealing with oil in specific ice conditions and seasons, including freeze-up, winter, and break-up. Both the waters of the Labrador Shelf and west Newfoundland can experience considerable amounts of ice during the winter months. Although the presence of ice precludes efficient mechanical recovery techniques, spilled oil can still be removed effectively from ice-covered waters using other techniques, such as in-situ burning, oil-mineral aggregate application, and dispersant application, the latter two techniques followed by mixing with propeller wash using ice-strengthened vessels. However, because of the vastly different ice environments and oil-in-ice situations, over-reliance on a single type of response will likely result in inefficient, ineffective clean-up after an actual spill.

Successful spill response hinges on more than the immediate availability of the best technology. Several important non-technical issues raised during the course of this project should also be considered when planning spill response programs and operations: (1) Encouragement of more flexible regulations so that all possible response tools can be considered for use from the outset of a response. (2) Development of long-term education and public outreach programs to explain the advantages and disadvantages of different response strategies. (3) Application of biological sciences as part of net environmental benefit analysis to assess the relative merits of different response strategies.

In conclusion, it is important to study spill incidents from the past to learn how the oil has affected the environment, what clean-up techniques work, and what improvements can be made, as well as to identify the gaps in technology.

CHAPTER 6

OFFSHORE OIL SPILL MONITORING AND ANALYSIS

6.1 Oil spill monitoring

The ability to detect and monitor oil spills at sea is becoming increasingly important due to the constant threat posed to marine wildlife and the ecosystem. As the demand for oil based products increases, shipping routes will consequently become much busier and the likelihood of slicks occurring will also increase. If applied correctly, monitoring tools can allow for early detection of slicks, provide size estimates, and help predict the movement of the slick and possibly the nature of the oil. This information will be valuable in aiding clean-up operations, and will not only help save wildlife and maintain the balance of the local ecosystem, but will also provide damage assessment and help to identify the polluters (Archetti, 2009).

As soon as an accidental spill occurs, a monitoring programme aiming at quantifying the environmental impacts of the spill is usually launched. The assessment of the environmental impact is crucial for the decision-making process over the selection and implementation of a prominent response and restoration plans (Kirby and Law, 2010). In addition, from a legal standpoint, the development of adequate monitoring tools are of chief importance, since they can be used to demonstrate ecological damage and economic losses in the context of spill-related claims and compensations. Depending on the formulated objectives, environmental monitoring programs may include different methodologies to monitor the chemical contamination of the various compartments (e.g. sediments, water, biota) and evaluate the biological and ecological impacts of the spill.

6.1.1 On-site monitoring

6.1.1.1 *Monitoring within station*

Analysis performed in the field is faster and more economical than analysis done in a laboratory (Lambert et al., 2001). As analytical techniques are constantly improving and lighter and more portable equipment is being developed, more analytical work can be carried out directly in the field. Test kits have also been developed that can measure total petroleum hydrocarbons directly in the field. Some new methods use enzymes that are selectively affected by oil components. While these test kits are less accurate than laboratory methods, they are a rapid screening tool that minimize laboratory analysis and may provide adequate data for making response decisions. It is important to stress, however, that these field kits may have limitations and that results should be verified by laboratory analysis.

Some data is best collected, or can only be collected and assessed in the field, such as shoreline oiling (visible), shoreline gradient, oil physical properties and biological damage (AMSA, 2003).

The different tools to detect and monitor oil spills are **vessels**, **airplanes**, and **satellites**. Vessels, especially if equipped with specialized radars, can detect oil at sea but they can cover a very limited area. The vessel, however, remains

necessary in case oil sampling is required. The main systems to monitor sea-based oil pollution are the use of airplanes and satellites equipped with Synthetic Aperture Radar (SAR). SAR is an active microwave sensor, which captures two dimensional images. The brightness of the captured image is a reflection of the properties of the target-surface. The possibility of detecting an oil spill in a SAR image relies on the fact that the oil film decreases the backscattering of the sea surface resulting in a dark formation that contrasts with the brightness of the surrounding spill-free sea. Spaceborne SAR sensors are extensively used for the detection of oil spills in the marine environment, as they are independent from sun light, they are not affected by cloudiness, they cover large areas and are more cost-effective than air patrolling (Topouzelis, 2008).

In recent years, some state-of-the-art technologies have been developed and implemented in on site monitoring, such as real-time ship-borne radar facility for the automated detection of oil spills and early warning system (e.g., Saleh, 2004). Several examples are summarized hereafter, including vessel monitoring (field measurement of oil in water) and airplane monitoring (oil slick monitoring, aerial suveys). Detailed summary of satellite monitoring will be covered in 6.1.2.

(1) Field measurement of oil in water

Determining the oil content of subsurface water samples may be required to assess if dispersed oil is present. This may be needed to determine whether dispersants are working or to determine the distribution (e.g. dilution) of dispersed oil in order to assess or predict possible environmental damage. The fluorometry-based field method measures the level of both chemically and physically dispersed oil in water. Measurements are taken from a suitable vessel using a continuous flow fluorometer. Aerial support is recommended for targeting the slick and plume.



Figure 6.1 Fluorometer on deck
(AMSA, 2003)

(2) Monitoring the oil slick

Oil slicks at sea are routinely monitored by aerial surveillance. This includes monitoring of both the position and the character of the slick. Observations of slick character include area covered, percentage cover and gross changes to oil character (e.g. emulsification). In some oil spill situations, trajectory can be calculated manually from wind, current and oil data, or by using computer-based oil spill trajectory models (OSTMs). For chemical spills, where the contaminant may not be visible, a variety of different field methods are available to facilitate visual tracking, e.g. the use of tracker buoys (drogues) and dyes. Three-dimensional spill models are also available.

(3) Aerial surveys

Aerial surveillance is the most rapid means of estimating the location of oil on shorelines, and the length and extent of the oily band. Locations can be accurately logged, and band widths and percentages of cover can be estimated. However, it is rare that an accurate indication of oil thickness can be obtained using this technique, and therefore it is very difficult to quantify the oil present. In aerial surveys, an aircraft, preferably a helicopter, should have downward visibility, GPS, slow speed, and be suitable for low altitude. Assemble equipment such as coastline map and camera are also needed. Airborne surveillance is limited by the high costs and is less efficient for wide area surveillance due to its limited coverage (Brekke and Solberg, 2005).

(4) Small remote-controlled aircraft

Several parties have suggested using remote-controlled aircraft to provide more economical solutions for response personnel (Lehr, 2008; Donnay, 2009). In fact, remote-controlled aircraft have been used by a number of parties for monitoring a variety of pollutants since the 1970s (Li et al., 1994). Belgium employs an Unmanned Aerial Vehicle (UAV) of the B-Hunter class to routinely monitor its portion of the North Sea (Donnay, 2009). This is a large UAV that has visible and IR camera systems aboard. The unit has a 10-hour endurance over the targets.

A variety of commercial platforms are now available that can carry small sensors such as visible and IR cameras. Furthermore, automatic navigation technology has now made these units, especially helicopters, very much easier to fly than in previous years.

(5) Underwater detection and tracking

When applying techniques to detect oil under water, the division should be made between oil in the water column or floating on a pycnocline, and oil on the bottom. Quite different physics and conditions can apply to these different situations

Oil on the bottom can appear as a softer surface than ordinary bottom sediment (Redman et al., 2008). Standard sonars have been tried to detect submerged oil on the bottom. The problem arises in that vegetation on the bottom also appears similar, and thus many false positives arise. In the water column, sonar

can be useful as it can locate intermediate oil on pycnoclines; however, there is no unique signature, and there are often weeds and other debris on pycnoclines.

Oil on the bottom has successfully been mapped by underwater cameras, often mounted on sleds (Michel, 2008; Pfeifer et al., 2008a, 2008b; Wendelboe, 2009). The problems with this technique are the bottom visibility – which is often insufficient to discriminate – and the difficulty in towing the camera vehicle as slow as 1 knot, the necessary speed. Pfeifer et al. (2008a, 2008b) were successful in employing mosaics of photographs to determine the aerial extent of oil on the seafloor.

Camilli et al. (Camilli et al., 2009) have successfully applied mass spectrometry to detect sunken heavy oil. The mass spectrometer is mounted in a submersible that is driven over the seafloor. The exact position of the submersible is monitored closely using an acoustic positioning system on the surface. Tests show that it is fully sufficient to monitor sunken oil, and were conducted later over actual spills in the Gulf of Mexico.

6.1.1.2 Monitoring with sampling

Taking a sample of oil and then transporting it to a laboratory for subsequent analysis is a common practice. While there are many procedures for taking oil samples, it is always important to ensure that the oil is not tainted from contact with other materials and that the sample bottles are pre-cleaned with solvents, such as hexane, that are suitable for the oil (Wang et al., 2002).

The simplest and most common form of analysis is to measure how much oil is in a water, soil, or sediment sample (Wang et al., 2003). Such analysis results in a value known as total petroleum hydrocarbons (TPH). The TPH measurement can be obtained in many ways, including extracting the soil, or evaporating a solvent such as hexane and measuring the weight of the residue that is presumed to be oil.

There now exist certified laboratories that use certified petroleum hydrocarbon measurement techniques (Wang et al., 2003). These should be used for all studies. One of the most serious difficulties in older studies occurred when inexperienced staff tried to conduct chemical procedures. Analytical methods are complex and cannot be conducted correctly without chemists familiar with the exact procedures. Furthermore, field instrumentation requires calibration using standard procedures and field samples during the actual test. These samples must be taken and handled by standard procedures. Certified standards must be used throughout to ensure good Quality Assurance/Quality Control (QA/QC) procedures. In this era, it is simply unacceptable not to use certified methods, laboratories, and chemists.

(1) Sampling of the oil

Oil samples can indicate which equipment or cleanup methods are likely to be most effective. Time constraints often necessitate field assessment based on observations of the slick behavior, rather than on a detailed laboratory analysis of

the oil itself. Although detailed laboratory analysis is often too slow to provide data of operational use, it can provide information relating to the potential persistence of oil and the likely recovery of oil impacted communities. This can be related back to decision making regarding the need for cleanup efforts (AMSA, 2003).

For cost recovery and prosecution purposes, oil samples should be collected from the slick and impacted areas to provide a direct link between the source of a spill, and the areas affected by it. These samples should be collected using techniques that allow chemical fingerprinting of the oil (including weathering) and should be collected periodically throughout the response. Samples should also be collected from other possible sources in the vicinity of the spill.

Oil is usually sampled via collection of discrete samples that target areas where information on oil in the water is likely to be needed, e.g. adjacent to aquaculture facilities, spawning areas, food gathering sites, swimming beaches, etc. If samples are to be used for comparative purposes, reference samples should also be collected from either representative areas not directly impacted by the spill, or from areas before they are impacted (but ideally, both) (AMSA, 2006).

(2) Sampling the water column

It is usual for grab samples to be taken at the water surface to collect samples for determination of oil or chemical characteristics to help guide decision making, and for prosecution purposes. Where dispersants are used to disperse large surface slicks it is also common to use visual observations or fluorometry to monitor the effectiveness of the operation. The latter will involve sampling at a number of depths over the affected area and control areas.

To obtain discreet water samples at variable water depths, samples are taken from a suitable vessel. Samples can be taken using scientific equipment such as a "Niskin" bottle or "Nankin" bottle, or using improvised equipment like that shown in Figure 6.3. Samples should be collected from clean seas so that background hydrocarbon levels of the sea can be compared. However, water column monitoring for the assessment of a spill's effects on phytoplankton, zooplankton or fish is rarely undertaken due to the difficulty and cost in establishing a direct cause and effect relationship with a spill (AMSA, 2003).



Figure 6.2 Water column sampling

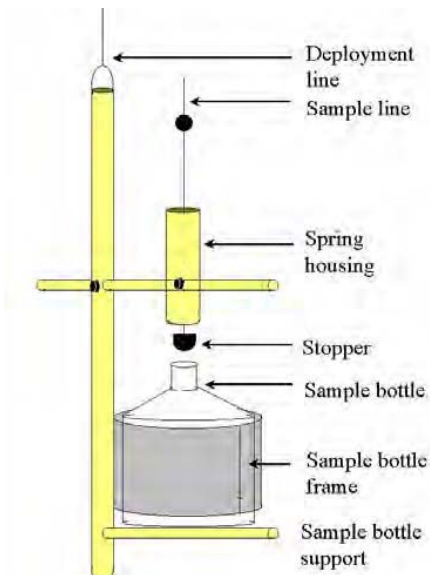


Figure 6.3 Improved water sampler

(3) Sampling sediment and associated biota

Oil can become incorporated into offshore sediments through natural processes or due to shoreline cleanup methods. If this accumulates to a significant extent then alternative cleanup strategies may be required. In contrast to the water column, sediment is a relatively stable medium. The physical, chemical and biological characteristics of the sediment substratum may integrate transient

changes from both dissolved contaminants in the water column and also deposited material. While substratum characteristics (e.g. sediment contaminants, ecological communities) will change over scales of months (e.g. seasonally) and years, they remain relatively stable over smaller time scales, and provide a good way of detecting change before and after an impact (AMSA, 2006).

This monitoring method is usually only required in shallow waters. Grab Samplers or Drop Corers can be used (Figure 6.4). The former are suitable for the wider set of sediments and sea conditions. Sample handling is also easier. Sample volume should be consistent between sites and surveys to allow cross comparison (AMSA, 2003).



Figure 6.4 Example of spring-loaded grab sampler

6.1.1.3 Quality of data

Control sites

A Control Site is an “unimpacted” site used for comparison with an impacted site. For example, if a program is looking at the effectiveness of various shore cleaning methods, cleaned sites should be compared with similarly oiled sites that have received no cleaning. In this way, all methods can be compared with natural oil removal. In practice, Control Sites may be difficult to locate or preserve. In the example used here, it may be difficult to convince spill responders, or regulatory agencies, of the value of leaving a beach uncleaned for comparative purposes (AMSA, 2003). In other cases there simply may be no control sites available.

Replicate Samples or Sites

Single observations and single samples are rarely adequate for drawing conclusions. Accordingly, replicate samples should be taken, and replicate assessment sites or locations must be established, wherever possible. The number required will depend on the nature of the program and the sensitivity of the issue being assessed. This sensitivity will reflect both environmental importance, as well as social, economic and political considerations.

Personnel responsible for the planning and execution of programs must have input into these discussions so that an adequate and feasible program is implemented. In some cases, the scale of the monitoring program will need to be determined at the highest level of the incident management team (AMSA, 2003).

6.1.2 Remote sensing

Large spills of oil and related petroleum products in the marine environment can have serious biological and economic impacts. Public and media scrutiny is usually intense following a spill, with demands that the location and extent of the oil spill be determined. Remote sensing is playing an increasingly important role in oil spill response efforts. Through the use of modern remote-sensing instrumentation, oil can be monitored on the open ocean around the clock. With knowledge of slick locations and movement, response personnel can more effectively plan countermeasures in an effort to lessen the effects of the pollution. In recent years, there has been a strong interest in detection of illegal discharges, especially in view of the large seabird mortality associated with such discharges (Serra-Sogas et al., 2008).

Even though sensor design and electronics are becoming increasingly sophisticated and much less expensive, the operational use of remote-sensing equipment lags behind the technology. In remote sensing, a sensor, other than the eye or conventional photography, is used to detect the target of interest at a distance. The most common forms of oil spill surveillance and mapping are still sometimes carried out with simple still or video photography. Remote sensing from an aircraft a common form of oil spill tracking. Attempts to use satellite remote sensing for oil spills continue, although success is not necessarily as claimed and is generally limited to identifying features at sites where known oil spills have occurred or for mapping discharges or known spills.

It is important to divide the uses of remote sensing into the end use or objective, as the utility of the sensor or sensor system is best defined that way. Remote-sensing systems for oil spills used for routine surveillance certainly differ from those used to detect oil on shorelines or land. A single tool does not serve for all functions. For a given nation and several functions, many types of systems may, in fact, be needed. Furthermore, it is necessary to consider the end use of the data. The end use of the data, be it location of the spill, enforcement, or support to cleanup, may also dictate the resolution or character of the data needed.

6.1.2.1 Optical sensors

Visible

The use of human vision alone is not considered remote sensing, however still forms the most common technique for oil spill surveillance. In the past, major campaigns using only human vision were mounted with varying degrees of success (Taft et al., 1995). Optical techniques are the most common means of remote sensing. Cameras, both still and video are common because of their low price. In recent years, visual or camera observation has been enhanced by the use of GPS (Global Positioning Systems) (Lehr, 1994).

In the visible region of the electromagnetic spectrum (approximately 400-700 nm), oil has a higher surface reflectance than water, but also shows limited nonspecific absorption tendencies. Oil generally manifests throughout this visible spectrum. Sheen shows up silvery and reflects light over a wide spectral region down to the blue. As there is no strong information in the 500-600 nm region, this region is often filtered out to improve contrast (O'Neil et al., 1983). Overall, however, oil has no specific characteristics that distinguish it from the background (Brown et al., 1996). Taylor studied oil spectra in the laboratory and the field and observed flat spectra with no usable features distinguishing it from the background (Taylor, 1992). Therefore, techniques that separate specific spectral regions do not increase detection capability.

Some researchers noted that while the oil spectra is flat, the presence of oil may slightly alter water spectra (Huang et al., 2008). It has been found that high contrast in visible imagery can be achieved by setting the camera at the Brewster angle (53° from vertical) and using a horizontally aligned polarizing filter which passes only that light reflected from the water surface (Ahmed et al., 2006). This is the component that contains the information on surface oil (O'Neil et al., 1983). It has been reported that this technique increases contrast by up to 100%. Filters with band-pass below 450 nm can also be used to improve contrast. View angle is important, and some researchers have noted that the thickness changes the optimal view angle (Carneseccchi et al., 2008).

On land, hyper spectral data (use of multiple bands, typically 10-100) has been used to delineate the extent of an oil well blowout (Bianchi et al., 1995). The technique used was spectral reflectance in the various channels as well as the usual black coloration.

Video cameras are often used in conjunction with filters to improve the contrast, in a manner similar to that noted for still cameras. This technique has had limited success for oil spill remote sensing because of poor contrast and lack of positive discrimination. Despite this, video systems have been proposed as remote sensing systems (Bagheri et al., 1995). With new light-enhancement technology (low lux), video cameras can be operated even in darkness. Tests of a generation III night vision camera shows that this technology is capable of providing imagery in very dark night conditions (Brown 2004a, 2004b).

Scanners are often used as sensors in the visible region of the spectrum. A rotating mirror or prism sweeps the field-of-view (FOV) and directs the light towards a detector. Before the advent of CCD (charge-coupled device) detectors, this sensor provided much more sensitivity and selectivity than a video camera. Another advantage of scanners is that signals can be digitized and processed before display. Recently, newer technology has evolved and similar digitization can be achieved without scanning by using a CCD imager and continually recording all elements, each of which is directed to a different field-of-view on the ground. This type of sensor, known as a push-broom scanner, has many advantages over the older scanning types. It can overcome several types of aberrations and errors, the units are more reliable than mechanical ones, and all data are collected simultaneously for a given line perpendicular to the direction of the aircraft's flight. Several types of scanners have been developed recently. In Canada, the MEIS (Multi-detector Electro-optical Imaging Scanner) (O'Neil et al., 1983) and the CASI (Compact Airborne Spectrographic Imagery) (Palmer et al., 1994) have been developed, and in Holland, the Caesar system was developed (Wadsworth et al., 1992).

Digital photography has enabled the combination of photographs and the processing of images. Locke et al. used digital photography from vertical images to form a mosaic for an area impacted by an oil spill (Locke, 2008). It was then possible to form a singular image and to classify oil types by color within the image. The area impacted by the spill was also carried out. Video cameras are often used in conjunction with filters to improve the contrast in a manner similar to that noted for still cameras. This technique has had limited success for oil spill remote sensing because of poor contrast and lack of positive discrimination.

The detection or measurement of oil in water has never been successfully accomplished using remote visible technology. There may be potential for light scattering technology. Stelmaszewski and coworkers measured the light scattering of crude oil in water emulsions and noted that scattering increases with wavelength in the UV range and decreases slightly with the wavelength of visible light (Stelmaszewski, 2009).

The use of visible techniques in oil spill remote sensing is largely restricted to documentation of the spill because there is no mechanism for positive oil detection. Furthermore, there are many interferences or false alarms. Sun glint and wind sheens can be mistaken for oil sheens. Biogenic material such as surface seaweeds or sunken kelp beds can be mistaken for oil. Oil on shorelines is difficult to identify positively because seaweeds look similar to oil and oil cannot be detected on darker shorelines. In summary, the usefulness of the visible spectrum for oil detection is limited. It is, however, an economical way to document spills and provide baseline data on shorelines or relative positions.

Infrared

Oil, which is optically thick, absorbs solar radiation and re-emits a portion of this radiation as thermal energy, primarily in the 8-14 μm region. In infrared (IR) images, thick oil appears hot, intermediate thicknesses of oil appear cool, and thin

oil or sheens are not detected (Brekke and Solberg, 2005). The thicknesses at which these transitions occur are poorly understood, but evidence indicates that the transition between the hot and cold layer lies between 50 and 150 μm and the minimum detectable layer is between 10 and 70 μm (Neville et al, 1979; Belore, 1982; Goodman, 1989; Hurford, 1989). The reason for the appearance of the 'cool' slick is not fully understood. One theory is that the evaporative cooling of the slick exceeds its radiative heating at a certain thickness and the oil thus appears cool compared to the surrounding water. Another more plausible theory is that a moderately thin layer of oil on the water surface causes destructive interference of the thermal radiation waves emitted by the water, thereby reducing the amount of thermal radiation emitted by the water.

IR devices cannot detect emulsions (water-in-oil emulsions) under most circumstances (Bolos, 1996). This is probably a result of the high thermal conductivity of emulsions as they typically contain 70% water and thus do not show a temperature difference.

IR cameras are now very common and commercial units are available from several manufacturers. In the recent past, scanners with IR detectors were largely used. A disadvantage of any type of IR detector, however, is that they require cooling to avoid thermal noise, which would overwhelm any useful signal. Liquid nitrogen, which provides about four hours of service, has traditionally been used to cool the detector. New, smaller sensors use closed-cycle or Joule-Thompson coolers which operate on the cooling effect created by expanding gas. While a gas cylinder or compressor must be transported with this type of cooler, refills or servicing may not be required for days at a time (Goodman, 1988).

Most IR sensing of oil spills takes place in the thermal IR at wavelengths of 8-14 μm . One sensor, which is designed as a fixed-mounted unit, uses the differential reflectance of oil and water at 2.5 and 3.1 μm (Seakem Oceanography, 1988). Tests of a mid-band IR system (3.4-5.4 μm) over the Tenyo Maru oil spill showed no detection in this range, however, ship scars were visible (Kennicutt et al., 1992; Rogne and Smith, 1992a; Rogne et al., 1992b). Specific studies in the thermal IR (8-14 μm) show that there is no spectral structure in this region (Salisbury et al., 1993). Tests of a number of IR systems show that spatial resolution is extremely important when the oil is distributed in windrows and patches, emulsions are not always visible in the IR, and cameras operating in the 3-5 μm range are only marginally useful (Hover, 1994). Nighttime tests of IR sensors show that there is detection of oil (oil appears cold on a warmer ocean), however, the contrast is not as good as during daytime (Shih and Andrews, 2008).

The relative thickness information in the thermal IR can be used to direct skimmers and other counter-measures equipment to thicker portions of the slick. Oil detection in the IR is not positive, however, as several false targets can interfere, including seaweeds, shoreline, and oceanic fronts. IR is reasonably inexpensive, however, and is currently the prime tool used by the spill remote sensor operator.

Ultraviolet

Ultraviolet sensors can be used to map sheens of oil as oil slicks display high reflectivity of ultraviolet (UV) radiation even at thin layers ($<0.01\mu\text{m}$). Overlaid UV and IR images are often used to produce a relative thickness map of oil spills. UV cameras, although inexpensive, are not often used in this process, however, as it is difficult to overlay camera images (Goodman, 1988). Data from IR scanners and that derived from push-broom scanners can be easily superimposed to produce these IR/UV overlay maps. UV data are also subject to many interferences or false images such as wind slicks, sun glints, and biogenic material. Since these interferences are often different than those for IR sensing, combining IR and UV can provide a more positive indication of oil than using either technique alone.

6.1.2.2 Laser fluorosensors

Laser fluorosensors are active sensors that take advantage of the fact that certain compounds in petroleum oils absorb ultraviolet light and become electronically excited. This excitation is rapidly removed through the process of fluorescence emission, primarily in the visible region of the spectrum. Since very few other compounds show this tendency, fluorescence is a strong indication of the presence of oil. Natural fluorescing substances, such as chlorophyll, fluoresce at sufficiently different wavelengths than oil to avoid confusion. As different types of oil yield slightly different fluorescent intensities and spectral signatures, it is possible to differentiate between classes of oil under ideal conditions (Brown et al., 1994a, b; 1996a, b, 2001, 2003; Fruhwirth et al., 1994; Hengstermann and Reuter, 1990; Balick et al., 1997; Brown and Fingas, 2001, 2003; Sarma et al., 2006; Samberg, 2007; Jha and Gao, 2008).

Most laser fluorosensors used for oil spill detection employ a laser operating in the ultraviolet region of 300-355 nm (Diebel et al., 1989; Geraci et al., 1993; Brown and Fingas, 2003; Jha and Gao, 2008). With this wavelength of activation, there exists a broad range of fluorescent response for organic matter, centered at 420 nm. This is referred to as Gelbstoff or yellow matter, which can be easily annulled. Chlorophyll yields a sharp peak at 685 nm. The fluorescent response of crude oil ranges from 400 to 650 nm with peak centers in the 480 nm region. The use of laser fluorosensors for chlorophyll and other applications has been well documented (Pantani et al., 1995). One laser fluorosensor operating at 488 nm from an Argon laser, was successful in detecting oil from a ship platform (Campbell and McStay, 1995).

Another phenomenon, known as Raman scattering, involves energy transfer between the incident light and the water molecules. The water molecules absorb some of the energy as rotational-vibrational energy and return the light as the incident energy, less this energy of rotation or vibration. The Raman signal for water occurs at 344 nm when the incident wavelength is 308 nm (XeCl laser). The water Raman signal is useful for maintaining wavelength calibration of the fluorosensor in operation, but has also been used in a limited way to estimate oil thickness, because the strong absorption by oil on the surface will suppress the water Raman signal in proportion to thickness (Hoge and Swift, 1980; Piskozub et al., 1997). The point at

which the Raman signal is entirely suppressed depends on the type of oil, since each oil has a different absorption strength. The Raman signal suppression has led to estimates of sensor detection limits of about 0.05 to 0.1 μm (Goodman and Brown, 2005).

The principle of fluorescence can also be used on a smaller scale. A hand-held UV light has been developed to detect oil spills at night at short range. Another related instrument is the 'Fraunhofer Line Discriminator' which is essentially a passive fluorosensor using solar irradiance instead of laser light (O'Neil et al., 1983). This instrument was not very successful because of the limited discrimination and the low signal-to-noise ratio. Laser fluorosensors have significant potential as they may be the only means to discriminate between oiled and unoled seaweeds and to detect oil on different types of beaches. Tests on shorelines show that this technique has been very successful (Dick et al., 1992). Algorithms for the detection of oil on shorelines have been developed (James and Dick, 1996). Work has been conducted on detecting oil in the water column, such as occurs with the product, Orimulsion (Brown et al., 2002a, 2002b, 2003a, 2003b, 2004). The fluorosensor is also the only reliable means of detecting oil in certain ice and snow situations. Recent usage shows that the laser fluorosensor is a powerful tool for oil spill remote sensing (Brown et al., 1997a).

6.1.2.3 Microwave sensors

Microwaves are commonly used for ocean pollution monitoring by remote sensing. They are often preferred to optical sensors due to the all-weather and all-day capabilities (Brekke and Solberg, 2005).

Radiometers

The ocean emits microwave radiation. Oil on the ocean emits stronger microwave radiation than the water and thus appears as a bright object on a darker sea. The emissivity factor of water is 0.4 compared to 0.8 for oil (O'Neil et al., 1983; Ulaby et al., 1989). A passive device can detect this difference in emissivity and could therefore be used to detect oil. In addition, as the signal changes with thickness, in theory, the device could be used to measure thickness.

This detection method has not been very successful in the field, however, as several environmental and oil-specific parameters must be known. In addition, the signal return is dependent on oil thickness but in a cyclical fashion. A given signal strength can imply any one of two or three film thicknesses within a given slick. Microwave energy emission is greatest when the effective thickness of the oil equals an odd multiple of one quarter of the wavelength of the observed energy. Biogenic materials also interfere and the signal-to-noise ratio is low. In addition, it is difficult to achieve high spatial resolution (Goodman, 1994a).

The Swedish Space agency has done some work with different systems, including a dual band, 22.4 and 31 GHz device, and a single band 37 GHz device (Fast, 1986). Skou, Sorensen and Poulson describe a 2-channel device operating at 37.5 and 10.7 GHz (Skou et al., 1994). Mussetto and co-workers at TRW described

the tests of 44-94 GHz and 94-154 GHz, 2-channel devices over oil slicks (Mussetto et al., 1994). They showed that correlation with slick thickness is poor and suggest that factors other than thickness also change surface brightness. They also suggest that a single-channel device might be useful as an all-weather, relative-thickness instrument. Tests of single-channel devices over oil slicks have also been described in the literature, specifically a 36 GHz (Zhifu and Wiesbeck, 1988) and a 90 GHz device (Stiss et al., 1989). A new method of microwave radio-metry has recently been developed in which the polarization contrasts at two orthogonal polarizations are measured in an attempt to measure oil slick thickness (Pelyushenko, 1995, 1997). A series of frequency-scanning radiometers have been built and appear to have overcome the difficulties with the cyclical behaviour (McMahon et al., 1997).

In summary, passive microwave radiometers may have potential as all-weather oil sensors. Their potential as a reliable device for measuring slick thickness, however, is uncertain at this time.

Radar

Capillary waves on the ocean reflect radar energy, producing a 'bright' image known as sea clutter. Since oil on the sea surface dampens some of these capillary waves, the presence of an oil slick can be detected as a 'dark' sea or one with an absence of this sea clutter (Nunziata et al., 2008). Unfortunately, oil slicks are not the only phenomena that are detected in this way. There are many interferences or false targets, including fresh water slicks, wind slicks (calms), wave shadows behind land or structures, seaweed beds that calm the water just above them, glacial flour, biogenic oils, and whale and fish sperm (Frysjnger et al., 1992; Alpers and Hfihnerfuss, 1987; Poitevin and Khaif, 1992; Hiihnerfuss et al., 1989; Gens, 2008). As a result, radar can be ineffective in locations such as Prince William Sound, Alaska where dozens of islands, fresh water inflows, ice, and other features produce hundreds of such false targets. Despite these limitations, radar is an important tool for oil spill remote sensing because it is the only sensor that can be used for searches of large areas and it is one of the few sensors that can 'see' at night and through clouds or fog.

The two basic types of radar that can be used to detect oil spills and for environmental remote sensing in general are Synthetic Aperture Radar (SAR) and Side-Looking Airborne Radar (SLAR). The latter is an older, but less expensive technology, which uses a long antenna to achieve spatial resolution. SAR captures two-dimensional images. The image brightness is a reflection of the microwave backscattering properties of the surface. SAR deployed on satellites is today an important tool in oil spill monitoring due to its wide area coverage and day and night all-weather capabilities (Brekke and Solberg, 2005). SLAR has predominated airborne oil spill remote sensing, primarily because of the lower price (Dyring and Fa"st, 2004; Zielinski and Robbe, 2004). There is some recognition among the operators that SLAR is very subject to false hits, but solutions are not offered.

Experimental work on oil spills has shown that X-band radar yields better data than L- or C- band radar (C-CORE, 1981; Intera Technologies, 1984). It has also been shown that vertical antenna polarizations for both transmission and reception

(V, V) yield better results than other configurations (Bartsch et al., 1987; Kozu et al., 1987; Macklin, 1992; Madsen et al., 1994). Radar is also limited by sea state. Sea states that are too low will not produce enough sea clutter in the surrounding sea to contrast to the oil and very high seas will scatter radar sufficiently to block detection inside the troughs. Indications are that minimum wind speeds of 1.5 m/s (~3 knots) are required to allow detectability and a maximum wind speed of 6m/s (~12 knots) will again remove the effect (Hielm, 1989; Hfihnerfuss et al., 1996; Marghany, 2009). This limits the environmental window of application of radar for detecting oil slicks. Gade et al. (1996) studied the difference between extensive systems from a space-borne mission and a helicopter-borne system. They found that at high winds, it was not possible to discriminate biogenic slicks from oil. At low wind speeds, it was found that images in the L-band showed discrimination. Under these conditions the biogenic material showed greater damping behavior in the L-band. Okamoto et al. (1996) studied the use of ERS-1 using an artificial oil (oleyl alcohol) and found that an image was detected at a wind speed of 11 m/s, but not at 13.7 m/s.

SAR can be polarimetric imaging that is horizontal-horizontal (HH), vertical-vertical (VV), and cross combinations of these. Several researchers have shown that VV is best for oil spill detection and discrimination (Gambardella et al., 2007; Migliaccio et al., 2007; Nunziata et al., 2008; Migliaccio et al., 2009).

Radar has also been used to measure currents and predict oil spill movements by observing frontal movements (Forget and Brochu, 1996). Recently, work has shown that frontal currents and other features can be detected by SAR (Marmorino et al., 1997). Shipborne radar has similar limitations and the additional handicap of low altitude, which restricts its range to between 8 and 30 km, depending on the height of the antenna. Ship radars can be adjusted to reduce the effect of sea clutter de-enhancement.

Shipborne radar successfully detected a surface slick in the Baltic Sea from 8 km away and during a trial off the coast of Canada at a maximum range of 17 km (Tennyson, 1985). The technique is very limited by sea state, however, and in all cases where it was used, the presence and location of the slick were already known.

In summary, radar optimized for oil spills is useful in oil spill remote sensing, particularly for searches of large areas and for night-time or foul weather work. The technique is highly prone to false targets, however, and is limited to a narrow range of wind speeds.

Scatterometers

A microwave scatterometer is a device that measures the scattering of microwave or radar energy by a target. The presence of oil reduces the scattering of the microwave signals just as it does for radar sensors, however, and this device is adversely affected by the same large number of false targets. One radar scatterometer was flown over several oil slicks and used a low-power transmitter operating in the Kuband (13.3 GHz) (O'Neil et al., 1983). The scatterometer detected the oil, but discrimination was poor. The 'Heliscat', a device with five frequencies

has been used to investigate capillary wave damping (Huhnerfuss et al., 1996). The advantage of a microwave scatterometer is that it has an aerial coverage similar to optical sensors and it operates in a nadir geometry, i.e. it looks straight down. The main disadvantages include the lack of discrimination for oil and the lack of imaging capability.

6.1.2.4 Slick thickness sensors

There has long been a need to measure oil slick thickness, both within the oil spill response community and among academics in the field. There are presently no reliable methods, either in the laboratory or the field, for accurately measuring oil-on-water slick thickness. The ability to do so would significantly increase understanding of the dynamics of oil spreading and behavior. Knowledge of slick thickness would make it possible to determine the effectiveness of certain oil spill countermeasures including dispersant application and in situ burning. Indeed, the effectiveness of individual dispersants could be determined quantitatively if the oil remaining on the water surface following dispersant application could be accurately measured (Jensen et al., 2008).

Finally, there is a need to calibrate some of the more economical and readily available pieces of remote sensing equipment. Several of these sensors provide relative indications of slick thickness, i.e. whether the slick is thick or thin. Calibration of these wide field-of-view sensors would provide a reliable method of estimating the volume of rogue oil slicks. Present airborne surveillance of slicks often results in erroneous estimates of oil quantity.

The suppression of the water Raman peak in laser fluorosensor data discussed in that section has not been fully exploited or tested. This technique may work for thin slicks, but not necessarily for thick ones, at least not with a single excitation frequency. Attempts have been made to calibrate the thickness appearance of IR imagery, but also without success. It is suspected that the temperatures of the slick as seen in the IR are highly dependent on oil type, sun angle, and weather conditions. If so, it may not be possible to use IR as a calibrated tool for measuring thickness. As accurate ground-truth methods do not exist, it is very difficult to calibrate existing equipment (Brown and Goodman, 1986; Brown et al., 2006). The use of sorbent techniques to measure surface thickness yields highly variable results (Goodman and Fingas, 1988). As noted in the section on microwave radiometers, the signal strength measured by these instruments can imply one of several thicknesses. This methodology does not appear to have potential, other than for measuring relative oil thickness.

A variety of electrical, optical, and acoustic techniques for measuring oil thickness has been investigated (Reimer and Rossiter, 1987; Goodman et al., 1997). Two promising techniques were pursued in a series of laboratory measurements. In the first technique, known as 'thermal mapping' (Aussel and Monchalain, 1989), a laser is used to heat a region of oil and the resultant temperature profiles created over a small region near this heating are examined using an IR camera. The temperature profiles created are dependent on the oil thickness. A more promising

technique involves laser acoustics (Krapez and Cielo, 1992; Choquet et al., 1993). The Laser Ultrasonic Remote Sensing of Oil Thickness (LURSOT) sensor consists of three lasers, one of which is coupled to an interferometer to accurately measure oil thickness (Choquet et al., 1993; Brown et al., 1994c, 1997b; Brown and Fingas, 2003; Brown et al., 2005). The sensing process is initiated with a thermal pulse created in the oil layer by the absorption of a powerful CO₂ laser pulse. Rapid thermal expansion of the oil occurs near the surface where the laser beam was absorbed, which causes a step-like rise of the sample surface as well as an acoustic pulse of high frequency and large bandwidth (~15 MHz for oil). The acoustic pulse travels down through the oil until it reaches the oil-water interface where it is partially transmitted and partially reflected back towards the oil-air interface, where it slightly displaces the oil's surface. The time required for the acoustic pulse to travel through the oil and back to the surface again is a function of the thickness and the acoustic velocity of the oil. The displacement of the surface is measured by a second laser probe beam aimed at the surface. Motion of the surface induces a phase or frequency shift (Doppler shift) in the reflected probe beam. This phase or frequency modulation of the probe beam can then be demodulated with an interferometer (Monchalín, 1986). The thickness can be determined from the time of propagation of the acoustic wave between the upper and lower surfaces of the oil slick. This is a very reliable means of studying oil thickness and has great potential. This technology is being researched by a consortium of agencies including Imperial Oil, Environment Canada, and the United States Minerals Management Service. Laboratory tests have confirmed the viability of the method and a test unit will be flown to confirm its operability.

6.1.2.5 Acoustic systems

Pogorzelski (1995) has shown that acoustic means can be used to measure oil viscosities on the surface. A directional acoustic system employing high-frequency forward specular scattering was used in the laboratory and at sea. Signals scattered are related to the rheological film properties. It is not known at this time if the system is scalable or exactly what the limitations are.

6.1.2.6 Satellite remote sensing

Satellite images can improve the possibilities for the detection of oil spills as they cover large areas and offer an economical and easier way of continuous coast areas patrolling (Topouzelis, 2008).

Recently, it has been strongly suggested that satellite remote sensing could replace airborne remote sensing. However, current technologies do not support this claim. The use of satellite remote sensing for oil spills has been attempted several times. The slick from the Ixtoc I well blowout in Mexico was detected using GOES (Geostationary Operational Environmental Satellite) and also by the AVHRR (Advanced Very High Resolution Radiometer) on the LANDSAT satellite (O'Neil et al., 1983). A blowout in the Persian Gulf was subsequently detected. The massive Exxon Valdez slick was detected on SPOT (Satellite Pour l'Observation de la Terre) satellite data (Dean et al., 1990). Oiled ice in Gabarus Bay resulting from the Kurdistan spill

was detected using LANDSAT data (Dawe et al., 1981; Alfoldi and Prout, 1982). Several workers were able to detect the Arabian Gulf War spill in 1991 (Cross, 1992; Rand et al., 1992; Al-Ghunaim et al., 1992; Al-Hinai et al., 1993). The Haven spill near Italy was also monitored by satellite (Cecamore et al., 1992). A spill in the Barents sea was tracked using an IR band on NOAA 10 (Voloshina and Sochnev, 1992). It is significant to note that, in all these cases, the position of the oil was known and data had to be processed to actually see the oil, which usually took several weeks. Newer findings show that the ability to detect oil may be a complex function of conditions, oil types, and view angles (Alawadi et al., 2008; Li et al., 2008; Lotliker et al., 2008).

There are several problems associated with relying on satellites for oil spill remote sensing. The first is the timing and frequency of overpasses (Clark, 1989) and the absolute need for clear skies to perform optical work. The chances of the overpass and the clear skies occurring at the same time give a very low probability of seeing a spill on a satellite image. This point is well illustrated in the case of the Exxon Valdez spill (Noerager and Goodman, 1991). Although the spill covered vast amounts of ocean for over a month, there was only one clear day that coincided with a satellite overpass, and that was on April 7, 1989. Another disadvantage of satellite remote sensing is the difficulty in developing algorithms to highlight the oil slicks and the long time required to do so. For the Exxon Valdez spill, it took over two months before the first group managed to 'see' the oil slick in the satellite imagery, although its location was precisely known. Recently, several workers have attempted to use MODIS visible data to detect oil spills (Li et al., 2007, 2008). To be successful, these techniques generally rely on ancillary data such as suspected position or other satellite data.

Several "automatic" systems have been designed for slick detection (Solberg and Theophilopoulos, 1997). Limited testing with ERS-1 has shown that many false signals are present in most locations (Wahl et al., 1993; Bern et al., 1993). Extensive effort on data processing appears to improve the chances of oil detection (Yan and Clemente-Colon, 1997).

6.2 Oil Spill Analysis

6.2.1 Physical analysis

During any uncontrolled release of oil, the properties of the spilled oil, including the bulk physical property changes due to weathering, must be immediately available, so that models can be used to predict the environmental impacts of the spill and guide the selection of various remediation alternatives.

Some of the key physical properties for determining the fate and behavior of oil and petroleum products in the environment are viscosity, density, specific gravity, flash point, pour point, distillation, and interfacial tension.

Viscosity

Viscosity is the resistance to flow in a liquid. The lower the viscosity, the more readily the liquid flows. The viscosity of an oil is a function of its composition; therefore, crude oil has a wide range of viscosities. For example, the viscosity of Federated oil from Alberta is 5 mPa·s while a Sockeye oil from California is 45 mPa·s at 15°C. In general, the greater the fraction of saturates and aromatics and the lower the amount of asphaltenes and resins, the lower the viscosity. As oil weathers, the evaporation of the lighter components leads to increased viscosity. As with other physical properties, viscosity is affected by temperature, lower temperatures giving higher viscosities. For most oils, the viscosity varies approximately exponentially with temperature. Oils that flow readily at high temperature can become a slow-moving, viscous mass at low temperature. In terms of oil spill cleanup, viscous oils do not spread rapidly, do not penetrate soils readily, and affect the ability of pumps and skimmers to handle the oil. The dynamic viscosity of an oil can be measured by a viscometer using a variety of standard cup-and-spindle sensors at controlled temperatures (Morrison and Murphy, 2006).

Density

Density is the mass of a unit volume of oil, usually expressed as grams per milliliter (g/mL) or, equivalently, as kilograms per cubic meter (kg/m³). It is used by the petroleum industry to grade light or heavy crude oils. Density is also important because it indicates whether a particular oil will float or sink in water. As the density of water is 1.0 g/mL at 15°C and the density of most oils ranges from 0.7 to 0.99 g/mL, oils typically float on water. As the density of seawater is 1.03 g/mL, even heavier oils will usually float on it. Only a few bitumens have densities greater than water at higher temperatures. However, as water has a minimum density at 4°C and oils will continue to contract as temperature decreases, heavier oils, including heavy crudes and residual fuel oils, may sink in freezing waters. Furthermore, as density increases as the light ends of the oil evaporate off, a heavily weathered oil, long after a spill event, may sink or be prone to over washing, where the fresh oil, immediately after the spill, may have floated readily.

Specific Gravity

A related measure is specific gravity, an oil's density relative to that of water. As the densities of both water and oil vary differently with temperature, this quantity can be highly variable. The American Petroleum Institute (API) uses the specific gravity of petroleum at 50°F (15.56°C) as a quality indicator for oil. Pure water has an API gravity of 10. Oils with progressively lower specific gravities have higher API gravities. Heavy, inexpensive oils have less than 25 API; medium oils are 25 to 35 API; and light commercially valuable oils are 35 to 45 API. API gravities generally vary inversely with viscosity and asphaltene content (Fingas, 2010).

Surface tension

Interfacial tensions are the net stresses at the boundaries between different substances. They are expressed as the increased energy per unit area (relative to the bulk materials), or equivalently as force per unit length. The 'Standard International (SI)' units for interfacial tension are milliNewtons per meter (mN/m). Surface

tension is thought to be related to the final size of a slick. The lower the interfacial tension of oil with water, the greater the extent of spreading and thinner terminal thickness of oil. In actual practice, the interfacial tension alone does not apparently account for spreading behavior; environmental effects and other effects seem to be dominant.

Flash point

The flash point of an oil is the temperature at which the vapor over the liquid can be ignited. A liquid is considered to be flammable if its flash point is less than 60°C. Flash point is an important consideration for the safety of spill cleanup operations. Gasoline and other light fuels can ignite under most ambient conditions and therefore are a serious hazard when spilled. Many freshly spilled crude oils also have low flash points until the lighter components have evaporated or dispersed. On the other hand, Bunker C and heavy crude oils generally are not flammable when spilled. The flash point of low viscosity oil is measured by ASTM method D1310, while that of heavier oils is measured by ASTM method D93 (Morrison and Murphy, 2006).

Pour point

The pour point of an oil is the temperature at which no flow of the oil is visible over a period of 5 seconds from a standard measuring vessel. The pour point of crude oils ranges from -60°C to 30°C. Lighter oils with low viscosities generally have lower pour points. As oils are made up of hundreds of compounds, some of which may still be liquid at the pour point, the pour point is not the temperature at which an oil will no longer pour. The pour point represents a consistent temperature at which an oil will pour very slowly and therefore has limited use as an indicator of the state of the oil. For example, waxy oils can have a very low pour point, but may continue to spread slowly at that temperature and can evaporate to a significant degree. The pour point of oil is measured by ASTM method D97 (Morrison and Murphy, 2006).

6.2.2 Chemical analysis

The fate and behaviour of crude oils and petroleum products are strongly determined by their chemistries. The main constituents of oils can be grouped into four categories: saturated hydrocarbons (including waxes), aromatics, resins, and asphaltenes (Wang, 2003).

Saturates: A group of hydrocarbons composed of only carbon and hydrogen with no double bonds or aromaticity. They are said to be “saturated” with hydrogen. They may be straight-chain (normal), branched, or cyclic. Typically, however, the group of “saturates” refers to the aliphatics generally including alkanes, as well as a small amount of alkenes. The lighter saturates, those less than ~C18, make up the components of an oil most prone to weathering. The larger saturates, generally those heavier than C18, are termed waxes.

Aromatics: These are cyclic organic compounds that are stabilized by a delocalized p-electron system. They include such compounds as BTEX (benzene,

toluene, ethylbenzene, and the three xylene isomers), polycyclic aromatic hydrocarbons (PAHs, such as naphthalene), and some heterocyclic aromatics such as the dibenzothiophenes. Benzene and its alkylated derivatives can constitute several percent in crude oils. PAHs and their alkylated derivatives can also make up as much as a percent in crude oils.

Resins: This is the name given to a large group of polar compounds in oil. They include heterosubstituted aromatics (typically oxygen- or nitrogen-containing PAHs), acids, ketones, alcohols, and monoaromatic steroids. Because of their polarity, these compounds are more soluble in polar solvents than the nonpolar compounds, such as waxes and aromatics, of similar molecular weight.

Asphaltenes: A complex mixture of very large organic compounds that precipitate from oils and bitumen by natural processes. For the purposes of this method, asphaltenes are defined as the fraction that precipitates in n-pentane.

Oil analytical techniques are a necessary part of the scientific, environmental, and engineering aspects of oil spills. Analytical techniques are used extensively in environmental assessments of fate and effects. Laboratory analysis can provide information to help identify an oil if its source is unknown or what its sources might be. With a sample of the source oil, the degree of weathering and the amount of evaporation or biodegradation can be determined for the spilled oil. Through laboratory analysis, the more toxic compounds in the oil can be measured, and the relative composition of the oil at various stages of the spill can be determined. This is valuable information to have as the spill progresses.

The complex mixtures of oil are composed by many compounds, ranging in size from the smallest to large compounds where the quantity of carbon atoms varies, which has different quantities of various compounds and special properties depending on the geographical source. Generally, crude oil includes hydrocarbons (paraffins, aromatics, Naphthenes, Asphaltenes, etc.) and Heterocompounds (Sulfur, oxygen, nitrogen, metal ions, etc.). It is necessary to characterize these substances in terms of chemical structure and their physical and chemical properties. The need of a specialised and exhaustive characterization is related to different compositions, namely different concentration of asphaltenes, sulfur, nitrogen and metal ions (normally heavy crude oils have high concentrations), and hence different chemical and physical properties that characterized heavy crude oils.

There are different methods to classify the chemical compounds present in crude oil that allows to analyze their properties. The primary method for oil analysis, as well as for many chemicals in the environment, is gas chromatography (GC). Other chromatography methods and other analytical methods are sometimes used for oils, such as high-performance liquid chromatography, thin-layer chromatography, and some spectroscopic techniques like infrared spectroscopy, Raman, and NMR spectroscopy and also mass spectrometry.

6.2.2.1 Gas Chromatography (GC)

GC is used in the separation and analysis of complex mixtures of many components that can be vaporized without decomposition. In the GC technique the sample is carried through the column by the moving phase (a gas). The rate taken by the chemical constituents of the sample to pass through the column depends on their chemical and physical properties and on the interaction with the stationary phase (liquid or solid) of the column. The time taken for each compound to leave the column is called the retention time. The quantity of separated substances coming out of the column is detected and represented by an electronic signal. These signals are detected by some detectors as the flame photometric detector (FPD), flame ionization detector (FID) and the thermal conductivity detector (TCD), having different sensitivity (smallest quantity of compounds in analysis) and selectivity (type of compound). FID is very sensitive and selective just for some compounds, being used in the analysis of organic substances as benzene in gasoline according to the ASTM D3606 method (Simanzhenkov and Idem, 2003). The FPD is used in the identification of organic compounds containing sulfur or phosphorus as heavily biodegraded spill samples (Butt et al., 1986). TCD is not very sensitive but very selective in detecting everything (Kenkel, 1994) being preferred in the analyses of crude oil fractions or products (Simanzhenkov and Idem, 2003). GC studies, using TCD detector, have proven that the mixture components are not destroyed during the analysis and just a small amount of the material is needed, while in the case of FID and FPD detectors the compounds are destroyed (Kenkel, 1994). Beyond FID, FPD and TCD there are other detectors, as electron trap detector and nitrogen/phosphor thermo ionic detector, that can be used depending on the exactly compound under investigation. In spite of the advantages that can be achieved with the GC technique, due to the short time needed to make an analysis and the required small amount of sample, it is possible to conclude that this is not a very good method for the analysis of heavy crude fractions since all the compounds analyzed by GC must be in the gaseous phase and need to have a boiling temperature less than 350 °C (Altgelt and Boduszynski, 1994; Simanzhenkov and Idem, 2003). The problem is that only the light fractions, as gasoline, kerosene and diesel, have a boiling point smaller than 350 °C. For the heaviest ones, as residue, the distillation temperature is much higher, over 350 °C. The use of GC in the crude oil composition is limited or even inadequate due to the complex mixture of components, its composition in heavy compounds and the low volatility. This method is rather used when we have light (de Andrade et al., 2010) (Figure 6.5) and middle distillates. Some examples on the application of GC for the crude oil characterization are the ASTM D2163 for the analysis of gaseous boiling range, ASTM D2427 method to gasoline boiling range, ASTM D3524 method for the analysis of diesel fuel and ASTM D3606 method for the aviation gasoline.

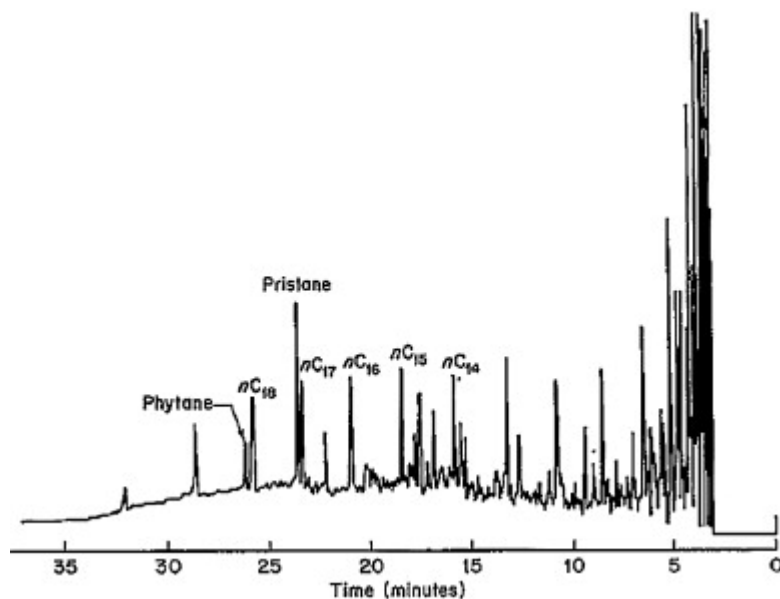


Figure 6.5 Example of a GC spectrum of a light Nigerian crude (fraction with a boiling temperature smaller than 343 °C)

(Butt et al., 1986)

6.2.2.2 High performance liquid chromatography (HPLC)

HPLC is characterized by using high pressure to force chemical compounds to pass the column (metal tube) containing a stationary phase. HPLC is an important tool for the analysis of compounds that do not present enough volatility to be analyzed by GC. Besides the similarities between HPLC and GC, there are compounds analyzed by HPLC but not by GC. A crude with 80% of heavy fractions needs temperatures above 350 °C to vaporize, thus is more efficiently analyzed with HPLC than with GC. The possibility to obtain a good and efficient separation of heavy oil fractions and a very precise analysis in a very short time are the main advantages of HPLC. The main disadvantage of HPLC is that depending on the used detector [e.g. UV absorption (UV), refractive index (RI) or fluorescence (F)] there are some compounds which are impossible to distinguish. UV and F spectrophotometries only detect some species (F only detect fluorescent species), while RI has the ability to analyze all the compounds. However, the latter is not very sensitive and temperature variation can affect the output of the recorder (Kenkel, 1994). HPLC is also a chromatography technique scarcely used in the analysis of crude oils since the objective is using one technique that provides precise analysis of every components and in a very short time, like minutes, if possible. When the objective is analysing group of compounds, such as paraffinic, naphthenic and aromatic compounds, HPLC continues to be a possibility, but to analyze individual compounds of crude oil the use of HPLC is inadequate. Besides that, HPLC does not give precise results when analysing hydrotreated and hydrocracked compounds which present identical boiling point range. However, HPLC was used in the identification of molecular types

in non-volatile feedstocks, in the study of asphaltene fractions aiming to identify molecular species (Speight, 2001) and in the identification of aromatic groups (mono, di, tri- aromatics) (Pasadakis et al., 2001). HPLC is very important in fingerprinting oils being used in the identification of vanadyl compounds (Fish et al., 1984).

6.2.2.3 Infrared spectroscopy (IR)

IR spectroscopy is one of the most important techniques that can provide miscellaneous information of complex mixtures of compounds, such as information about hydrocarbon skeleton and functional groups (e.g. hydroxyl and carbonyl groups). It allows to measure a great number of structural parameters like paraffinic and naphthenic character, aromatic hydrocarbons and methyl group content and gives information about functional features of various petroleum constituents, nature of polymethylene chains and the nature of polynuclear aromatic systems. It also contributes to the aging determination of oils related to the oxidation of carboxylic acids (Gautam, 1998). The main advantage of this technique is the possibility to analyze the hydrogen bonding in the crude oil mixture. It is possible to say that the IR can give more qualitative rather than quantitative information making impossible to detect some compounds. There is more limitations associate with this technique like the overlap that occurs between frequency ranges, which can be overcome by the use of NMR spectroscopy. There are some studies in the application of IR in the analysis of crude oil fractions (**Figure 6.6**) but the implementation of this technique is more related with the study of middle distillates. An example is the determination of fatty methyl esters (FAME) content in middle distillates (EN 14078) and of benzene content in motor and aviation gasoline (ASTM D4053), the method of carbon type analysis in lubricating oils (EU AJ 051-01) and even the identification of chemical species as contaminated species (by comparison IR spectra). Another example is the use of IR in the study of spilled oils (derivatives from crude) but only in the definition of the chemical class to which they belong, since their use in the characterization and differentiation of different classes of hydrocarbons, from different heavy products, is difficult. In this case, once again, IR should be combined with other spectroscopic techniques (Butt et al., 1986). On the other hand, it is possible to use multivariate techniques, such as the partial least squares regression (PLS) and principal component analysis (PCA) to predict properties of the sample in analysis (Aske et al., 2002) and with this establish correlations which could be an improvement for online IR.

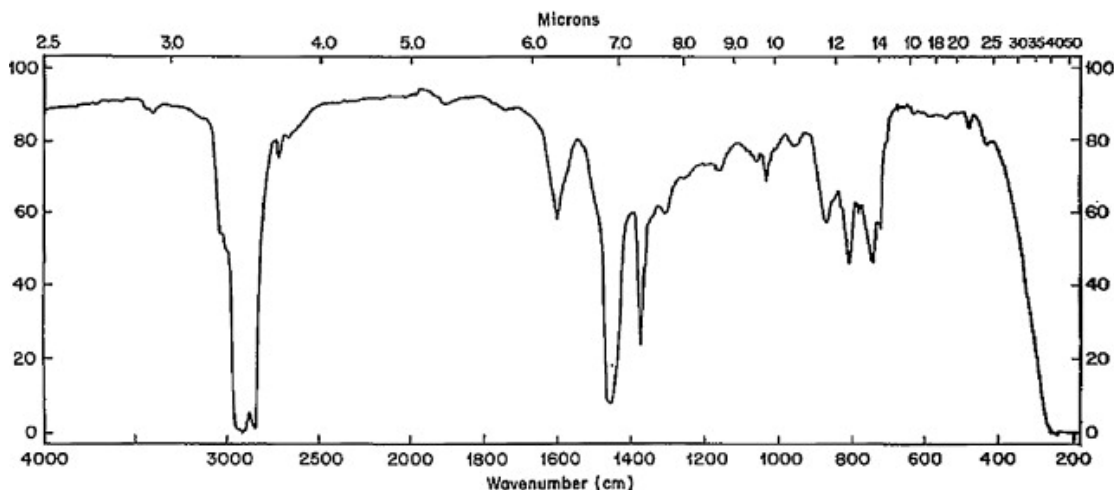


Figure 6.6 Example of an IR spectrum of a heavy fuel oil

(Butt et al., 1986)

6.2.2.4 Mass spectrometry (MS)

MS can give information on the structure of some compounds, for example assigning their molecular formula based on the molecular weight, contributing to the identification of some compounds or to have an idea about new compounds. There are many different MS techniques that can be used, such as electron impact (EI), chemical ionization (CI), field ionization (FI), fast atom bombardment (FAB), among others. EI-MS is a technique of major importance and is characterized by the existent of a set of electrons with high energy that will contact with the molecules of compounds and will be responsible for the fragmentation of these molecules (Kenkel, 1994). Normally each compound has a representative signal that results in the fragmentation of the molecule. For example, in alkyl chains the most pronounced fragments are caused by the loss of CH_3 , C_2H_5 or C_2H_4 . Fragments with four carbon atoms are an example of the most common ions of paraffinic chains. Other examples of fragments are those with C_3 , C_2 and C_5 . The monoalkylbenzenes are characterized by the fragment of C_6H_5 . Besides these examples there are others related to monoalkylnaphthalenes, monoalkylphenanthrene, monocyclic alkanes and other molecules (Altgelt and Boduszynski, 1994). Being heavy petroleum fractions rich in thousand of compounds it is expected that due to such complexity and closely related compounds that the fragmentation patterns became crowded and impossible to distinguish. With this, EI-MS is not frequently used in the analysis of heavy petroleum fractions. Therefore, the most common type of MS techniques used in the analysis of heavy crude oil is the non-fragmenting (NF)-MS, also called, “soft ionization”. These techniques produce simpler spectra, when compared with the spectra resulting from the fragmentation (Skoog et al., 1998). For example, the hard fragmentation of aliphatic hydrocarbons does not follow a given pattern, making very difficult to identify these compounds. Sulfur and nitrogen compounds and species with the same chemical formula are also difficult to analyze, while other

compounds like the aromatics has a good behaviour in the final spectra and are easy to identify, especially with “soft-ionization” techniques. Recently, the combination of some “soft-ionization” techniques as the low-voltage electron ionization, electrospray ionization (ESI), field desorption ionization (FDI) and atmospheric pressure photo-ionization (APPI) contributed to the development of FT-ICR-MS (Fourier transform ion cyclotron resonance mass spectrometry), which was used in the analysis of thousands of chemical constituents in heavy petroleum fractions. This new technique has already been used, for example, in the analysis of polycyclic aromatic sulfur heterocycles in different Arabian crude oils (**Figure 6.7**) (Panda et al., 2007). When the boiling point increases it becomes more difficult to use the MS in sample analysis due to the increase in the number of types of compound and the decrease in the concentration of these compounds (Behera et al., 2008). Concluding, aromatic hydrocarbons sulfur and nitrogen compounds are examples of compounds complicated to be analyzed by MS, and thus, to obtain information about all the heavy crude oil fractions it is necessary to use this technique conjugated with other complementary techniques. There is a possibility to use MS hyphenated techniques, like GC-MS or HPLC-MS, in other words a spectral method combine with chromatographic methods in order to exploit the advantages of both and obtain better information about the sample in analysis.

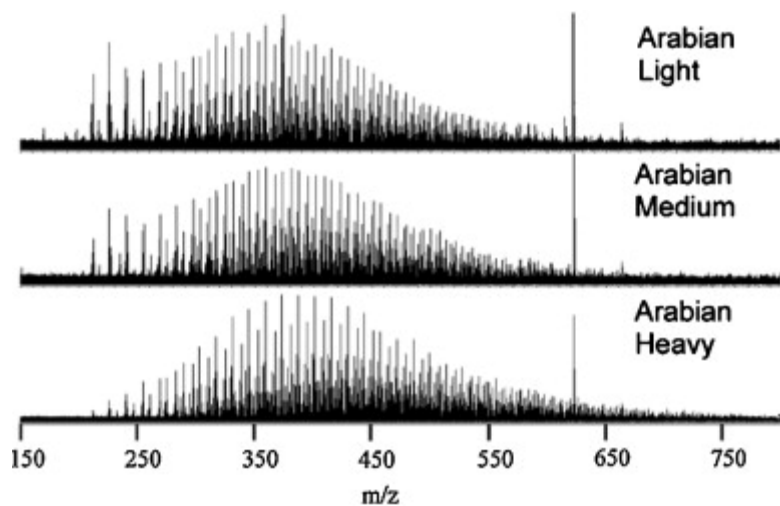


Figure 6.7 Example of an ESI FT-ICR mass spectra of condensed thiophenes in different Arabian crude oil

(Panda et al., 2007)

6.2.3 Biological analysis

Marine biological resources are sometimes monitored to guide response options and clean-up activities, or to assist in media and public relations management. Detailed biological assessments are more commonly conducted aimed at determining the effects of a spill. Biological assessments must take into account the

particular circumstances of a spill incident, and often require expert input to ensure the study objectives are met. (AMSA, 2003).

Biological monitoring includes responses at sub-individual and individual level: physiological and epidemiological markers, biomarkers of exposure/effect and/or biological responses in ecotoxicological assays, and ecologically, monitoring studies at population or community level (population dynamic and/or community structure parameters). In addition, pelagic, benthic, birds and marine mammals are main categories of the ecological domains that were studied.

In terms of habitats, monitoring may be divided into three broad habitat areas. (1) Surface water: as most fresh oils float on seawater, organisms at the water surface are usually most vulnerable. Marine birds and mammals (particularly seals) are highly vulnerable because oil adheres readily to feathers and fur. (2) Water column: Water column organisms are less vulnerable but can be exposed when oil is dispersed into the water column. Plankton and nekton are often affected, but effects are usually localised. Natural recovery of populations is usually rapid. (3) Seabed: Benthic communities are generally only of concern in shallow areas, and areas where oil either sinks or is entrained within sediment, e.g. by wave action or remobilisation of oiled shoreline sediment (AMSA, 2003).

6.2.3.1 Basic biological parameters to be monitored

Mortality For large animals and plants, this can be monitored using relatively simple procedures. Smaller organisms, such as plankton, require specialist input. Mortality of mobile organisms can be difficult to interpret particularly if estimates are based on counts of beach-cast individuals. In any case, estimates of bodies lost at sea are not likely to be accurate. Identification of mortality amongst plants may also need specialist input.

Sublethal effects Sublethal effects may be difficult to monitor and this generally requires specialist input. The most common example of a sublethal effect is tainting. Other potential sublethal effects include bioaccumulation, behavioural changes or histopathological effects (e.g. presence of disease or lesions) but these are unlikely to be monitored as part of initial monitoring programme unless such effects can be directly attributed to the spill or response and if the information would influence response decisions.

Changes in community structure e.g. changes in species' diversity or relative proportions.

Tainting Tainting occurs when oil is ingested by fish, crustaceans or molluscs and hydrocarbons are incorporated into fatty tissues. This imparts an oily taste to the meat and makes it unpalatable. Tainting can adversely affect commercial fisheries and also predatory species such as birds. Taint can be detected through chemical analysis or by a panel of individuals undertaking a "taste test". The latter method is slower to establish, requires testing and calibration of participants and on occasion may be of questionable reliability. If tainting is detected then further monitoring may be required to determine the extent or financial cost of this (Reilly and York, 2001; Yender et al., 2002; IMO/FAO, 2003).

6.2.3.2 Biomarkers

It is possible to predict how long the oil has been in the environment and what percentage of it has evaporated or biodegraded (Stout et al., 2002, 2006; Daling et al., 2002; Wang 2002, 2005, 2006), because some components in oils, particularly crude oils, are very resistant to biodegradation, whereas others are resistant to evaporation. This difference in the distribution of components then allows the degree of weathering of the oil to be measured. The same technique can be used to “fingerprint” an oil and positively identify its source. Certain compounds are consistently distributed in oil, regardless of weathering, and these are used to identify the specific type of oil.

Biological markers or biomarkers are an important hydrocarbon group in petroleum analysis (Prince et al., 1994; Wang et al., 2004, 2007). Biomarkers are complex molecules derived from formerly living organisms. Biomarkers found in crude oils, rocks, and sediments show little change in structures from their parent organic molecules, or so-called biogenic precursors (for example, hopanoids, and steroids), in living organisms. Biomarker concentrations are relatively low in oil, often in the range of several hundred ppm. Biomarkers are useful because they retain all or most of the original carbon skeleton of the original natural product; this structural similarity reveals more information about oil origins than other compounds. Petroleum geochemists have historically used biomarker fingerprinting in characterizing oils in terms of (1) the type(s) of precursor organic matter in the source rock (such as bacteria, algae, or higher plants); (2) correlation of oils with their source rocks; (3) determination of depositional environmental conditions (such as marine, terrestrial, deltaic, or hypersaline environments); (4) assessment of thermal maturity and thermal history of oil and the degree of oil biodegradation; and (5) providing information on the age of the source rock for petroleum. For example, oleanane ($C_{30}H_{52}$) is a biomarker characteristic of angiosperms (flowering plants) found only in Tertiary and Cretaceous (<130 million years) oils (Peters and Moldowan, 1993).

The conversion of precursor biochemical compounds from living organisms into biomarkers creates a vast suite of compounds in crude oils that have distinct structures. Due to the wide variety of geological conditions under which oil has formed, every crude oil exhibits a unique biomarker fingerprint. Biomarkers can be detected in very low quantities (ppm and below) in the presence of many other types of petroleum hydrocarbon by using GC-MS. Relative to other hydrocarbon groups such as alkanes and many aromatic compounds, biomarkers are highly stable and degradation-resistant. Therefore, the usefulness of analyzing biomarkers is that they generate information useful in determining the source of spilled oil, monitoring the degradation process, and weathering the state of oils. They have proven useful in identifying petroleum-derived contaminants in the marine environment (Volkman, et al., 1992; Kaplan et al., 1997; Kvenvolden et al., 2002; Stout et al., 2002). In the past decades, the use of biomarker fingerprinting

techniques to study spilled oils has rapidly increased, and biomarker parameters have been playing a prominent role in almost all oil-spill forensic investigations.

6.2.3.3 Sesquiterpanes and Diamondoids

The commonly used biomarkers that occur within crudes and heavier refined products include pentacyclic triterpanes (e.g., hopanes), regular and rearranged steranes, and mono- and tri-aromatic steranes (Stout et al., 2005). However, the high boiling point pentacyclic triterpanes and steranes are generally absent or in very low abundances in lighter petroleum products such as jet fuels and midrange diesels. For lighter petroleum products, refining processes have removed most high-molecular-weight biomarkers from the crude oil feed stocks, while the smaller compounds of bicyclic sesquiterpanes are greatly concentrated in these petroleum products.

Sesquiterpanes are ubiquitous components of crude oils and ancient sediments. Bicyclic sesquiterpanes are also widely found in intermediate petroleum distillates and finished petroleum products. Early studies focused mainly on geological application of sesquiterpane compounds. The naturally occurring bicyclic sesquiterpanes are stable in biodegradation, and therefore in recent years, they found potential applications in oil-source correlation and differentiation.

Recently, environmental scientists have also considered fingerprinting the diamondoid hydrocarbons as a promising forensic technique for oil spill studies. These naturally occurring compounds are thermodynamically stable, and therefore, they may have potential applications both in oil-source correlation and differentiation for those cases where the traditional biomarker terpanes and steranes are absent due to removal in the refining processes. There is increased awareness of possible application of diamondoid compounds for source identification. Diamondoids are a class of saturated hydrocarbons that consist of threedimensional fused cyclohexane rings, which results in a diamond-like structure. Adamantine and diamantane and their various substituted equivalents are widely found in crude oils, intermediate petroleum distillates, and other petroleum products. Diamondoid compounds (adamantanes and diamantanes) in petroleum are believed to be the result of carbonium ion rearrangements of suitable cyclic precursors on clay substances in the source rock. The higher homologues of diamondoids are considered to be formed from the smaller diamondoid compounds under extreme temperature and pressure conditions (Grice, 2000; Dahl, 2003; Stout, 2004; Yang 2006a, 2006b).

6.3 Challenges in the Harsh Environments in Offshore Newfoundland and Labrador

Newfoundland and Labrador's climate is characterized by its harsh condition, such as windiness, low temperature, ice coverage, etc. Such harsh environment can make ocean waters less accessible for sea transport and spared the region from oil spills

in the past. In general, oil spill is more problematical in the harsh environment because of the simple and highly seasonal ecosystems and the logistic challenges of cleaning up spills in remote regions. The low temperature will also make hydrocarbons persist, making ice-edge communities particularly vulnerable (AMAP, 2008).

The difficulties in detecting oil in or under ice are numerous. Ice is never a homogeneous material but rather incorporates air, sediment, salt, and water, many of which may present false oil-in-ice signals to the detection mechanisms. In addition, snow on top of the ice or even incorporated into the ice adds complications. During freeze-up and thaw in the spring, there may not be distinct layers of water and ice. There are many different types of ice and different ice crystalline orientations, making oil spill monitoring in harsh environment more challenging (Fingas, 2011).

6.4 Summary

This chapter outlines on-site oil spill monitoring, including monitoring within-station and with sampling. Vessels, airplanes and satellites are major tools to conduct on-site monitoring. Although vessels are only able to detect oil at sea within very limited area, they remain necessary for oil sampling. Satellites monitoring can be used for a first warning, and aircrafts are more suitable to be applied to identify the polluter, extent, and type of a spill. In recent years, some state-of-the-art technologies have been developed and implemented for on-site monitoring, such as ship-borne radar for the automated detection of spilled oil. On site sampling methods are introduced, such as sampling of oil, water column, sediment and biota.

Specifically, this chapter reviews remote sensing for oil spill. Various sensors are summarized. An economical sensor is an infrared camera or an IR/UV system. This sensor class has the lowest cost of any sensor. The inherent weaknesses include the inability to discriminate oil on beaches, among weeds or debris. Under certain lighting conditions, oil is not detected. Furthermore, water-in-oil emulsions are often not detected in the infrared. The laser fluorosensor is a most useful instrument because of its unique ability to identify oil on backgrounds that include water, soil, weeds, ice, and snow. It is the only sensor that can positively discriminate oil on most backgrounds.

Radar offers great potential for large area searches and foul weather remote sensing. It is costly, requires a dedicated aircraft, and is prone to many interferences. Satellite-borne radar sensors are useful, however. Their frequency of overpass and lesser spatial resolution render them useful for mapping large spills or assisting in ship and platform discharge monitoring. Much effort is currently underway to remove oil look-alikes such as low-wind areas, biogenic slicks, and oceanographic

fronts from the imagery.

Equipment that measures relative slick thickness is still under development. The passive microwave has been studied for several years, but many commercial instruments lack sufficient spatial resolution to be practical, operational instruments. A laser-acoustic instrument, which provides the only technology to measure absolute oil thickness, has been tested.

Equipment operating in the visible spectrum, such as cameras and scanners, is useful for documentation or providing a basis for the overlay of other data. It is not useful beyond this because oil shows no spectral characteristics in the visible region. Less use has been made of visible equipment in recent years.

Sensors for measuring oil thickness are briefly reviewed. The technology is relatively new, although there are some promising concepts that require further research.

Upon the oil spill incident, properties of the spilled oil are needed to predict the environmental impact and guide the remediation response. Some common physical, chemical and biological parameters and testing methods are introduced, summarized in **Table 6.1**.

Table 6.1 Summary of needed parameters and analytical tests in oil spill monitoring
(AMSA, 2003)

Data needed	Analytical test	Comment
Amount of oil in the sediment	For all oils: "Total Petroleum Hydrocarbons (TPH)". For heavy oils and longer term study of medium to heavy oils, do "Total Oil and Grease (TOG)" in addition to TPH.	Results are in mg/kg or ppm (dry weight)
Oil Physical Character	viscosity pour point density (specific gravity) water content	Degrees Celsius (°C). As a percentage.
Predicting Oil Behaviour	Physical Properties. Wax Content Asphaltene Content	As a percentage As a percentage
Fingerprinting (Identifying the Oil)	Biomarkers	
	Metals (Vanadium, Zinc, Nickel Cadmium, Lead) and Sulphur	Usually Vanadium, Nickel, with Sulphur.
Weathering	C17/Prystane & C18/Phytane	

	ratios
Tainting	Hydrocarbons in edible tissue or whole animal/plant
Bioaccumulation	Hydrocarbons in whole animal/plant

To increase the monitoring performance further, incorporation of more knowledge is needed. Brekke and Solberg (2005) suggested that the future oil spill system should be an integrated system, including automatic algorithms, a database of hotspots (e.g. oilrigs, sunken ships and seepages), ship lanes, alga information, and more extensive use of wind information.

A large challenge in detection of oil spills in some satellite monitoring is the accurate discrimination between oil spills and look-alikes. Most low wind situations can be handled by analysing the surroundings of a slick, but natural films cannot always be properly distinguished from oil spills based on a satellite image alone. Additional information about algal blooms, for example, is desired, where alga is common during the summer in some areas. Such information can be derived from optical sensors. Future oil spill systems should incorporate alga information either from multisensory studies, or by using prior knowledge about the likelihood of observing alga in a given area at a certain time of the year.

CHAPTER 7

TECHNOLOGIES FOR OFFSHORE OIL SPILL

RESPONSE AND COUNTERMEASURES

The primary objective of a spill response operation is to minimize the size of affected area and damage to vulnerable resources. The operational response strategies are illustrated in **Figure 7.1** (Owens, 2010). Ideally, this would be achieved by operations launched to contain, recover, and/or eliminate (i.e., disperse or burn) the oil on the water as near to the source as possible. If control at or near the source cannot be achieved due to feasibility, practicality, or safety factors, and if the spilled oil poses a threat to the coastal zone, then a defensive strategy would be implemented to minimize the size of the affected area and prevent oil from reaching the coastal zone. The objective of this strategy would be to prevent oil from reaching vulnerable shoreline area(s) and would involve on-water recovery and/or elimination (dispersion or burning). In the event that oil cannot be contained, recovered, or eliminated on the open water due to feasibility, practicality, or safety factors, the next line of defense would be at or near the shoreline to protect site-specific vulnerable and sensitive shoreline resources or habitats at risk. The objective of a protection strategy would be to contain and recover oil, divert oil away from the shore, and/or redirect or deflect oil to strand on a shoreline that does not have sensitive resources at risk and where shoreline recovery could be effective. If all of the first series of control or protection strategies are not completely successful, the final step could be the cleanup of stranded oil, which, typically, is designed to accelerate natural recovery or to minimize further effects of the oil, for example, to prevent wildlife contact. In some cases, natural recovery of an oiled shoreline or section of shoreline may be a preferred strategy. The objectives, or endpoint criteria, for shoreline cleanup vary within the area affected by a spill depending, in part, on shore type and are set on a segment-by-segment basis. In most spills where oil reaches the coast, shoreline cleanup is the longest and most expensive component of a response operation (Owens, 2010).

At different stage of response strategies, there are some common treatment options available and proven by authorities. These options can be grouped as physical/mechanical removal technologies (e.g. booming, skimming, manual recovery, and sorption), biological removal technologies (e.g. bioremediation and natural attenuation) and chemical removal technologies (e.g. dispersion, emulsification, in situ burning, and siltification). These options will be discussed in detailed in the following sections.

7.1 Physical/mechanical countermeasures

The main purpose of physical/mechanical counter-measurements is to contain an oil spill to prevent it from spreading to a particular area, to divert it to another area where it can be recovered or treated, or to concentrate the oil so that it can be recovered, burned, or otherwise treated (Fingas, 2010).

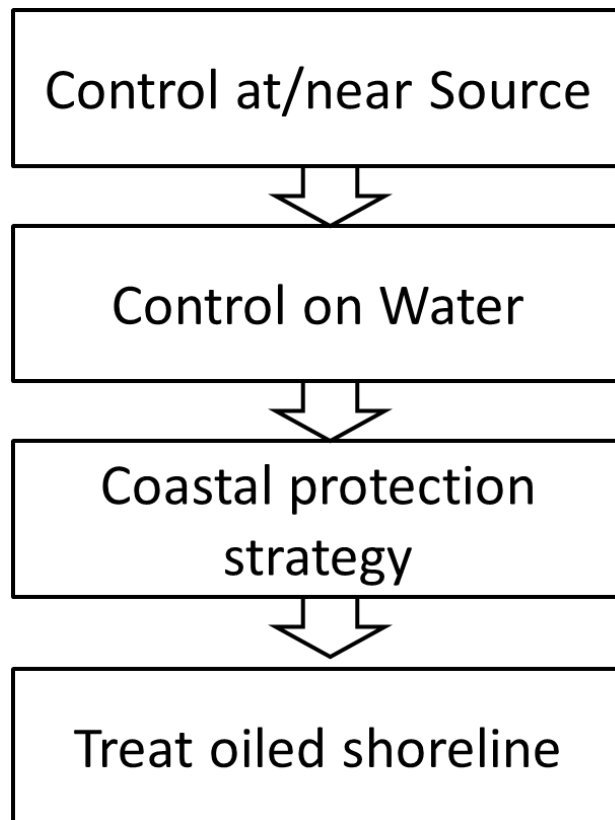


Figure 7.1 Fallback operational response strategies (source: Owens, 2010).

7.1.1 Booming

Booms are used to enclose oil and prevent it from spreading, to protect harbors, bays, and biologically sensitive areas, to divert oil to areas where it can be recovered or treated, and to concentrate oil and maintain an sufficient thickness so that skimmers can be used or other cleanup techniques, such as *in-situ* burning, can be applied.

7.1.1.1 Basic boom construction

Most commercial booms consist of four basic components: a means of flotation, a freeboard member (or section) to prevent oil from flowing over the top of the boom, a skirt to prevent oil from being swept underneath the boom, and one or more tension members to support the entire boom as illustrated in **Figure 7.2**

(Fingas, 2001). Booms are constructed in sections, usually 15 or 30m long, with connectors installed on each end so that sections of the boom can be attached to each other, towed, or anchored. The means of flotation, which located along the center line, determine the buoyancy of the boom and the level above the water surface. It generally made of either plastic foam or inflatable material. The freeboard member is the portion of boom above the water. The skirt is the portion of the boom below the floats, which helps to contain the oil. It is usually made of the same types of fabric as the freeboard member. The tension members run along the bottom of the boom and reinforce it against the horizontal load imposed by waves and currents. Tension members are usually made of steel cables or chains but sometimes consist of nylon or polyester ropes (Violeau et al., 2007). Booms are sometimes constructed with ballast or weights designed to maintain the boom in an upright position. Lead weights have been used for this, but steel chain in the bottom of the boom often serves as both ballast and a tension member (Fingas, 2010).

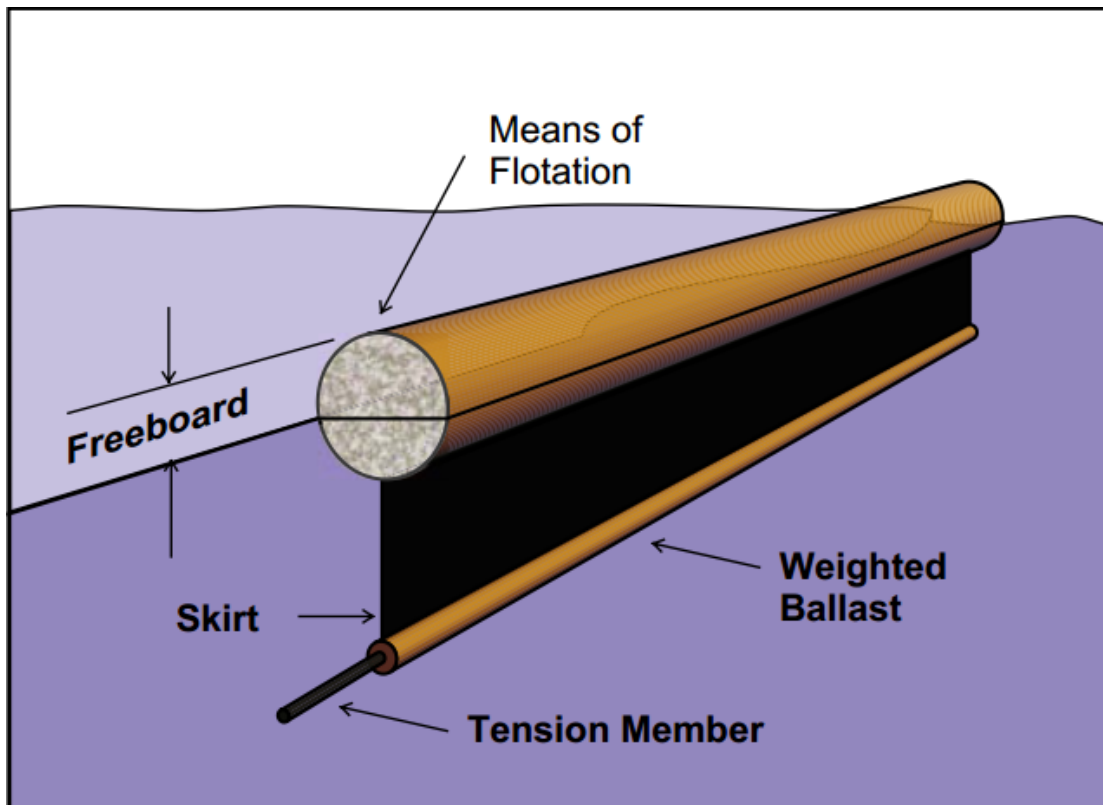


Figure 7.2 Basic boom construction (source: Fingas, 2010)

7.1.1.2 Basic types of booms

The three basic types of booms are fence, curtain booms, which are most common, and external tension member booms, which are relatively rare. The fence boom is constructed with a freeboard member above the float. Though relatively inexpensive, these booms are not recommended for use in high winds or strong water currents. Curtain booms are constructed with a skirt below the floats and no

freeboard member above the float. Curtain booms are most suitable for use in strong water currents. External tension member booms, which are constructed with a tension member outside the main structure, are used in strong currents and in water containing ice or debris (Fingas, 2010).

7.1.1.3 Characteristics of booms

The characteristics of booms that are important in determining their operating ability are the buoyancy-to-weight ratio or reserve buoyancy, the heave response, and the roll response (Castro, 2010). The buoyancy-to-weight ratio or reserve buoyancy is determined by the amount of flotation and the weight of the boom. This means that the float must provide enough buoyancy to balance the weight of the boom with the force exerted by currents and waves, thereby maintaining the boom's stability. The greater a boom's reserve buoyancy, the greater its ability to rise and fall with the waves and remain on the surface of the water. The heave response is the boom's ability to conform to sharp waves. It is indicated by the reserve buoyancy and the flexibility of the boom. A boom with good heave response will move with the waves on the surface of the water and not be alternately submerged and thrust out of the water by the wave action. The roll response refers to the boom's ability to remain upright in the water and not roll over (Castro, 2010).

7.1.1.4 Configuration and failures of booms

Booms are used primarily to contain oil, although they are also used to deflect oil. When used for containment, booms are often arranged in a U-, V-, or J-configuration. The U-configuration is the most common and is achieved by towing the boom behind two vessels, anchoring the boom, or combining these two techniques. The J-configuration is a variation of the U-configuration and is usually used to contain oil as well as to deflect it to the containment area. The V-configuration usually consists of two booms with a counterforce such as a skimmer at the apex of the two booms. Encirclement is another way that booms can be used for containment. Stricken ships in shallow waters are often encircled or surrounded by booms to prevent further movement of oil away from the ship. Booms are also used in a "sweep" configuration to either deflect oil or contain it for pickup by skimmers. If strong currents prevent the best positioning of the boom in relation to the current, several booms can be deployed in a cascading pattern to progressively move oil toward one side of the watercourse (Fingas, 2010). The above mentioned configurations are illustrated in **Figure 7.3**.

A boom's performance and its ability to contain oil are affected by water currents, waves, and winds (Amini et al., 2008; Castro et al., 2010; Muttin, 2008a; Muttin, 2008b). Either alone or in combination, these forces often led to boom failure and loss of oil. Common ways of boom failures includes entrainment failure, drainage failure, critical accumulation, splashover, submergence failure, planning as illustrated in **Figure 7.4**.

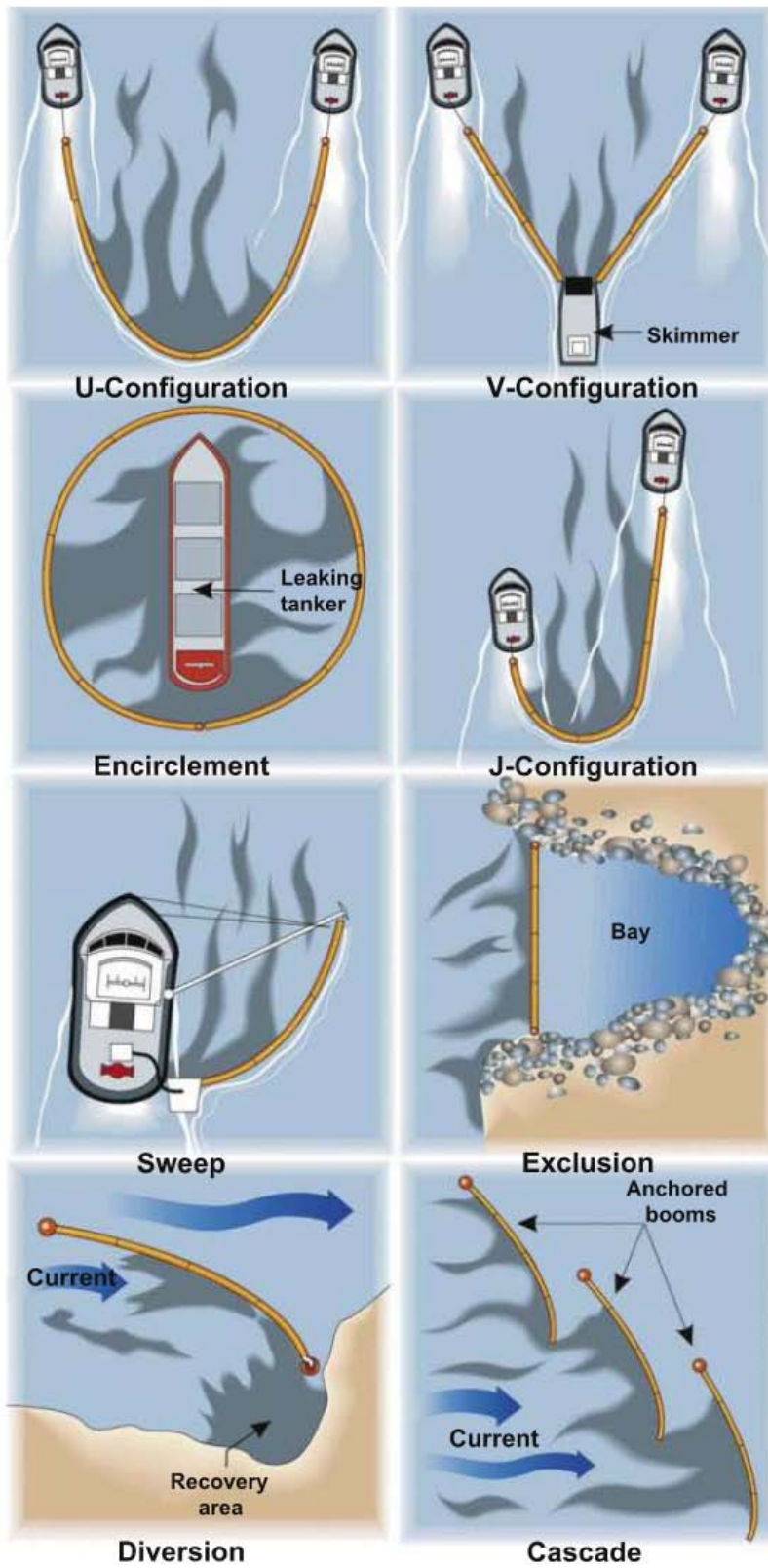


Figure 7.3 The illustration of various configuration used in boom deployment (source: Fingas, 2010)

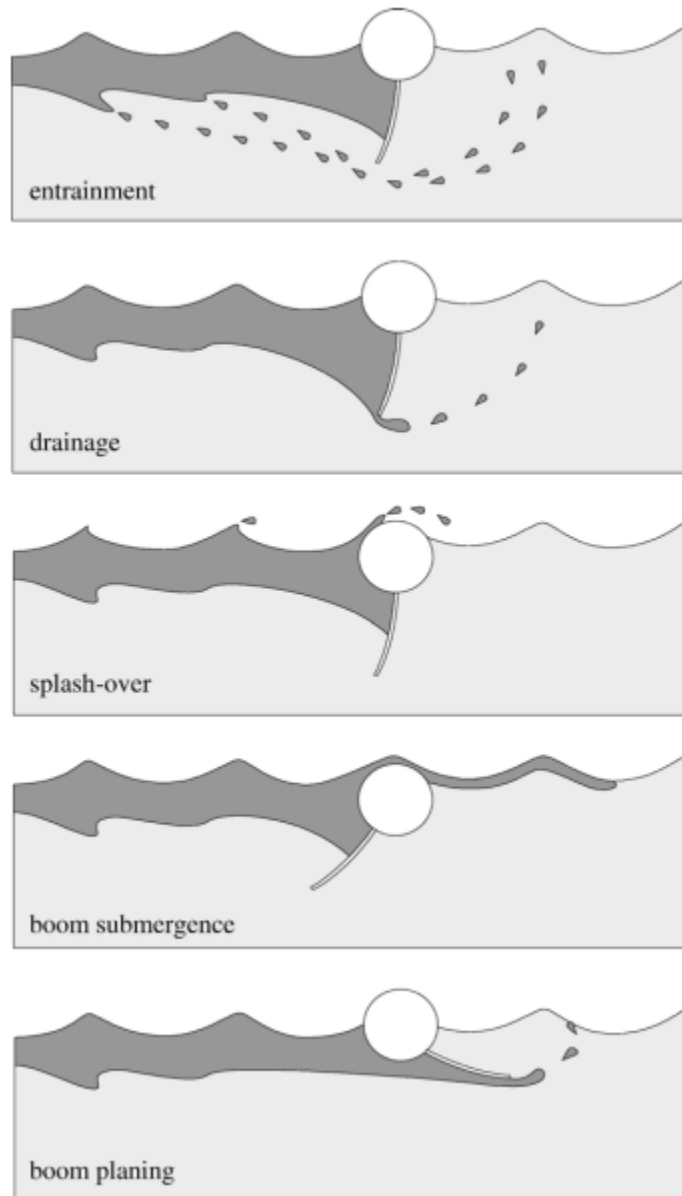


Figure 7.4 The illustration of several modes of boom failure (source: violeau et al., 2007)

Entrainment failure is caused by the speed of the water current and is more likely to happen with a lighter oil. When oil is being contained by a boom in moving water, if the current is fast enough, the boom acts like a dam and the surface water being held back is diverted downward and accelerates in an attempt to keep up with

the water flowing directly under the boom. The resulting turbulence causes droplets to break away from the oil that has built up in front of the boom, referred to as the oil headwave, pass under the boom, and resurface behind it. The water speed at which the headwave becomes unstable and the oil droplets begin to break away is referred to as the critical velocity. At current speeds greater than the critical velocity, this type of boom failure can be overcome by placing the boom at an angle to the current or in the deflection mode. Since currents in most rivers and many estuaries exceed the critical velocity of 0.5m/s (1 knot), this is the only way the oil can be contained.

Drainage failure is related to the speed of the water current, except that it affects the oil directly at the boom. After critical velocity is reached, large amounts of the oil contained directly at the boom can be swept under the boom by the current. Both entrainment and drainage failure are more likely to occur with lighter oils. One or both of these two types of failure can occur, depending on the currents and the design of the boom.

Critical accumulation usually occurs when heavier oils, which are not likely to become entrained in water, are being contained. Heavier oils tend to accumulate close to the leading edge of the boom and are swept underneath the boom when a certain critical accumulation point occurs. This accumulation is often reached at current velocities approaching the critical velocities.

Splashover occurs in rough or high seas when the waves are higher than the boom's freeboard and oil splashes over the boom's float or freeboard member. It can also occur as a result of extensive oil accumulation in the boom compared to the freeboard.

Submergence failure occurs when water goes over the boom. Often the boom is not buoyant enough to follow the wave motion, and some of the boom sinks below the water line and oil passes over it. Submergence failure is usually the result of poor heave response, which is measured by both the reserve buoyancy and the flexibility of the boom. Failure due to submergence is not that common as other forms of failure, such as entrainment, usually occur first.

Planing occurs when the boom moves from its designed vertical position to almost a horizontal position on the water. Oil passes over or under a planing boom. Planing occurs if the tension members are poorly designed and do not hold the boom in a vertical position or if the boom is towed in currents far exceeding the critical velocity (Violeau et al., 2007).

7.1.1.5 Special-purpose booms

A variety of special-purpose booms is available. Sorbent booms are specialized containment and recovery devices made of porous sorbent material such as woven or fabric polypropylene, which absorbs the oil while it is being contained. A tidal seal boom floats up and down, but forms a seal against the bottom during low tide. An ice boom is used to contain or divert oil in ice-infested waters. Bubble barriers

are occasionally used at fixed facilities such as harbors and loading platforms where the water is generally calm. High-pressure air or water streams can be used to contain and deflect oil. Because of their high-power requirements, they are usually used only to deflect oil in front of skimmers or fixed separator systems. Chemical barriers use chemicals that solidify the oil and prevent its spread (Fingas, 2010).

7.1.2 Skimming

Skimmers are mechanical devices designed to remove oil from the water surface. They vary greatly in size, application, and capacity, as well as in recovery efficiency (Schulze, 1998; Schwartz, 1979). By classification according to their basic operational principles, skimmers can be grouped as oleophilic surface skimmers; weir skimmers; suction skimmers or vacuum devices; elevating skimmers; submersion skimmers; and vortex or centrifugal skimmers.

7.1.2.1 Oleophilic surface skimmers

Oleophilic surface skimmers, sometimes called sorbent surface skimmers, use a surface to which oil can adhere to remove the oil from the water surface. This oleophilic surface can be in the form of a disc, drum, belt, brush, or rope, which is moved through the oil on the top of the water (Broje and Keller, 2007). A wiper blade or pressure roller removes the oil and deposits it into an onboard container or the oil is directly pumped to storage facilities on a barge or on shore. The oleophilic surface itself can be steel, aluminum, fabric, or plastics such as polypropylene and polyvinylchloride. Oleophilic skimmers pick up very little water compared to the amount of oil recovered. They therefore operate efficiently on relatively thin oil slicks. They are not as susceptible to ice and debris as the other types of skimmers. These skimmers are available in a range of sizes and work best with light crude oils, although their suitability for different types of oil varies with the design of the skimmer and the type of oleophilic surface used. The operating principles of oleophilic skimmers are illustrated in **Figure 7.5** (Fingas, 2001).

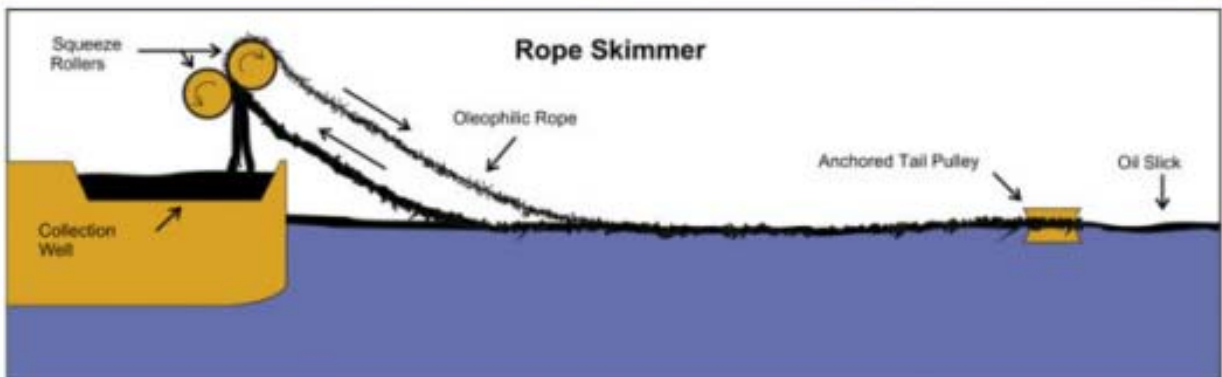
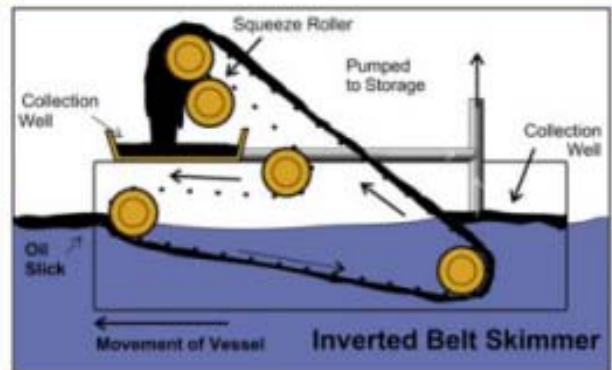
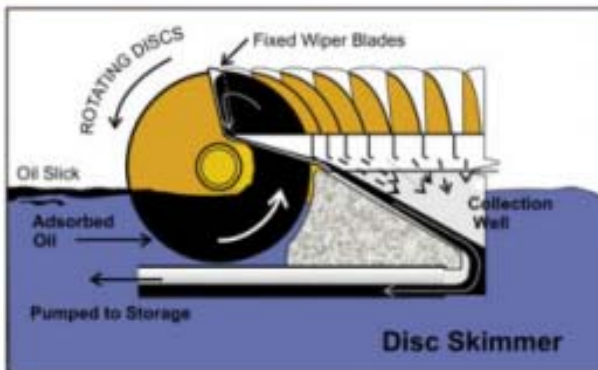
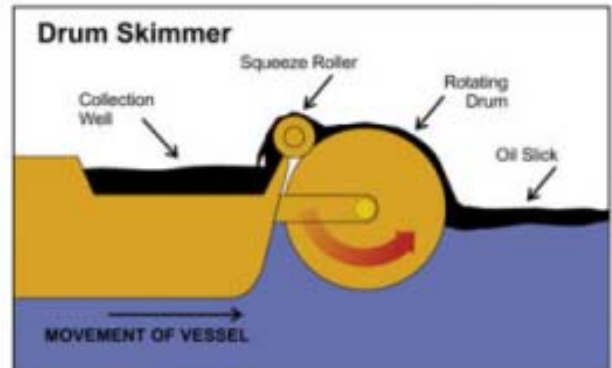
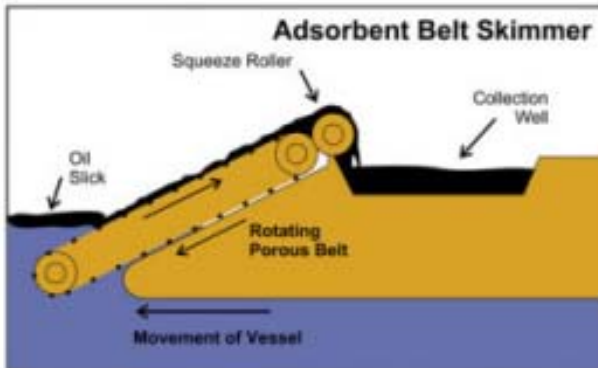
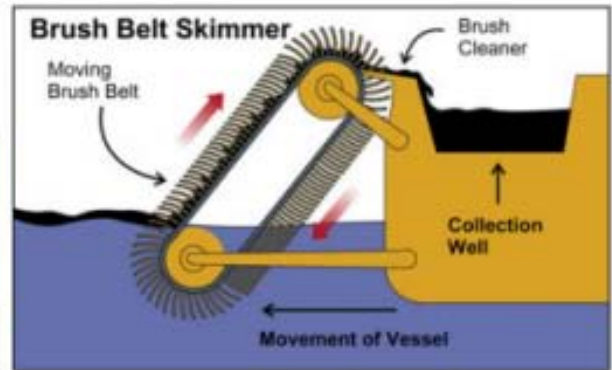
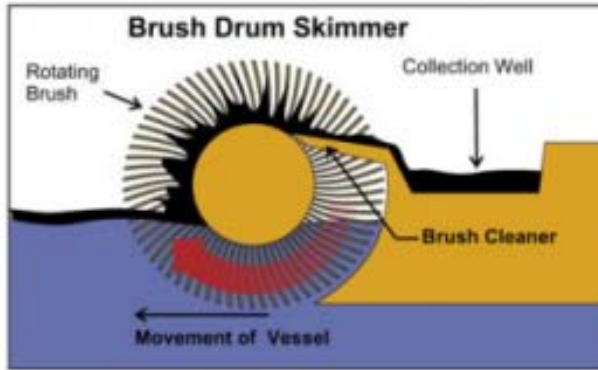


Figure 7.5 An illustration of the principles of oleophilic surface skimmers (source: Fingas, 2010)

Disc skimmers work best with light crude oil and are well suited to working in waves and among weeds or debris. The discs are usually made of either polyvinyl chloride or steel. These skimmers are usually small and can be deployed by one or two people. Disadvantages are that the recovery rate is slow and they work poorly with light fuels or heavy oils. The drum skimmer is another type of oleophilic surface skimmer. The drums are made of either a proprietary polymer or steel. The drum skimmer works relatively well with fuels and light crude, but is ineffective with heavy oils. Drum skimmers are often smaller in size like the disc skimmer (Turner and Najar, 2007). Belt skimmers have been designed with one that pumps the oily water through a porous belt and the inverted belt skimmer that carries the oil under the water. The oil is subsequently removed from the belt by scrapers and rollers after the belt returns to a selected position at the bottom of the skimmer. Brush skimmers use tufts of plastic attached to drums or chains to recover the oil from the water surface. The oil is usually removed from the brushes by wedge-shaped scrapers. Brush skimmers are particularly useful for recovering heavier oils, but are ineffective for fuels and light crudes. Rope skimmers remove oil from the water surface with an oleophilic rope of polymer, usually polypropylene. Some skimmers have one or two long ropes that are held in the slick by a floating, anchored pulley. Others use a series of small ropes that hang down to the water surface from a suspended skimmer body. The rope skimmer works best with medium viscosity oils and is particularly useful for recovering oil from debris- and ice-laden waters. (Fingas, 2010).

7.1.2.2 Weir skimmers

Weir skimmers are a major group of skimmers that use gravity to drain the oil from the surface of the water into a submerged holding tank. The configurations of weir skimmers are illustrated in **Figure 7.6**.

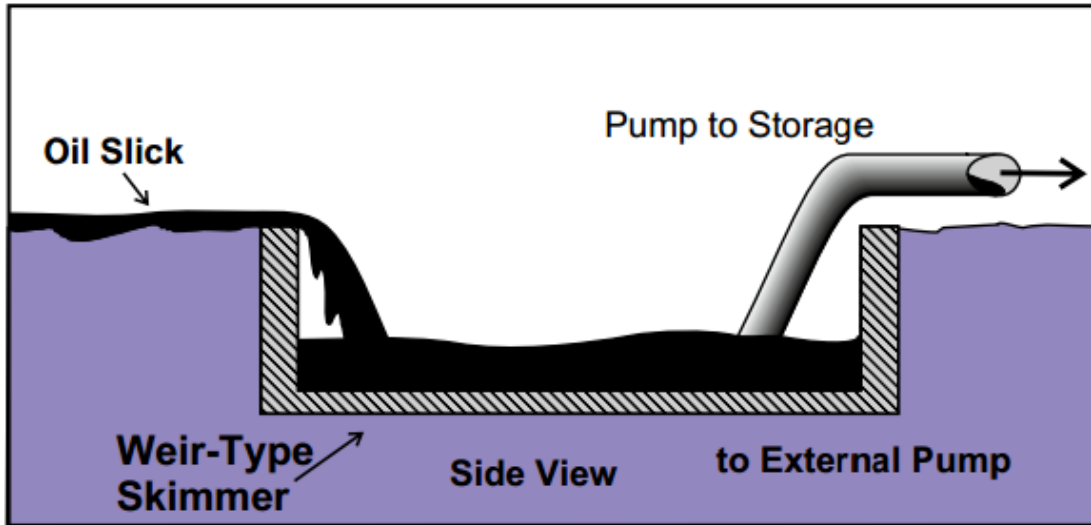


Figure 7.6 An illustration of the weir skimmer concept (source: Fingas, 2010).

Weir skimmers, with their crest just above or at the oil/water interface surface, collect oil floating on the water surface via gravity action. Once collected, the oil is transferred from the weir central sink by gravity or by pump to storage tanks. Because they are widely available, weir skimmers are the most commonly selected type of skimmer for environmental protection. They have been used to recover oil in many marine oil spill accidents and industrial wastewater treatment systems. A wide variety of weir skimmers are produced and they are often classified according to their size, surface area, and mode of operation (Hammoud, 2006). A problem with some older weir skimmers is their tendency to rock back and forth in choppy water, alternately sucking in air above the slick and water below. This increases the amount of water and reduces the amount of oil recovered. Some models include features for self-levelling and adjustable skimming depths so that the edge of the weir is precisely at the oil-water interface, minimizing the amount of water collected. Weir skimmers do not work well in ice and debris or in rough waters, and they are not effective for very heavy oils or tarballs. Weir skimmers are economical, however, and they can have large capacities. They are best used in calm, protected waters. Weir skimmers have also been built into booms and have been moderately successful in providing high recovery rates of lightercrudes (Fingas, 2010).

7.1.2.3 Suction or Vacuum skimmers

Suction or vacuum skimmers use a vacuum or slight differential in pressure to remove oil from the water surface. Often the “skimmer” is only a small floating head connected to an external source of vacuum, such as a vacuum truck. The head of the skimmer is simply an enlargement of the end of a suction hose and a float. The principle of operation of a suction skimmer is shown in **Figure 7.7**.

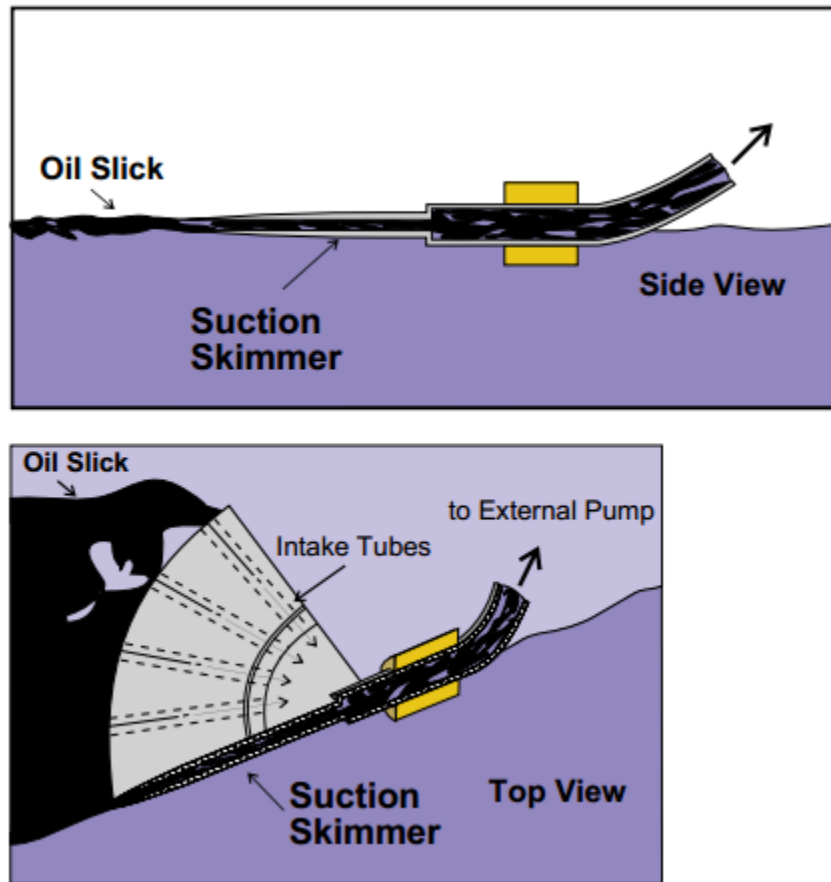


Figure 7.7 An illustration of suction skimmer principles (source: Fingas, 2010).

Suction skimmers are similar to weir skimmers in that they sit on the water surface, generally use an external vacuum pump system such as a vacuum truck, and are adjusted to float at the oil-water interface. They also tend to be susceptible to the same problems as weir skimmers. They are prone to clogging with debris, which can stop the oil flow and damage the pump. They also experience the problem of rocking in choppy waters, which causes massive water intake, followed by air intake. Their use is restricted to light to medium oils. Despite their disadvantages, suction skimmers are the most economical of all skimmers. Their compactness and shallow draft make them particularly useful in shallow water and in confined spaces. They operate best in calm water with thick slicks and no debris. Very large vacuum pumps, called air conveyors and suction dredges have been used to recover oil, sometimes directly without a head. Both of these adaptations, however, have the same limitations as smaller suction skimmers (Fingas, 2001).

7.1.2.4 Elevating skimmers

Elevating skimmers or devices use conveyors to lift oil from the water surface into a recovery area as illustrated in **Figure 7.8**. A paddle belt or wheel or a conveyor belt with ridges is adjusted to the top of the water layer, and oil is moved up the recovery device on a plate or another moving belt. The operation is similar to removing liquid from a floor with a squeegee. The oil is usually removed from the conveyor by gravity. When operating these skimmers, it is difficult to maintain the conveyor at the water line. In addition, they cannot operate in rough waters or in waters with large pieces of debris, and they cannot deal with light or very heavy oils. Elevating skimmers work best with medium to somewhat heavy oils in calm waters. They are generally large and are sometimes built into specialized vessels (Fingas, 2001).

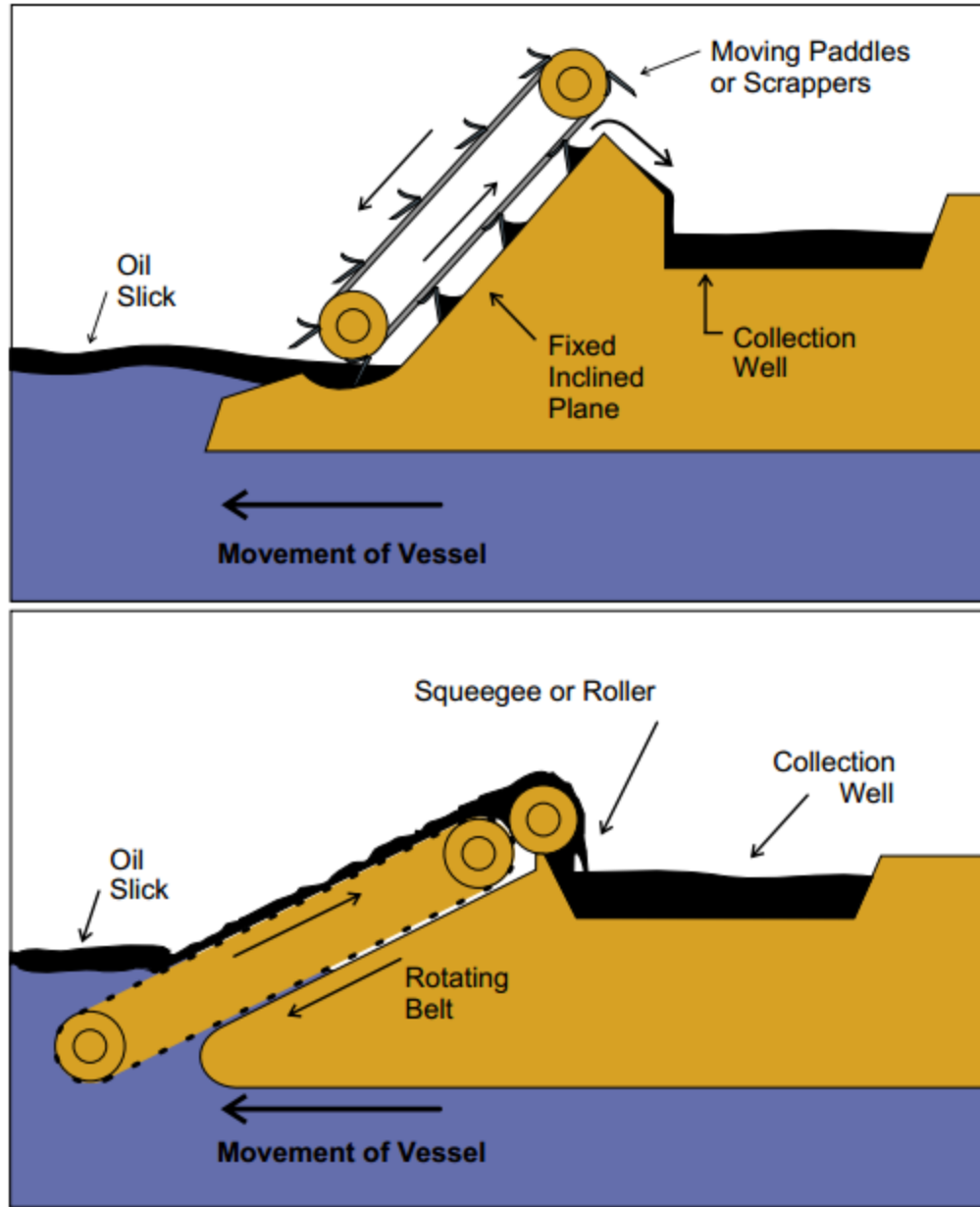


Figure 7.8 A illustration of elevating skimmer principles (Source: Fingas, 2001).

7.1.2.5 Submersion skimmers

Submersion skimmers use a belt or an inclined plane to force the water beneath the surface. The belt or plane forces the oil downward toward a collection well where it is removed from the belt by a scraper or by gravity. The oil then flows upward into the collection well and is removed by a pump. Submersion skimmers move faster than other skimmers and can therefore cover a large area, making them suitable for use at larger spills. They are most effective with light oils with a low viscosity and when the slick is relatively thin. Disadvantages include a poor tolerance to debris compared to other skimmers, and they cannot be used in shallow

waters. Submersion skimmers are larger than other types of skimmers and are usually mounted on a powered vessel (Fingas, 2010).

7.1.2.6 Evaluation of skimmer performance

A skimmer's performance is affected by a number of factors including the thickness of the oil being recovered, the extent of weathering and emulsification of the oil, the presence of debris, and weather conditions at the time of recovery operations. A skimmer's overall performance is usually determined by a combination of its recovery rate and the percentage of oil recovered. The maximum amount of oil that a skimmer could recover is called the Nameplate Recovery Rate and is typically provided by the manufacturer of a skimmer (Meyer et al., 2009; Potter, 2008). A similar definition is the Effective Daily Recovery Capacity, which is the amount that a skimmer could recover in daylight hours under ideal conditions. The recovery rate is the volume of oil recovered under specific conditions. It is measured as volume per unit of time, for example, m³/h, and is usually given as a range. If a skimmer takes in a lot of water, it is detrimental to the overall efficiency of an oil spill recovery operation. The results of performance testing on various types of skimmers are given in **Table 7.1** (Fingas, 2001; Fingas, 2010b; Potter, 2008; Schulze, 1998).

Table 7.1 Performance of typical skimmers (source: Fingas, 2001; Fingas, 2010b; Potter, 2008; Schulze, 1998)

Skimmer type	Recovery Rate (m ³ /hr) for given oil type ^a				
	Diesel	Light crude	Heavy crude	Bunker C	Percent Oil ^b
Oleophilic skimmers					
Small disc	0.4-1	0.2-2			80-95
Large disc		10-20	10-50		80-95
Brush	0.2-0.8	0.5-20	0.5-2	0.5-2	80-95
Large drum		10-30			80-95
Small drum	0.5-5	0.5-5			80-95
Large belt	1-5	1-20	3-20	3-10	75-95
Inverted belt		10-30			85-95
Rope		2-20	2-10		
Weir skimmers					

Small weir	0.2-10	0.5-5	2-20		20-80
Large weir		30-100	5-10	3-5	50-90
Advancing weir	1-10	5-30	5-25		30-70
Elevating skimmers					
Paddle conveyer		1-10	1-20	1-5	10-40
Submersion skimmers					
Large	0.5-1	1-80	1-20		70-95
Suction skimmers					
Small	0.3-1	0.3-2			3-10
Large trawl unit		2-40			20-90
Large vacuum unit		3-20	3-10		10-80
Vortex/centrifugal skimmers					
Centrifugal unit	0.2-0.8	0.2-10			2-20

a. Recovery rate depends very much on the thickness of the oil, type of oil, sea state, and many other factors

b. This is the percentage of oil in the recovered product. The higher the value, the less the amount of water and thus the better the skimmers' performance

7.1.3 Sorption

Sorbents are materials that recover oil through either absorption or adsorption. They play an important role in oil spill cleanup and are used in the following ways: to clean up the final traces of oil spills on water or land; as a backup to other containment means, such as sorbent booms; as a primary recovery means for very small spills; and as a passive means of cleanup. An example of such passive cleanup is when sorbent booms are anchored off lightly oiled shorelines to absorb any remaining oil released from the shore and prevent further re-oiling of the shoreline (Fingas,2010a).

Sorbents can be natural or synthetic materials. Natural sorbents are divided into organic materials, such as peat moss or wood products, and inorganic type of plastic sorbent is formed into flat strips or "pom-poms." which are particularly useful for recovering very heavy oils. The use of synthetic sorbents in oil spill recovery has increased in the last few years. These sorbents are often used to wipe other oil spill recovery equipment, such as skimmers and booms, after a spill

cleanup operation. Sheets or rolls of sorbent are often used for this purpose. Synthetic sorbents can often be reused by squeezing the oil out of them, although extracting small amounts of oil from sorbents is sometimes more expensive than using new sorbent. Furthermore, oil-soaked sorbent is difficult to handle and can result in minor releases of oil between the regeneration area and the area where the sorbent issued (Fingas, 2010a).

The capacity of a sorbent depends on the amount of surface area to which the oil can adhere as well as the type of surface. A fine porous sorbent with many small capillaries has a large amount of surface area and is best for recovering light crude oils or fuels. Sorbents with a coarse surface would be used for cleaning up a heavy crude oil or Bunker. Pom-poms intended for recovering heavy Bunker or residual oil consist of ribbons of plastic with no capillary structure. General-purpose sorbents are available that have both fine and coarse structure, but these are not as efficient as products designed for specific oils (Fingas, 2010a).

Some sorbents are treated with oleophilic (oil-attracting) and hydrophobic (water-repelling) agents to improve the ability of the material to preferentially absorb oil rather than water. As natural sorbents often recover large amounts of water along with the oil, they can be treated to prevent water uptake. This type of treatment usually increases the ability of certain sorbents to remain afloat. The performance of sorbents is measured in terms of total oil recovery and water pickup, similar to skimmers. "Oil recovery" is the weight of a particular oil recovered compared to the original weight of the sorbent. The amount of water picked up is also important, with an ideal sorbent not recovering any water. Some results of performance testing of typical sorbents with various types of oils are given in **Table 7.2** (Carmody et al., 2007; Cooper et al., 2005a; Cooper et al., 2005b; Potter, 2008). A number of precautions must be considered when using sorbents. First, the excessive use of sorbents at a spill scene, especially in a granular or particulate form, can compound cleanup problems and make it impossible to use most mechanical skimmers. Sorbents may cause plugging in discharge lines or even in the pumps themselves. Second, sorbents that sink should not be used as they could be harmful to the environment. Many countries do not allow the use of sorbents that sink in applications on water, as the oil will usually be released from the sorbent over time and both the oil and the sorbent are very harmful to benthic life.

Table 7.2 Performance of some sorbents (Carmody et al., 2007; Cooper et al., 2005a; Cooper et al., 2005b; Potter, 2008)

Sorbent type	Recovery Rate (m ³ /hr) for given oil type ^a				
	Diesel	Light crude	Heavy crude	Bunker C	Percent Oil ^b

Synthetic sorbents					
Polyester pad	7	9	12	20	90+
polyethylene pads	25	30	35	40	90+
polyolefin pom-poms	2	2	3	8	90+
polypropylene pads	6	8	10	13	90+
polypropylene pom-poms	3	6	6	15	90+
polyurethane pads	20	30	40	45	90+
Natural organic sorbents					
bark or wood fiber	1	3	3	5	70
bird feathers	1	3	3	2	80+
peat moss	2	3	4	5	80+
treated peat moss	5	6	8	10	80+
straw	2	2	3	4	70+
vegetable fibre	9	4	4	10	80+
Natural inorganic sorbents					
clay (kitty litter)	3	3	3	2	70
treated pearylite	8	8	8	9	70
treated vermiculite	3	3	4	8	70
Vermulite	2	2	3	5	70

^a. Recovery rate depends very much on the thickness of the oil, type of oil, sea state, and many other factors

^b. This is the percentage of oil in the recovered product. The higher the value, the less the amount of water and thus the better the skimmers' performance

Finally, recovery and disposal of the oiled sorbent material must be considered. As oiled sorbent is most often burned or buried, the sorbent must retain the oil long enough so that it is not lost during recovery operations or in transport to disposal sites (Fingas, 2010a).

7.1.4 Manual recovery

Small oil spills or those in remote areas are sometimes recovered by hand. Heavier oils are easier to remove this way than lighter oils. Spills on water close to shorelines are sometimes cleaned up with shovels, rakes, or by cutting the oiled vegetation. Hand bailers, which resemble a small bucket on the end of a handle, are sometimes used to recover oil from the water surface. Manual recovery is tedious and may involve dangers such as physical injury from falls on the shore. Much shoreline cleanup is usually done manually.

7.1.5 Temporary storage, separation and disposal of recovered oil

When oil is recovered, sufficient storage space must be available for the recovered product. The recovered oil often contains large amounts of water and debris that increase the amount of storage space required. Several types of specially built tanks are available to store recovered oil. Flexible portable tanks, often constructed of plastic sheeting and a frame, are the most common type of storage used for spills recovered on land and from rivers and lakes. These are available in a range of sizes from approximately 1 to 100 m³ and require little storage space before assembly. Most of these types of tanks do not have a roof, however, so rain or snow can enter the tank and vapor can escape. Rigid tanks, which are usually constructed of metal, are also available but are less common than flexible tanks. Pillow tanks, constructed of polymers and heavy fabrics, are usually used to store oil recovered on land. These are placed on a solid platform so that rocks cannot puncture the tank when full. Pillow tanks are also sometimes used on the decks of barges and ships to hold oil recovered at sea. Oil recovered on land is often stored in stationary tanks built for other purposes, and in dump trucks and modular containers, lined with plastic. Recovered oil can also be temporarily stored in pits or berms lined with polymer sheets, although this open type of storage is not suitable for volatile oils. Towable, flexible tanks, usually bullet-shaped are also used to contain oil recovered at sea. Oil recovered at sea is often temporarily stored in barges. Many cleanup organizations have barges that are used solely for storing recovered oil and lease barges for use at larger spills. Recovered oil is also stored in the holds of ships, usually using older vessels. This is more economical than using designated tanks on land, especially when the recovered oil has to be stored for long periods of time until a final disposal method is found (Fingas, 2010).

The oil must be separated from the recovery mixture for disposal, recycling, or direct reuse by a refinery. Sometimes settling tanks or gravity separators are incorporated into skimmers, but separators are more often installed on recovery ships or barges. Portable storage tanks are often used as separators, with outlets installed on the bottom of the tanks so that water that has settled to the bottom of the tank can be drained off, leaving the oil in the tank. Vacuum trucks are also used in this way to separate oil and water. Screens or other devices for removing debris are sometimes incorporated into separators. A gravity separator is the most common type of separator. In its simplest form, it consists of a large holding tank in

which the oil and water mixture is held long enough for the oil to separate by gravity alone. This is referred to as the residence time and varies from minutes to hours. When inflow volumes are large, it can be difficult to find large enough separators to provide the long residence times required. Oil refineries have large separators that may cover several hectares and are used for treating refinery waste and are sometimes also used to treat oil recovered from spills. Separators are often made with baffles or other interior devices that increase the residence time and thus the degree of separation. The parallel plate separator is a special model of gravity separator. Many parallel plates are placed perpendicular to the flow, creating areas of low water turbulence where drops of oil can re-coalesce from the water and rise to the surface. Centrifugal separators have spinning members that drive the heavier water from the lighter oil, which collects at the center of the vessel. These separators are very efficient but have less capacity than gravity separators and cannot handle large debris. They are best suited to constant amounts of oil and water (Fingas, 2010).

Disposing of the recovered oil and oiled debris can be the most difficult aspects of an oil spill cleanup operation (Davies, 2000; Jones and Najafi, 2002; Richardson, 2004). Any form of disposal is subject to a complex system of local, provincial or state, and federal legislation. Unfortunately, most recovered oil consists of a wide range of contents and material states and cannot be classified as simply liquid or solid waste. The recovered oil may contain water that is difficult to separate from the oil and many types of debris, including vegetation, sand, gravel, logs, branches, garbage, and pieces of containment booms. This debris may be too difficult to remove, and thus the entire bulk material may have to be disposed of. Spilled material is sometimes directly reused either by reprocessing in a refinery or as a heating fuel. Some power plants and even small heating plants such as those in greenhouses can use a broad spectrum of hydrocarbon fuels. Often the equipment at refineries cannot handle oils with debris, excessive amounts of water, or other contaminants and the cost of pretreating the oils can far exceed the value that might be obtained from using them. Heavier oils are sometimes sufficiently free of debris to be used as a road cover when mixed with regular asphalt. Recovered material from cleaning up beaches can be used in this way. If the material is of the correct consistency, usually sand, the entire mixture might be mixed with road asphalt. Incineration is a frequent means of disposal for recovered oil, as large quantities of oil and debris can be disposed of in a relatively short time. Disadvantages are the high cost, which may include the cost of transporting the material to the facility. In addition, approval must be obtained from government regulatory authorities. Local emission guidelines for incinerators may preclude simply placing the material into an incinerator. Oiled debris, beach material, and sorbents are sometimes disposed of at landfill sites. Legislation requires that this material not contain free oil that could migrate from the site and contaminate groundwater. Some governments have standard leachability test procedures that determine whether the material will release oil. Several stabilization processes have been developed to ensure that free oil does not contaminate soil or groundwater. One process uses quicklime (calcium

oxide) to form a cement-like material, which can be used on roads as a dust-inhibitor (Fingas, 2010).

7.2 Chemical countermeasures

Chemical methods can be used in conjunction with mechanical means for containing and cleaning up oil spills. *In situ* burning requires good combination of fuel, oxygen, and an ignition source. Dispersing agents and Solidifiers are most useful in helping to keep oil from reaching shorelines and other sensitive habitats. Research into these technologies continues to improve oil spill cleanup.

7.2.1 In-situ burning

In-situ burning is the oldest technique applied to oil spills and is also one of the few techniques that have not been explored in scientific depth until recently. The fundamentals of in-situ burning are similar to those of any fire. The vaporization of the oil must be sufficient to yield a steady-state burning, that is, one in which the amount of vaporization is about the same as that consumed by the fire. Once an oil slick is burning burns at a rate of about 0.5 to 4 mm per minute (Crawley, 1982; Evans, 1991). The amount of vapors produced is dependent on the amount of heat radiated back to the oil. This has been estimated to be about 2 to 3% of the heat from a fire for a pool fire (Buist et al., 1994; Nakakuki, 2002). If the oil slick is too thin, some of this heat is conducted to the water layer below it. Since most oils have the same insulation factor, most slicks must be about 0.5 to 3 mm thick to yield a quantitative burn. Once burning, the heat radiated back to the slick and the insulation is usually sufficient to allow combustion down to about 1 mm of oil. Chatris and co-workers (2001) noted that burns of diesel fuel and gasoline went through a three-phase process. If greater amounts of fuel are vaporized than can be burned, more soot is produced as a result of incomplete combustion, fuel droplets are released downwind, or, more typically, small explosions or fireballs occur (Xu et al., 2003a; Xu et al., 2003b). The last-named phenomenon is often observed when gasoline or light crudes are burning. It has been shown that diesel fuel burns differently than other fuels, with a tendency to atomize rather than vaporize. This results in an obviously heavier soot formation. Soot formation occurs by several processes. One common process is the aggregation of molecular species into larger compounds, and another process is the partial combustion of fuels such as diesel fuels. Diesel fuels and kerosene are known to burn with more soot than most other fuels (Edding et al., 2005; Dagaut P, 2006a; Daguat P, 2006b; Morandini et al., 2005; Sazhin, 2006). **Table 7.4** summarizes the burnability of several types of oils. Studies conducted in the last 10 years have shown that the type of oil is relatively unimportant in determining how an oil ignites and burns, except for heavier or emulsified oils. However, heavy oils require longer heating times and a hotter flame to ignite than lighter oils and may often require a primer such as kerosene or diesel fuel. Earlier studies appeared to indicate that heavier oils and oils with water

content required greater thicknesses to ignite. However, recent testing has shown this position to be incorrect (Fingas, 2002). Several workers have tested various oils to determine their ignitability, with the general result that most oils are similar without stable emulsion formation (McCourt et al., 2000; McCourt et al., 2005).

Table 7.4 Burning properties of various fuels

Fuel	Burnability	Ease of ignition	Flame spread	Burning rate (mm/min)	Sootiness of flame	Efficiency range (%)	Reference (s)
Gasoline	Very high	Very easy	Rapid	3.5	Medium	95-99	Fay, 2003; Fingas and Punt, 2000
Diesel Fuel	High	Easy	Moderate	2.9	Very high	90-98	Chatris et al., 2001; Fingas and Punt, 2000
Light Crude	High	Easy	Moderate	3.5	High	85-98	Fingas and Punt, 2000
Medium Crude	Moderate	Easy	Moderate	3.5	Medium	80-95	Fingas and Punt, 2000
Heavy Crude	Moderate	Medium	Moderate	3	Medium	75-90	Fingas and Punt, 2000
Weathered Crude	Low	Difficult	Slow	2.8	Low	50-90	Fingas and Punt, 2000
Light Fuel Oil	Low	Difficult	Slow	2.5	Low	50-80	Fingas and Punt, 2000
Heavy Fuel Oil	Very low	Difficult	Slow	2.2	Low	40-70	Fingas and Punt, 2000
Lube Oil	Very low	Difficult	Slow	2	Medium	40-60	Fingas and Punt, 2000
Waste Oil	Low	Difficult	Slow	2	Medium	30-60	Fingas and Punt, 2000
Emulsified Oil	Low	Difficult	Slow	1-2	Low	30-60	Fingas and Punt, 2000

In-situ burning has some distinct advantages over other spill cleanup methods. These advantages include: (1) Rapid removal of large amounts of oil from the water surface; (2) Significantly reduced volume of oil requiring disposal; (3) High efficiency rates; (4) Less equipment and labor required ; and (5) May be only cleanup option in some situations, for example, oil-in-ice conditions (ASTM, 2008).

The most significant of these advantages is the capacity to rapidly remove large amounts of oil. When used at the right time, that is, early in the spill before the oil weathers and loses its flammable components, and under the right conditions, in-situ burning can be very effective at rapidly eliminating large amounts of spilled oil, especially from water. This can prevent oil from spreading to other areas and contaminating shorelines and biota. Compared to mechanical skimming of oil, which generates a large quantity of oil and water that must be stored, transferred, and disposed of, burning generates a small amount of burn residue. This residue is relatively easy to recover and can be further reduced by repeated burns. Although the efficiency of a burn varies with a number of physical factors, removal efficiencies are generally much greater than those for other response methods such as skimming and the use of chemical dispersants. During the NOBE conducted off the coast of Newfoundland in 1993, efficiency rates of 98 and 99% were achieved (Fingas, 2010c). In ideal circumstances, in-situ burning requires less equipment and labor than other techniques. It can be applied in remote areas where other methods cannot be used because of distances and lack of infrastructure. Often not enough of these resources are available when large spills occur. Burning is relatively inexpensive in terms of equipment needed and actually conducting the burn operations. *In-situ* burning also has disadvantages, some of which are the following: (1) Large black smoke plume created and public concern about toxic emissions to the air and water; (2) Limited time frame in which the oil can be ignited; (3) Oil must be a minimum thickness in order to ignite and burn and must usually be contained to achieve this thickness. Risk of fire spreading to other combustible materials; and (4) Burn residue must be disposed of (ASTM, 2008).

The most obvious disadvantage of burning oil is the large black smoke plume that is produced and public concern about emissions. The second disadvantage is that the oil will not ignite and burn unless conditions such as thickness are right. Most oils spread rapidly on water, and the slick quickly becomes too thin for burning to be feasible. Fire-resistant booms can be used to concentrate the oil into thicker slicks so that the oil can be burned. While this obviously requires equipment, personnel, and time, concentrating oil for burning requires less equipment than collecting oil with skimmers. And finally, burning oil is sometimes not viewed as an appealing alternative to collecting the oil and reprocessing it for reuse. It must be pointed out; however, that recovered oil is usually incinerated as it often contains too many contaminants to be economically reused. Furthermore, reprocessing facilities are not readily accessible in most parts of the world.

7.2.2 Oil dispersion

The use of dispersants still generates debate four decades after the Torrey Canyon incident. Some of the same issues predominate (NAS, 2006). The motivations for using dispersants are the same: reduce the possibility of shoreline impact, lessen the impact on birds and mammals, and promote the biodegradation of oil. The issues surrounding dispersants also remain the same: effectiveness, toxicity, the effect of dispersants on biodegradation, and long-term considerations. Recently, the National Academy of Sciences released its study of the use of chemical dispersants in the United States (NAS, 2006).

This report is particularly instructive and provides some useful assessments of the situation. Their assessments and recommendations will be summarized. The prime motivation for using dispersants has been stated to be reduction of the impact of oil on shorelines. To accomplish this reduction, the dispersant application must be highly successful and effectiveness high. As some oil would still come ashore following treatment, there is much discussion on what effectiveness is required to significantly reduce the shoreline impact (Fingas, 2002). A major issue that remains is the actual effectiveness during spills so that these values can be used in estimates and models in the future. A significant physical fact must also be considered, that is, the lifetime of the dispersion. Because not all dispersions are stable and will degrade to surface slick and some residual dispersion, the utility of dispersants in any case should consider this fact. The second motivation for using dispersants is to reduce the impact on birds and mammals on the water surface. The third motivation for using dispersants is to “promote the biodegradation of oil in the water column.” A number of papers state that dispersants do not promote biodegradation, whereas others indicate that dispersants suppress biodegradation. The most recent papers, however, confirm that promotion or suppression is a matter of the surfactant in the dispersant itself and the factors of environmental conditions. Further, there are issues about the biodegradability of the surfactants themselves, and this fact can confound many tests of dispersed oil biodegradation.

7.2.2.1 The basic physics and chemistry of dispersants

Dispersants are oil spill treating agents formulated to disperse oil into water in the form of fine droplets. Typically, the hydrophilic-lipophilic balance (HLB) of dispersants ranges from 9 to 11. Ionic surfactants can be rated using an expanded scale and have HLBs ranging from 25 to 40. Ionic surfactants are strong water-in-oil emulsifiers, very soluble in water, and relatively insoluble in oil, which generally work from the water onto any oil present. Such products disappear rapidly in the water column and are not effective on oil (Fingas, 2010d). Because they are readily available at a reasonable price, however, many ionic surfactants are proposed for use as dispersants. These agents are better classified as surface-washing agents. Some dispersants contain ionic surfactants in small proportions, yielding an average HLB more toward 15 than 10. Studies on the specific effect of this mixing on effectiveness or mode of action have not been done. A typical dispersant

formulation consists of a pair of nonionic surfactants in proportions to yield an average HLB of 10 and some proportion of ionic surfactants. Studies have been done on this mixture, one of which used statistical procedures in an attempt to determine the best mixture of the three ingredients (Brandvik and Daling, 1990).

7.2.2.2 Nature of surfactant interaction with oil

Surfactants interact with oil and oil droplets to yield a temporary lower-energy state given many conditions and circumstances (Birdi, 2003; Hiemenz et al., 1997; Hunter, 2001; Rosen, 2004). The dispersed state is often called an emulsion, and in the oil spill trade it is known as a dispersion to distinguish these oil-in-water emulsions from water-in-oil emulsions (called emulsions and sometimes mousse). Some surfactants will align along slick and droplet interfaces and thus promote the temporary stabilization of droplets in water. This droplet stabilization is enhanced by the presence of surfactants at the interface. There are some measurements of the half-lives of oil and hydrocarbon emulsions in the literature (Fingas and Ka'aihue, 2006). Some of these papers presented data from which the half-life of the particular emulsion could be calculated (Fingas and Ka'aihue, 2006). The half-life data for crude oil emulsions are all very similar with an average half-life of about 12 hours. Resurfacing has been noted during several large tank tests as well.

7.2.2.3 Effectiveness of dispersants

Effectiveness remains a major issue with oil spill dispersants. It is important to recognize that many factors influence dispersant effectiveness, including oil composition, sea energy, state of oil weathering, type of dispersant used and amount applied, temperature, and salinity of the water. The most important of these factors is the composition of the oil, followed closely by sea energy and the amount of dispersant applied (NAS, 2006). It is equally important to recognize that the only thing that really counts is effectiveness on real spills at sea. More emphasis should be put on monitoring this real effectiveness so that there is real information for assessment and modeling. Effectiveness issues are confounded by the simple fact that many tests, regardless of scale, show highly different results depending on how they are constructed and operated.

Dispersant effectiveness is typically defined as the amount of oil that the dispersant puts into the water column compared to the amount of oil that remains on the surface. Many factors influence dispersant effectiveness, including oil composition, sea energy, state of oil weathering, type of dispersant used and the amount applied, temperature, and salinity of the water. The most important of these is the composition of the oil, followed closely by sea energy and the amount of dispersant applied. One of the major confusions that persist is the relationship of effectiveness to viscosity. There is a certain belief that a "viscosity cut-off" of effectiveness for dispersants exists (Fingas, 2008). In fact, certain components of oil, such as resins, asphaltenes, and larger aromatics or waxes, are barely dispersible, if at all. Oils that are made up primarily of these components will disperse poorly

when dispersants are applied. On the other hand, oils that contain mostly saturates, such as diesel fuel, will readily disperse both naturally and when dispersants are added. The additional amount of diesel dispersed when dispersants are used compared to the amount that would disperse naturally depends primarily on the amount of sea energy present. In general, less sea energy implies that a higher dose of dispersant is needed to yield the same degree of dispersion as when the sea energy is high. This should not be attributed to viscosity alone, but primarily to oil composition. Oils that typically contain a larger amount of resins, asphaltenes, and other heavier components are typically more viscous and less dispersible.

Viscosity, however, does not track composition very well and thus is only an indicator of dispersibility. A “viscosity cut-off” does not exist. While it is easier to measure the effectiveness of dispersants in the laboratory than in the field, laboratory tests may not be representative of actual conditions. Important factors that influence effectiveness, such as sea energy and salinity, may not be accurately reflected in laboratory tests. Results obtained from laboratory testing should therefore be viewed as representative only and not necessarily reflecting what would take place in actual conditions. When testing dispersant effectiveness in the field, it is very difficult to measure the concentration of oil in the water column over large areas and at frequent enough time periods. It is also difficult to determine how much oil is left on the water surface as there are no methods available for measuring the thickness of an oil slick and the oil at the subsurface often moves differently than an oil slick on the surface. Any field measurement at this time is best viewed as an estimate. The NAS committee on dispersants reviewed effectiveness testing (NAS, 2008).

It noted that as the physical scale of the effectiveness increases, the cost and realism increase, but the degree to which factors that affect dispersion can be controlled and the ability to quantitatively measure effectiveness decrease. The committee also states that when modeling or prediction is carried out, viscosity is an insufficient predictor of dispersion efficiency. The chemical composition of oil is important, and several factors of composition have been shown to correlate well with dispersant effectiveness. Two other factors relating to dispersant effectiveness are the dispersant-to-oil ratio and the oil-to-water ratio, but the most important factor may be the energy applied, energy dissipation rate, or mixing energy. In reviewing testing, the NAS committee notes that several important principles of experimental design are often ignored, including systematic errors that affect the outcome in one direction and random errors. Common systematic errors in dispersant effectiveness measurement included ignoring the evaporation of volatile compounds, poor analytical methods, and incomplete recovery of floating oil. These three errors, as an example given in the NAS report, introduce a positive bias in the estimates of dispersant effectiveness.

7.2.2.4 Toxicity of dispersants

The results of dispersant toxicity testing are similar to those found in previous years, namely, that dispersants vary in their toxicity to various species. However, dispersant toxicity is less than the toxicity of dispersed oil, by whatever tests. In recent toxicity studies of dispersed oil, most researchers found that chemically dispersed oil was more toxic than physically dispersed oil. About half of these researchers found that the cause for this difference was the increased PAHs (typically about 5 to 10 times) in the water column. Others noted the increased amount of total oil in the water column. Some researchers observed damage to fish gills caused by the increased amount of droplets. Few researchers found that chemically dispersed oil was roughly equivalent to physically dispersed oil.

The reasons for the change in findings in recent years might be attributed to better analytical techniques, both biological and chemical, as well as the use of newer tests. The increase in the toxicity of chemically dispersed oil can be attributed to the increase (~5 times) in PAHs in the water column as a result of dispersant action; the large increase in number of droplets, conveying more oil into the water column; the detected action of droplets on fish gills; and the increased partitioning of more toxic oil components from surface or sediment into the water column. Some studies depart from the traditional lethal aquatic toxicity assay, and some focus on the longer-term effects of short-term exposures. There certainly is a need for more of these types of studies. There is also a need to shift from the traditional lethal assays to some of the newer tests for genotoxicity, endocrinedisruption, and similar tests (Fingas, 2010d).

7.2.2.5 Biodegradation of oil treated by dispersants

Of the recent studies noted, most researchers focused on inhibition of oil biodegradation by dispersants, and some found that biodegradation rates were about the same. No researcher in recent times has found enhanced biodegradation as a result of dispersant use. The NAS committee notes in commenting on some of the old studies that overall one might consider the experimental systems used to investigate biodegradation to be inappropriate for representing the environment because they applied high mixing energy in an enclosed, nutrient sufficient environment and allowed sufficient time for microbial growth. Microbial growth on open ocean slicks is likely to be nutrient limited and may be slow relative to other fate processes, many of which are resistant to biodegradation. The NAS also suggested that the most toxic components of the oil, the biodegradation of PAHs, has never been shown to be stimulated by dispersants (NAS, 2008). The NAS study concludes that only PAH mineralization can be equated with toxicity reduction; stimulation of alkane biodegradation would not be meaningful in the overall toxicity of oil spills.

7.2.3 Solidification

The use of solidifiers was never widespread from the 1960s, when the concept started. Solidifiers are used to recover oil from smaller areas quickly, to prevent the spread of slicks, to recover thin sheens, and to protect areas and wildlife on a rapid basis. The issues surrounding solidifiers also remain the same: their effectiveness, problems involved in mixing the solidifier with the oil, long-term considerations, and possible toxicity. The most important issue of all is that solidifying the oil precludes the use of most other countermeasures. It is an important point to recognize that most other countermeasures, especially booms and skimmers, are designed to recover liquid oil. Oil weathering and oil becoming more viscous and even solid are major problems in the oil spill business. So unless solidified oil can be recovered easily and quickly, solidification will compound the oil spill problem. This, and other factors, may restrict the use of solidifiers to small, thin, and nearshore spills. This limits the widespread use of the products. The prime motivation for using solidifiers is to reduce the spread of oil and protect wildlife and receptor areas. To accomplish this objective, the solidifier application must be highly successful and its effectiveness high. Furthermore, the recovery of the solidified oil must occur rapidly and efficiently before the oil leaves the immediate vicinity. The second motivation for using solidifiers is to reduce the impact on birds and mammals on the water surface. No research at all has been carried out on this aspect of treating agent use (Fingas and Fieldhouse, 2010)

7.2.3.1 Types of Solidifiers

There are several different kinds of solidifiers, some of them form chemical bonds, whereas others work only by adsorbing into polymer chains.

The polymer sorbent is currently the most common type of solidifier. This type is sometimes called a super sorbent, but would be best called a polymer sorbent. Strictly speaking, these products are not solidifiers but sorbents. There is no chemical bonding; instead, van der Waals forces-weak attraction forces between molecules-hold the oil between polymer strands. These types of sorbents have the advantages that they are relatively simple, probably of low toxicity, and slower to react and thus mix better-given a similar density to oil. Furthermore, these products do not link to other materials such as booms, docks, organic material, or stone. The disadvantages of these types of solidifiers are that they are more like sorbents and oil can be released from these products, especially under some pressure.

Cross-linking agents are chemical products that chemically form bonds between two hydrocarbons to solidify the oil. The reaction is a chemical one and typically can release a small amount of heat or absorb that amount of heat depending on the chemical used. The advantages of cross-linking agents are that the final product is truly solidified (if mixed before the product reacts completely). If fully solidified, the product leaches little oil and forms a durable mat that is easy to recover. The disadvantages of this technology is that it is difficult to get complete solidification, especially of a thicker slick as the product is reactive and reacts with

the first hydrocarbon with which it comes into contact. Cross-linking agents also have the disadvantage of linking with other hydrocarbons such as those in containment booms, docks, and organic matter.

The last type of agent combines a polymeric sorbent with a cross-linking agent. Often the cross-linking agent is attached to a polymer end. The purpose of this combination is to gain the advantages of both types of agent. Often the cross-linking agent is attached to a polymer end. The purpose of this combination is to gain the advantages of both types of agent. This type of solidifier agent has two chief advantages: the product mixes with oil better than cross-linking agent alone, and solidification, if achieved, is better than for polymeric sorbents alone. The disadvantages of this type of agent are that generally it has two components that must be mixed immediately before application and that solidification may be difficult to achieve because the product may form a crust with the oil on the top. This type of agent may also adhere to booms, docks, and other carbon-containing materials (Fingas and fieldhouse, 2010).

7.2.3.2 Effectiveness of solidifiers

Solidifier effectiveness is defined as the amount of agent that is required to solidify oil under standard conditions. Many factors may influence solidifier effectiveness, including oil composition, sea energy, state of oil weathering, type of solidifier used, and the amount applied. The most important of these factors is the composition of the oil, but there is very little data on testing with these factors. Although it is easier to measure the effectiveness of solidifiers in the laboratory than in the field, laboratory tests may not be representative of actual conditions. Important factors that influence effectiveness, such as sea energy and mixing, may not be accurately reflected in laboratory tests. Results obtained from laboratory testing should therefore be viewed as representative only and not necessarily reflecting what would take place in actual conditions. However, laboratory testing is useful in establishing chemical and physical relationships, and phenomena (Fingas and fieldhouse, 2010).

7.2.3.3 Toxicity of solidifiers

A standard aquatic toxicity test is to measure the acute toxicity to a standard species such as the rainbow trout. The LC50 of a substance is the "Lethal Concentration to 50% of a test population," usually given in mg/L, which is approximately equivalent to parts per million. The specification is also given with a time period, which is often 96 hours for larger test organisms such as fish. The smaller the LC50 number, the higher the toxicity of the product. The aquatic toxicity of solidifiers has always been low (LC50<<1000) or not measurable as the products are not water soluble (Fingas and fieldhouse, 2010).

7.2.4 Shoreline surface washing

Surface-washing agents (SWAs) or beach cleaners are formulations of surfactants designed to remove oil from solid surfaces such as shorelines. In some countries they are also used on solid surfaces such as roads. Since they are intended to remove oil rather than to disperse it, SWAs contain surfactants with higher hydrophilic-lipophilic balance (HLB) than those in dispersants. Most SWAs are formulated not to disperse oil into the water column, but to release oil from the surface where it floats. Higher water flushing energy will typically result in some dispersion. SWAs are a recent phenomenon. Agents have been classified as SWAs rather than dispersants in the past 20 years, with most of the newer products promoted after the Exxon Valdez spill in 1989. Before that, dispersants were assessed on shorelines, with mixed results (Fingas, 2001b; Morris and Thomas, 1987) In the oil spill industry, the new specially designed products may still be called dispersants by some. As with dispersants, effectiveness and toxicity are the main issues with SWAs, although the level of concern is not as great. There are several reasons for this. First, SWAs have not been used on a large scale anywhere in the world. Unlike dispersants, they are not a universally applicable agent, but are used in specific cases of supra-tidal or intertidal oiling. Second, no adverse incidents have been documented using SWAs, such as the killing of aquatic life when dispersants were used after the Torrey Canyon spill (Etkin, 1998). Finally, many SWAs can be relatively effective and much less toxic than dispersants. Removing oil from a surface appears to be easier than dispersing it from the sea surface. Furthermore, some of the surfactants used in SWAs have far less aquatic toxicity than those used for dispersants. There is some concern about whether SWAs can result in appreciable amounts of dispersed oil. Some products currently listed as surface-washing agents do disperse the oil when exposed to moderate agitation or sea energies. Tests of products at high-sea energies show that they do disperse the oil to a degree. If this occurs, the situation can be similar to that with dispersants (Fieldhouse, 2008). At this time, the only product approved by Environment Canada as an SWA is Corexit 9580 from Nalco (Environment Canada Standard List of Approved Treating Agents), the U.S. Environmental Protection Agency (EPA) has approved 30 agents.

7.3 Biological countermeasures

7.3.1 Bioremediation

Crude oils, composed mostly of diverse aliphatic and aromatic hydrocarbons, regularly escape into the environment from underground reservoirs. Because petroleum hydrocarbons occur naturally in all marine environments, there has been time for numerous diverse microorganisms to evolve the capability of utilizing hydrocarbons as sources of carbon and energy for growth. Oil-degrading microorganisms are ubiquitous, but may only be a small proportion of the pre-spill microbial community. There are hundreds of species of bacteria, archaea, and fungi

that can degrade petroleum. Most petroleum hydrocarbons are biodegradable under aerobic conditions; though a few compounds found in crude oils, for example, resins, hopanes, polar molecules, and asphaltenes, have practically imperceptible biodegradation rates.

Lighter crudes, such as the oil released from the BP Deepwater Horizon spill, contain a higher proportion of simpler lower molecular weight hydrocarbons that are more readily biodegraded than heavy crudes, such as the oil released from the Exxon Valdez. The polycyclic aromatic hydrocarbons (PAHs) are a minor constituent of crude oils; however, they are among the most toxic to plants and animals. Bacteria can convert PAHs completely to biomass, CO₂, and H₂O, but they usually require the initial insertion of O₂ via dioxygenase enzymes. Anaerobic degradation of petroleum hydrocarbons can also occur albeit at a much slower rates. Petroleum hydrocarbons can be biodegraded at temperatures below 0°C to more than 80°C. Microorganisms require elements other than carbon for growth.

The concentrations of these elements in marine environments—primarily nitrates (NO₃⁻), phosphates (PO₄³⁻), and iron (Fe)—can limit rates of oil biodegradation. Having an adequate supply of these rate limiting nutrients when large quantities of hydrocarbons are released into the marine environment is critical for controlling the rates of biodegradation and hence the persistence of potentially harmful environmental impacts.

Bioremediation, which was used extensively in the Exxon Valdez spill, involved adding fertilizers containing nitrogen (N) nutrients to speed up the rates of oil biodegradation. Most petroleum hydrocarbons are highly insoluble in water. Hydrocarbon biodegradation takes place at the hydrocarbon water interface. Thus the surface area to volume ratio of the oil ~~can~~ ~~significantly~~ ~~impact~~ the biodegradation rate. Dispersants, such as Corexit 9500, which was used during the BP Deepwater Horizon spill, increase the available surface area and, thus, potentially increase the rates of biodegradation (Atlas and Hazen, 2011).

7.3.1.1 Efficacy and safety of bioremediation

Because of the difficulty of achieving sufficient oil removal by physical washing and collection, especially for oil that had moved into the subsurface, bioremediation became a prime candidate for continuing treatment of the shoreline. Bioremediation had been independently identified as a potential emerging technology within weeks of the spill. Both the EPA and Exxon quickly began laboratory tests, which were soon followed by field trials to determine whether fertilizer addition would enhance the rates of oil biodegradation (Bragg et al., 1992; Pitchard and Costa, 1991). The focus of these tests was on the changes in oil composition due to microbial degradation, that is, the emphasis was placed on changes in oil chemistry rather than on the microbes themselves. Field tests showed that fertilizer addition enhanced rates of biodegradation by the indigenous hydrocarbon-degrading microorganisms. Rates of biodegradation in bioremediation studies resulted in total petroleum-hydrocarbon losses as high as 1.2% per day. The

rate of biodegradation slowed down once the more readily degradable components were depleted even when fertilizer was reapplied. The rate of oil degradation was a function of the ratio of N/biodegradable oil and time. Both polynuclear aromatic and aliphatic compounds in the oil were extensively biodegraded. Bioremediation increased the rate of polycyclic aromatic-hydrocarbon (PAH) degradation in relatively undegraded oil by a factor of 2, and of alkanes by 5 relative to the controls. O₂ dissolved in water was not rate-limiting—there was up to a 30% decline in O₂ concentration in pore water following fertilizer application, but hypoxia was not detected (Atlas and Hazen, 2011).

7.3.1.2 Full-scale application of bioremediation

Based upon the laboratory and field demonstration test results, the federal on-scene-coordinator approved the use of bioremediation employing fertilizer application for use on oiled shorelines of Prince William Sound. Several fertilizer formulations were considered; key considerations were retention in the oiled shorelines long enough to support biodegradation, availability in quantities needed to treat these shorelines, and lack of toxicity. Two fertilizers were selected for full scale bioremediation: the oleophilic fertilizer Inipol EAP22, manufactured by Elf Aquitaine of France; and the slow release fertilizer Customblen 28-8-0, manufactured by Sierra Chemicals of California. Customblen was spread at a rate of 27.8 g/m². Inipol was then applied at a rate of 300 g/m². These rates ensured a safe margin below concentrations of ammonium (NH₄⁺) or NO₃⁻ ions considered toxic by EPA water quality standards. Results for sediment samples collected and analyzed in 1989 indicated that about 25-30% of the total hydrocarbon in the oil originally stranded on Prince William Sound shorelines had been lost within the first days to weeks after the spill. The natural background rates of oil biodegradation initially were estimated at 1.3 g oil/kg sediment/yr for surface oil and 0.8 g oil/kg sediment/yr for subsurface oil. Concentrations of naturally occurring oil-degrading bacteria during this period were (1-5) × 10³ cells/mL of seawater or about 1-10% of the total heterotrophic bacterial population. In late 1989 oil-degrading bacterial populations had greatly increased to about 1 × 10⁵ cells/mL and made up about 40% of the heterotrophic population in oiled shoreline pore waters. Large-scale applications of fertilizer during summer 1990 included over 1400 individual site treatments at 378 shorelines.

7.3.2 Natural attenuation

To select the most appropriate remedial response and to focus enhanced remediation efforts on the highest priority sites, it is important to understand natural attenuation and be able to determine the extent to which it is occurring at individual sites. If natural processes are likely to prevent migration of significant levels of oil spill, then a monitoring only plan may be sufficient for the site (McAllister and Chiang, 2007)

Cozzarelli et al., (2001) conducted a 16-year study on the progression of natural attenuation processes at a crude oil spill site. Their results showed that the extent of contaminant migration and compound-specific behavior have changed as redox reactions, most notably iron reduction, have progressed over time. The small-scale data show clearly that the hydrocarbon plume is growing slowly as sediment iron oxides are depleted. Contaminants, such as ortho-xylene that appeared not to be moving down-gradient from the oil on the basis of observation well data, are migrating in thin layers as the aquifer evolves to methanogenic conditions. However, the plume-scale observation well data show that the downgradient extent of the Fe²⁺ and BTEX plume did not change between 1992 and 1995. Instead, depletion of the unstable Fe (III) oxides near the subsurface crude-oil source has caused the maximum dissolved iron concentration zone within the plume to spread at a rate of approximately 3m/year. The zone of maximum concentrations of benzene, toluene, ethylbenzene and xylene (BTEX) has also spread within the anoxic plume. In monitoring the remediation of hydrocarbon contaminated ground water by natural attenuation, subtle concentration changes in observation well data from the anoxic zone may be diagnostic of depletion of the intrinsic electron-accepting capacity of the aquifer. Recognition of these subtle patterns may allow early prediction of growth of the hydrocarbon plume.

7.4 Comparison of existing technologies

The comparison of the above discussed methods was listed in **Table 7.5**.

7.6 Oil spill response in NL

7.6.1 Response framework in NL

In the case of any spill, the offshore operator is in charge and must activate its response plan (René Grenier, 2010). Operators have a tiered response program, with each tier providing equipment and resources appropriate to the size of the spill. Small, Tier One, spills can be dealt with immediately by the operator itself on site, while others would require further outside assistance, in addition to the operator's on-site resources and assets. Meanwhile, the responsible government agency, C-NLOPB acts in a monitoring role. It does, however, have the authority to supersede the operator if it determines that the response is inadequate. This situation was described by the CEO of the C-NSOPB in testimony before the committee: Depending on the significance of the spill, our role would range from monitoring the operator's activities to giving direction to the operator or in the most severe or extreme cases to managing the spill response (Stuart Pinks, 2010). The tiered response system forms a cascade. As such, a Tier Two response will incorporate on site equipment and resources from a Tier One response. A Tier Three response will bring additional resources on top of the assets and personnel mobilized during Tier Two.

If the oil spill is of a greater magnitude and cannot be immediately contained by equipment on site, offshore operators mobilize a Tier Two response. As all Atlantic offshore oil and gas projects have a contract with ECRC to provide assistance with oil spill cleanup responses, this organization is brought in at this stage.

A severe oil spill or simultaneous small spills that exceed regional resource capacity trigger the Tier Three response plan. This is the ultimate step in the tiered response and therefore signifies a critical situation, such as a blowout. All available resources are pooled to assist in the containment. Offshore operators such as ExxonMobil are international corporations that can bring in equipment and expertise from abroad (Angus and Mitechell, 2010).

Table 7.5 Oil spill response technologies overview (excerpted from Walker et al., 2003)

Response technology	Mechanisms of action	When to use	Target Areas	Characteristics of effective products	Limiting factors	Waste generation	Oil types	Impacts to sensitive resources
Traditional Mechanical/Manual countermeasures e.g., boom, skimmers, shovels	Mechanical containment and removal of oil from the water surface (i.e., booms, skimmers) Manual removal of Oil from shorelines and land (i.e., loaders, shovels)	Typically first line of defense during a response Spills on water, on land or hard surface	varies	Contains, removes spilled product	Weather conditions Site accessibility	Varies by method	Varies	May cause stress/impacts on sensitive resources due to presence of response personnel; May be invasive/destructive to land habitats
Sorbents	Absorption (uptake into the sorbent material) and adsorption (coating of the sorbent surface)	Spill on land or hard surface To create a physical barrier around the leading edge; To immobilize small amounts of free oil that cannot be removed from inaccessible sites	Shorelines at the water/land interface Hard surfaces with recoverable oil	Low application rate; Applied with available equipment; Easy to recover; oil does not drip out	Access to deploy and retrieve products	Concern if only lightly oiled; May be burned or recycled	Light to heavy oils; Not effective on viscous oils	May cause smothering of benthic/attached wildlife if not recovered; May be ingested by wildlife if not recovered
Bioremediation Agents	Accelerate rate of degradation by adding nutrients, microbes, and/or surfactants; Surfactants break oil into droplets to increase the surface area	After removal of gross contamination; When further oil removal will be destructive, or ineffective; When nutrients are limiting natural degradation rates	Any size spill in area where other cleanup methods would be destructive or ineffective As a polishing tool for any size spill	Treated samples show oil degradation greater than control samples in lab tests; Key factors are site-specific	Nutrient availability; temperature (>60°F); pH 7-8.5 Moisture Surface area of oil; Rate of nutrient wash out, especially for intertidal use	Can significantly reduce volume of oily wastes, if effective	Less effective on heavy refined products; Not for gasoline, which will evaporated	None expected; Unionized ammonia can be toxic to aquatic life in low concentrations; Dissolved O ₂ levels may be affected
Natural Attenuation	Leave oil in situ and do not treat or recover	Access to spill site is limited or other methods will not provide value	In areas where other response strategies result in more harm than value	Must have monitoring plan in place to assess effectiveness	Resources present in the affected area	Not applicable	Varies	No additional impacts other than the effect of the oil alone

Table 7.5 Oil spill response technologies overview cont'd (excerpted from Walker et al., 2003)

Response technology	Mechanisms of action	When to use	Target Areas	Characteristics of effective products	Limiting factors	Waste generation	Oil types	Impacts to sensitive resources
Dispersants	<ul style="list-style-type: none"> Break oil into small droplets that mix into the water and do not reflect 	<ul style="list-style-type: none"> When dispersing the oil will cause less impact than slicks that strand onshore or affect surface water resources 	<ul style="list-style-type: none"> Open water 	<ul style="list-style-type: none"> Products have to pass a dispersant effectiveness test to be listed 	<ul style="list-style-type: none"> Low effectiveness with heavy, weathered, or emulsified oils 	<ul style="list-style-type: none"> Can significantly reduce volume of oil wastes, if effective 	<ul style="list-style-type: none"> Any oil with a viscosity less than 20,000-40,000 cP 	<ul style="list-style-type: none"> Consult with Resource Trustees on environmental issues.
Emulsion treating agents	<ul style="list-style-type: none"> Composed of surfactants that prevent the formation of or break, water-in-oil emulsions 	<ul style="list-style-type: none"> To separate water from oil, increasing oil storage capacity; To increase effectiveness of dispersants & <i>in situ</i> burning 	<ul style="list-style-type: none"> varies 	<ul style="list-style-type: none"> Low application rate; rapid oil/water separation (within 1-2 hours) 	<ul style="list-style-type: none"> Not possible to predict effectiveness for an oil, but there is a standard test; will wash out, so emulsion can reform 	<ul style="list-style-type: none"> Will reduce the amount of oily material for handling and disposal 	<ul style="list-style-type: none"> Light to heavy oils 	<ul style="list-style-type: none"> Consult with Resource Trustees on environmental issues.
<i>In situ</i> Burning	<ul style="list-style-type: none"> Remove free oil or oily debris from water surface or land surface by burning oil in place 	<ul style="list-style-type: none"> To quickly remove oil to prevent its spread to sensitive areas or over large areas; To reduce generation of oily waste When access is limited When oil recovery is limited 	<ul style="list-style-type: none"> Remote areas on land or water where oil is thick enough for an effective burn 	<ul style="list-style-type: none"> Removal of free oil from the water surface or land surface Need oil thickness that will sustain burn 	<ul style="list-style-type: none"> Heavy, weathered or emulsified oils may not ignite, even with accelerants Wind speed and direction could affect smoke plume Air Quality monitoring needs to be done 	<ul style="list-style-type: none"> Burn residue can be formed; residue may sink, a semi-solid, tar-like layer may need to be recovered Erosion in burned on-land areas may occur if burn kills plants in area 	<ul style="list-style-type: none"> Fresh volatile crudes burn best; most oil types will burn Oil thickness required for min ignitable slicks increases with oil weathering, & heavy-component content 	<ul style="list-style-type: none"> Consult with Resource Trustees on environmental issues.
Fire-Fighting Foams	<ul style="list-style-type: none"> Act as a barrier between the fuel and fire; suppress vapors; cool the liquid 	<ul style="list-style-type: none"> To prevent ignition or re-ignition of spilled oil 		<ul style="list-style-type: none"> Forms stable heat-resistant foam blanket; applied with standard equipment 	<ul style="list-style-type: none"> Polar solvents can destroy foam; water currents can break foam blanket 	<ul style="list-style-type: none"> Not applicable 	<ul style="list-style-type: none"> Any type of oil that can burn 	<ul style="list-style-type: none"> Consult with Resource Trustees on environmental issues.

Table 7.5 Oil spill response technologies overview cont'd (excerpted from Walker et al., 2003)

Response technology	Mechanisms of action	When to use	Target Areas	Characteristics of effective products	Limiting factors	Waste generation	Oil types	Impacts to sensitive resources
Solidifiers	<ul style="list-style-type: none"> Most products are polymers that physically or chemically bond with the oil, turning it into a coherent mass 	<ul style="list-style-type: none"> To immobilize oil, preventing further spread or penetration; apply to edge to form a temporary barrier; to reduce vapors 		<ul style="list-style-type: none"> Low application rate (10-25% by weight); cure time of a few hours; forms a cohesive mass; easily applied using available equipment 	<ul style="list-style-type: none"> Not effective with viscous oils where mixing is difficult wave will form clumps not a mass; must be able to recover the solidified oil; 	<ul style="list-style-type: none"> Most products have minimal increase in volume; most are not reversible, so oil must be disposed of or burned 	<ul style="list-style-type: none"> Light to heavy oils; not effective on viscous oils 	<ul style="list-style-type: none"> Consult with Resource Trustees on environmental issues.
Surface washing agents	<ul style="list-style-type: none"> Contain solvents, surfactants, and additives to clean oiled surfaces; can "lift and disperse" like detergents or "lift and float" to allow recovery 	<ul style="list-style-type: none"> To increase oil removal, often at lower temperature and pressure; to flush oil trapped in inaccessible areas; for vapor suppression in sewers 	<ul style="list-style-type: none"> Oiled, hard-surface shorelines Where oil has weathered and is difficult to remove; When flushing with containment is possible; Volatile fuel spills in enclosed environments 	<ul style="list-style-type: none"> Soak time less than 1 hr; single application; minimum scrubbing, esp. for sensitive substrate 	<ul style="list-style-type: none"> Applied on land only where washwaters can be collected for treatment; use "lift and float" products on shorelines to allow oil recovery rather than allowing dispersion into water body 	<ul style="list-style-type: none"> Can produce large volumes of washwater which needs collection and treatment 	<ul style="list-style-type: none"> All oil types 	<ul style="list-style-type: none"> Consult with Resource Trustees on environmental issues.

7.6.2 Challenges of oil spill responses in NL

One of the key factors that impacts the success of a spill-response is the weather and sea state at the time of the response. For example, oil-spill containment booms are designed and built in different sizes and strengths for different wave environments. Offshore-type containment booms are designed and built to accepted standards (e.g., ASTM- F1523) and will function effectively to hold oil when the relative velocity between the boom and the water does not exceed 0.4 m/s ($\frac{3}{4}$ knot) and the waves do not exceed about 2 metres in height. Visibility is also crucial to spill-response operations. Effective spill-response is not possible with the present state of the art in offshore oil-spill response, in conditions where the visibility is < 1 kilometre and at night. The presence of ice will also affect a spill-response operation, necessitating a change in strategies and techniques.

7.6.2.1 Waves

Wave information from the MSC50 data set (an Environment Canada hindcast database of hourly winds and waves off Eastern Canada covering the years 1954 to 2005-Swaillet al. 2006) was analyzed to identify the occurrence of waves suitable for offshore containment booming operations. The locations in the database selected to represent the wave climate of the different areas of offshore oil and gas activity were chosen based on proximity to the region from which visibility statistics were generated in the corresponding C-NLOPB Strategic Environmental Assessment (SEA) for the specific area. Figure 5.9 shows the percentage of the time that wave conditions favorable for spill-containment operations occurred in the various areas of offshore Newfoundland and Labrador. It is clear that in most areas, wave conditions favorable for spill containment will occur for more than half the time from late spring until early fall, with the best conditions for containment occurring in July for all the areas examined. In winter, the percentage of time that favorable conditions exist, ranges from 2% to 3% in the Jeanne D'Arc and Orphan Basin areas to nearly 37%, with the more sheltered areas (Sydney Basin and west Newfoundland) having, by far, the most favourable conditions for containment operations in winter (Turner, 2010)

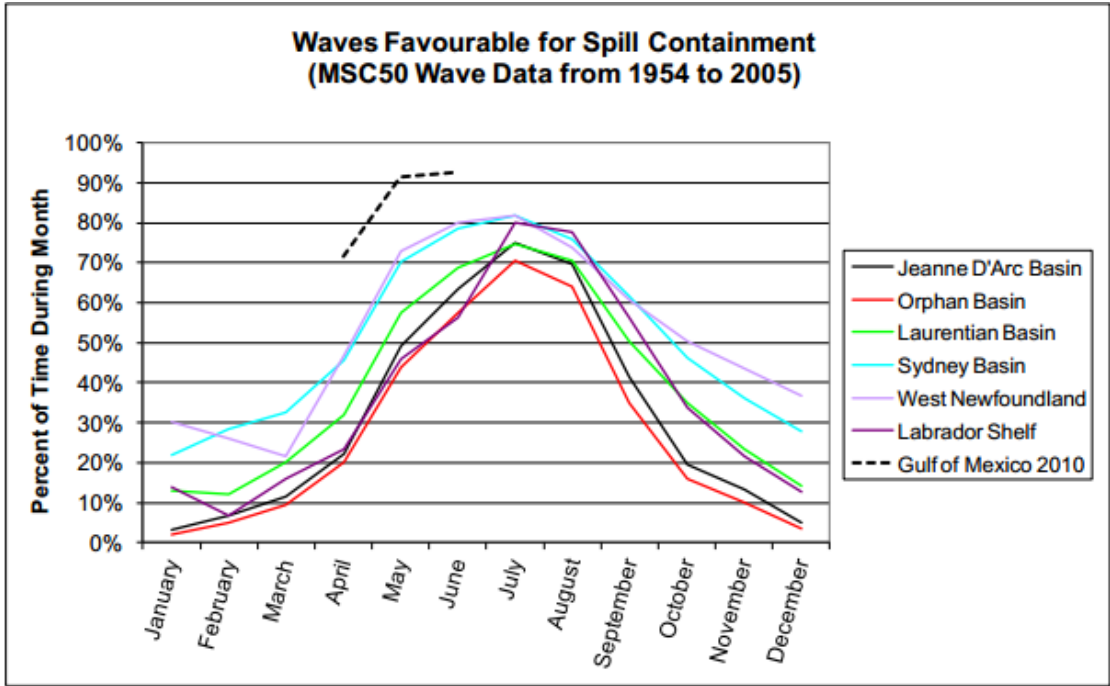


Figure 7.9 Wave conditions offshore Newfoundland favourable for spill-containment operations (Swail et al., 2006)

7.6.2.2 Visibility

In conditions where the visibility is restricted to less than 1 kilometre it is impossible to direct response operations from the air and extremely difficult to find and recover oil slicks using vessels, even with state of the art remote sensing techniques. **Figure 7.10** shows the occurrence of these conditions in the various areas, as gleaned from visibility graphs in the various SEAs for each area. There is little change in the occurrence of poor visibility throughout the year in west Newfoundland waters: the monthly values range from 2 to 11%.

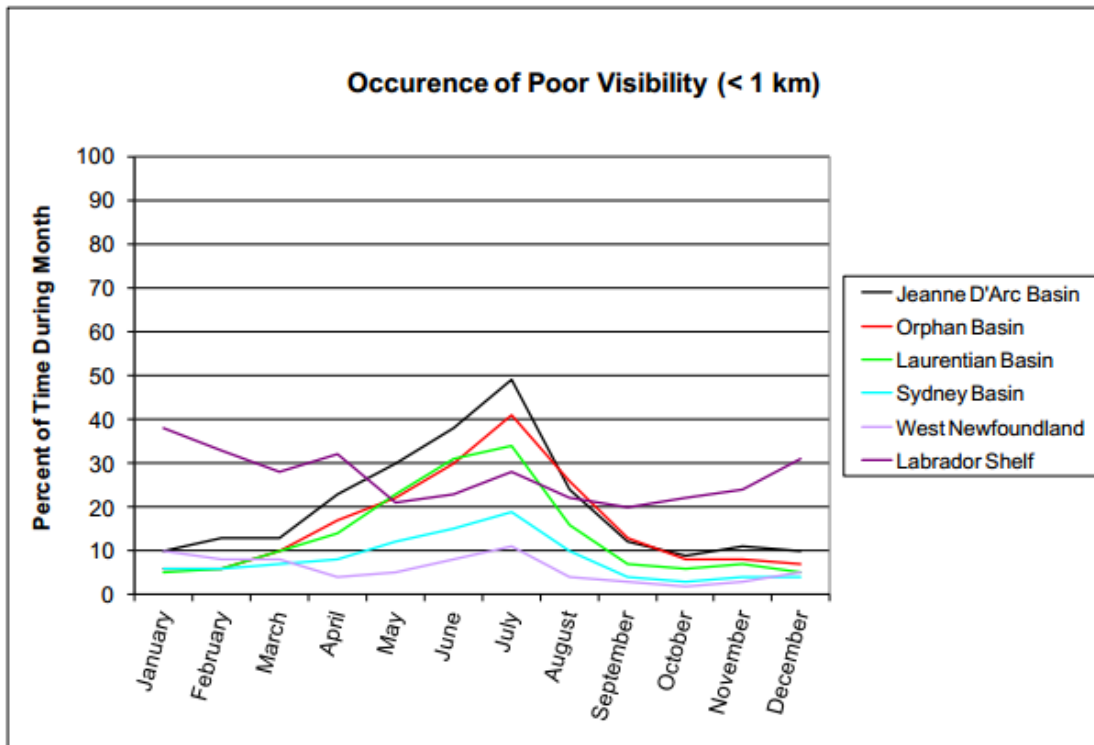


Figure 7.10 Poor visibility conditions offshore NL
(LGL et al., 2010)

7.6.2.3 Daylight

Although it may be possible to recover oil already collected and contained in a boom, spray one last oil slick with dispersants or complete an in-situ burn of oil in a fire boom at dusk, it is not possible with the state of the art to continue offshore oil cleanup operations at night. **Figure 7.11** shows the number of daylight hours calculated for each of the offshore areas. Five of the areas lie close to the same latitude, and the hours of daylight for each vary only slightly. Daylight lasts about 9 hours in December and about 15 hours in June for these five areas. On the Labrador Shelf, daylight lasts about 7 hours in December and 17 in June.

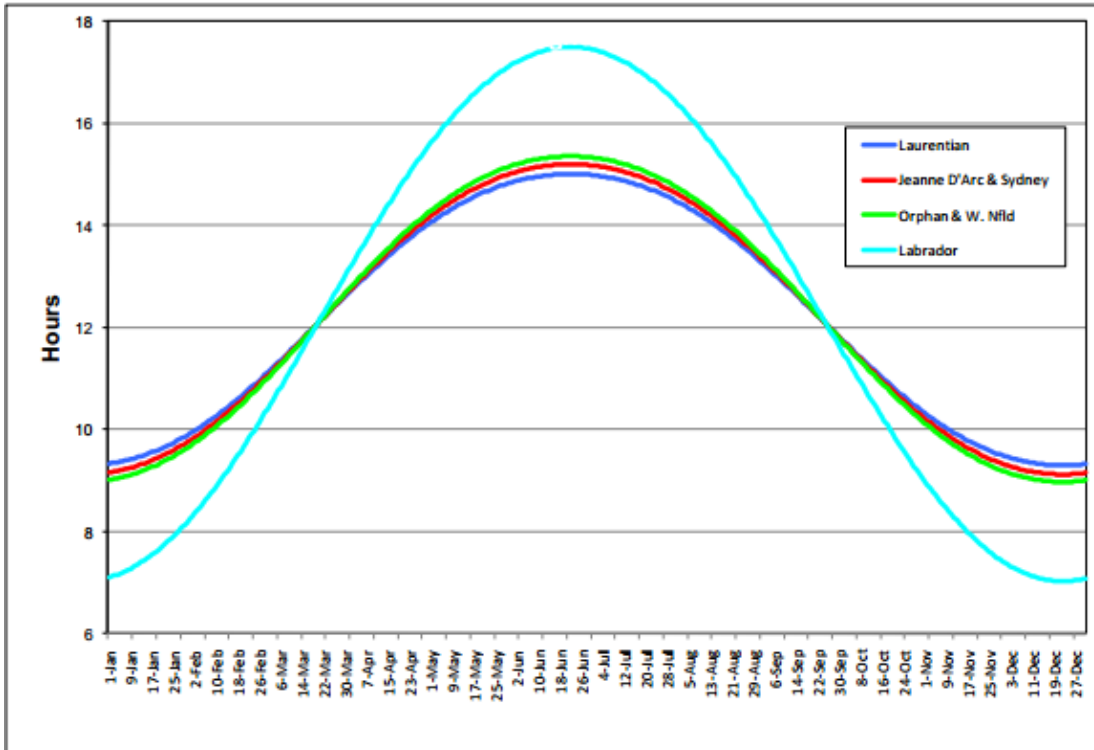


Figure 7.11 Hours of daylight at the various offshore areas (LGL et al., 2010)

7.6.2.4 Fraction of time open-water response is possible

A method to estimate the impact of the weather and seas on the likely effectiveness of offshore countermeasures is to estimate the fraction of the time each month that offshore countermeasures would be possible, considering the time that the waves are favorable, the visibility is acceptable, and the amount of daylight available. The variable calculated by this approach is called F_{TRP} , or the fraction of time response is possible. **Figure 7.12** compares the calculated F_{TRP} for open-water mechanical response (i.e., using offshore containment booms) for the various Newfoundland and Labrador offshore areas over the year. In the Jeanne D'Arc and Orphan Basin areas, the calculated F_{TRP} ranges from 0.01 to 0.03 in winter (i.e., mechanical response could be effective only 1 to 3% of the time) to 0.26 to 0.30 in summer. In the Laurentian Basin area the situation is similar, having F_{TRP} values of about 0.04 in winter and 0.30 to 0.35. In the slightly more protected waters of the Sydney Basin area, the winter values of F_{TRP} range from 0.07 to 0.11 and summer values range from 0.40 to 0.45 (Tuner, 2010).

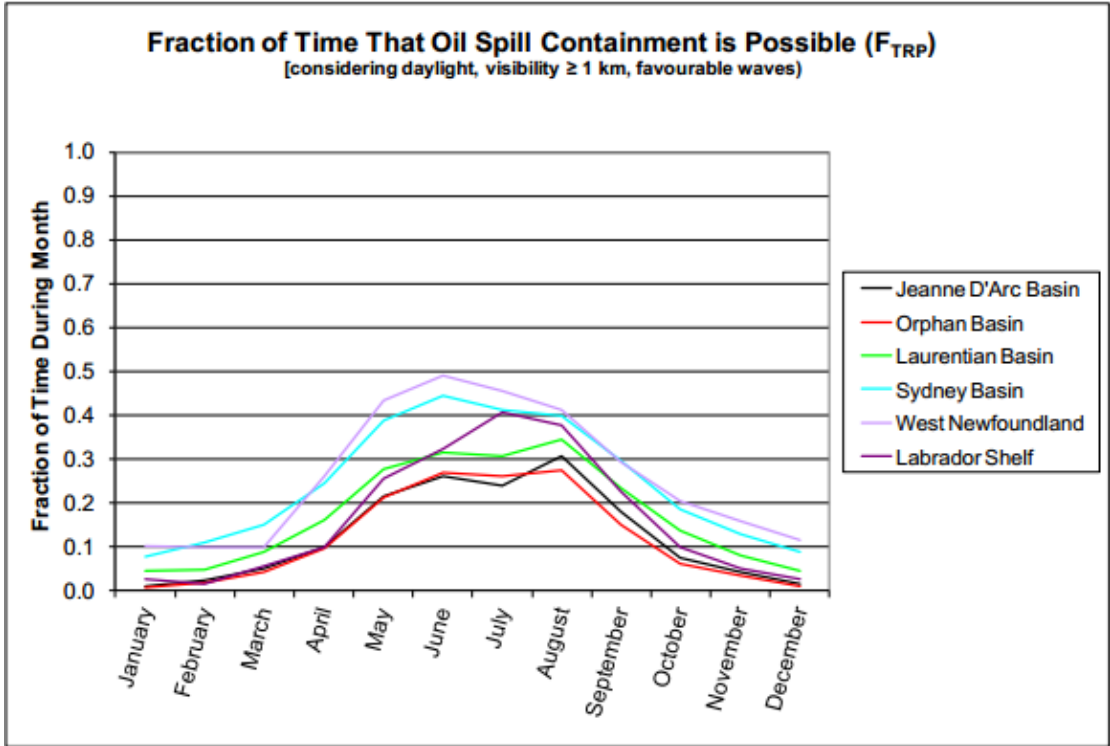


Figure 7.12 Fraction of time during the year that mechanical response is possible (LGL et al., 2010; Swail et al., 2006; Tuner, 2010).

7.6.2.5 Ice

Both the waters of the Labrador Shelf and west Newfoundland can experience considerable amounts of ice during the winter months. Although the presence of ice precludes efficient mechanical recovery techniques, spilled oil can still be removed effectively from ice-covered waters using other techniques, such as in-situ burning, and dispersant application, the latter technique followed by mixing with propeller wash using ice-strengthened vessels. **Figure 7.13** presents the occurrence of ice (50% or greater coverage) at each of the areas. There is a high probability that ice will be present in the Labrador Shelf and west Newfoundland areas in winter.

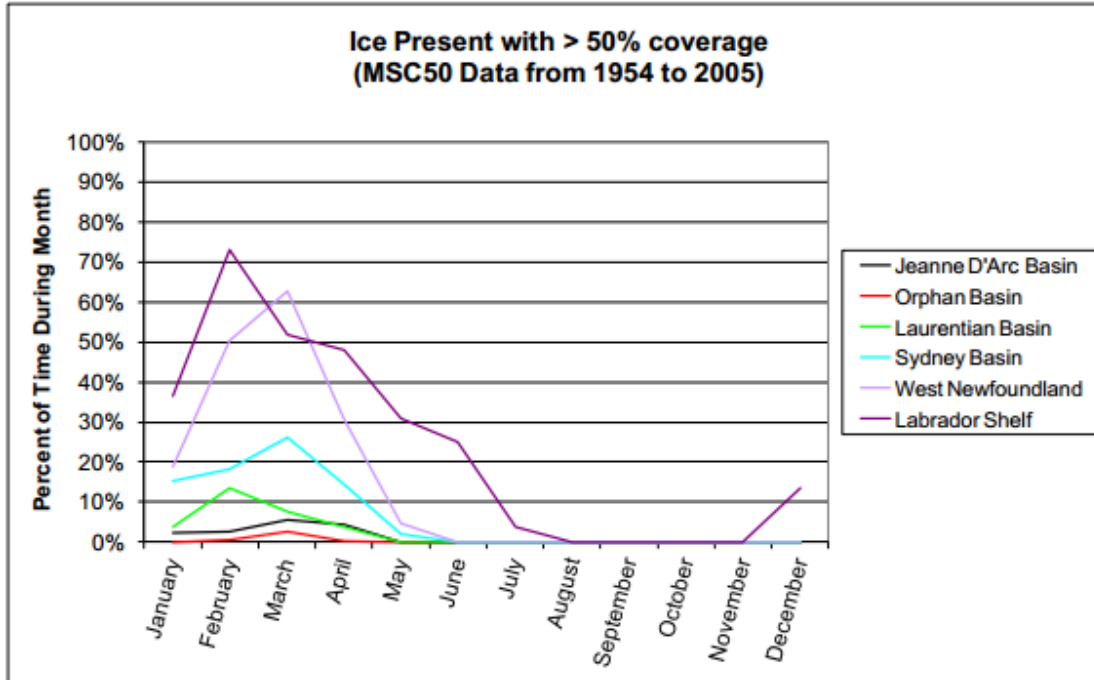


Figure 7.13 Occurrence of ice cover in the offshore areas (LGL et al., 2010).

7.7 Summary

The response strategy of oil spills involves different stages aiming at the minimization of size of the affected area and damage to vulnerable resources. Some common treatment options of the response technologies were reviewed in detail, including physical/mechanical technologies (e.g. booms, skimmer, manual recovery, sorbents), biological technologies (e.g. bioremediation and natural attenuation) and chemical technologies (e.g. dispersants, emulsion treating agents, in situ burning, solidifier and surface washing agents)..

In terms of physical/mechanical responses, booms, skimmers, manual recovery and sorbents have been reviewed including their basic construction/configuration, type, characteristics and performances. Procedures for temporarily storage, separation and disposal of the recovered oil were also tackled. Chemical countermeasures such as in-situ burning, oil dispersion and solidification have been discussed, including their principles, effectiveness, advantages and disadvantages, as well as the toxicity and biodegradability of involved materials (e.g., dispersants and solidifiers). Two biological countermeasures, bioremediation and natural attenuation, have been reviewed. These two countermeasures were not studied in depth as they both required long operational time and cannot act as immediate response techniques.

The above mentioned countermeasures were compared comprehensively in terms of mechanisms, when to use, target areas, characteristic of effective products, limited factors and waste generation in the chapter.

Among the various physical and mechanical countermeasures, booms and skimmers were designed in such a diverse ways, while their recommended employment for certain type and scale of oil spills are not clear enough. These techniques are primarily used as the emergent responding defenses that have limited operational time-window. Therefore, it is important to consider an effective management system to better cooperate these techniques according to the spill situation.

Chemical countermeasures received a lot more attention in this decade as emergent response techniques. However, their effectiveness and toxicity are still of great concern. Studies on these aspects are primarily conducted in a smaller-scale while it is important to understand these issues in larger scale which can reflect their application in real-world cases.

Studies on the biological countermeasures are limited, while these approaches may be more environmentally friendly and cost-effective for the mitigation of oil spills impacts, especially for long-term effects. It is recommended that more studies may address on the scale-up and real-world application of these techniques and their merits to long-term remediation.

CHAPTER 8

OFFSHORE OIL SPILL MODELING AND RESPONSE DECISION SUPPORT

8.1 Early warning of offshore oil spill

8.1.1 Spill imaging and analysis

The source of the oil pollution can be located on the main land or directly at sea. Sea-based sources are discharges coming from ships or offshore platforms. Oil pollution from sea-based sources can be accidental or deliberate. Fortunately, the number of marine accidents and the volume of oil released accidentally are on the decline. On the other side, routine tanker operations can lead still to the release of oily ballast water and tank washing residues. Furthermore, fuel oil sludge, engine room wastes and foul bilge water produced by all type of ships, also end up in the sea. In the last decade maritime transportation has been growing steadily. More ships also increase the potential number of illegal oil discharges. Both oil tankers and other kinds of ships are among the suspected offenders of illegal discharges.

The different tools to detect oil spills and provide early warning messages are vessels, airplanes, and satellites. Vessels, especially if equipped with specialized radars, can detect oil at sea but they can cover a very limited area. The vessel, however, remains necessary in case oil sampling is required. The main systems to monitor sea-based oil pollution are the use of airplanes and satellites equipped with Synthetic Aperture Radar (SAR). SAR is an active microwave sensor, which captures two dimensional images. The brightness of the captured image is a reflection of the properties of the target-surface. The possibility of detecting an oil spill in a SAR image relies on the fact that the oil film decreases the backscattering of the sea surface resulting in a dark formation that contrasts with the brightness of the surrounding spill-free sea. Space borne SAR sensors are extensively used for the detection of oil spills in the marine environment, as they are independent from sun light, they are not affected by cloudiness, they cover large areas and are more cost-effective than air patrolling.

Radar backscatter values from oil spills are very similar to backscatter values from very calm sea areas and other ocean phenomena named "look-alikes" (e.g. currents, eddies). Several studies aiming at oil spill detection have been conducted. The first comprehensive publications on the subject concerned methodologies to distinguish oil spills from look-alikes (Espedal and Wahl, 1999; Fiscella et al., 2000). Solberg et al. (1999) presented an automatic statistical approach while Del Frate et al. (2000) used a neural network classifier. Espedal and Wahl (1999) used wind history information to detect oil spills, Espedal et al. (2000) focused on detection near offshore platforms and Fiscella et al. (2000) used a probabilistic approach for detection and discrimination.

The first reconnaissance study for the Mediterranean Sea using more than 1600 SAR images was given by Pavlakis et al. (2001). The second wave of interest on the subject came some years later, with new techniques and methodologies. De Souza et al. (2006) presented an intelligent system to extract features from oil slicks, Keramitsoglou et al. (2006) an automatic system based on fuzzy logic,

Karathanassi et al.(2006) an object-oriented methodology, Mercier and Girard-Ardhuin (2006) a classification method using kernel expansion and Ramalho - Medeiros (2006) used boosting techniques. Topouzelis et al. (2007) presented an updated study on discrimination using neural networks, Solberg and Brekke (2008) summarized the detection techniques in Northern European waters while Serra-Sogas et al. (2008) were focused in western Canadian waters. Finally, a detailed introduction to oil spill detection by satellite remote sensing is given by Brekke and Solberg (2005).

Long term monitoring using SAR data was firstly performed by Pavlakis *et al.* (1996, 2001) for the Mediterranean basin and Gade and Alpers (1999) for specific areas in Mediterranean Sea. The Joint Research Centre (JRC) continued these initiatives and monitored the European seas for the following years. Bernardini *et al.* (2005) focused on the Adriatic Sea, Ferraro *et al.* (2006) on the French Environmental Zone, Ferraro *et al.* (2007) presented an overview of the existing operational techniques in the Mediterranean Sea, Tarchiet *et al.* (2006) focused on the seas around Italy for the years 1999-2004 and Topouzelis *et al.* (2006) on the Mediterranean basin for the years 1999-2002.

Two main approaches exist for analyzing the oil spill images: the manual approach, where operators are trained to analyze images for detecting oil spills and the semi-automatic or fully automatic approaches, where automatizations are inserted. Any formation on the image which is darker than the surrounding area has a high probability of being an oil spill and needs further examination. Although this process seems to be simple for a human operator, it contains three main difficulties for semi-automated or automated methods. First, fresh oil spills are brighter than older spills. They have a weak backscattering contrast relative to their surroundings and thus cannot be easily discriminated. Second, dark areas can have various contrast values, depending on local sea state, oil spill type, image resolution and incidence angle. Third, look-alike phenomena are presented as dark areas too.

Solberg et al. (1999) proposed a statistical modeling with a rule based approach. The probabilities assigned using Gaussian density function and derived from a signature database of 7,051 dark formations containing 71 oil spills and 6,980 look-alikes. These dark formations were extracted from 84 ERS SAR images, from which 36 did not contain any oil spills. The method correctly classified 94% (67 out of 71) of oil spills and 99% (6,905 out of 6,980) of look-alikes using a leave-one-out approach. In a recent study (2007) an updated version of the method was presented for Radarsat and Envisat images. Their training dataset consisted from 56 Envisat WS ASAR images and 71 Radarsat SAR images while the reported test set consisted of 27 Envisat images containing 37 oil spills and 12110 look-alikes. The method had an accuracy of 78% in oil spill classification (29 out of 37) and of 99% in look-alike classification (12,033 out of 12,110).

A similar statistical classification methodology was presented by Fiscella et al. (2000). They applied a Mahalanobis and a compound probability classifier. Their training set was 80 oil spills and 43 look-alikes and they measured the probability p of dark formations to be oil spill (a priory classification probability). They used

three classification categories: oil spills, uncertain and look-alikes. The percentage of the total data correctly classified for the Mahalanobis classifier with $p > 2/3$ (i.e. three classification categories) was 78% and with $p > 1/2$ (i.e. only oil spills and look-alikes) was 83%. For compound probability classifier with $p > 2/3$ was 79% and with $p > 1/2$ was 82%. The test set contained 21 dark formations of which 11 oil spills, 4 uncertain and 6 look-alikes. Mahalanobis classifier corresponded correctly at 71% of the cases and a compound probability classifier at 76% of the cases.

Nirchio et al. (2005) presented another statistical approach based on multi regression analysis (or Fisher discrimination approach). They used 13 features as inputs and tried to set up a relation between the predictor variables and the dependent variable on a dataset contained 153 verified oil spills and 237 look-alikes. They reported a priori percentage of correct classification higher than 90% on the training dataset. For the testing dataset they used 14 images, in which 31 oil spills were present. Their method detected correctly 23 of them i.e. 74% oil spill detection accuracy.

A different classification methodology was presented by Del Frate et al. (2000). They used neural networks to classify the dark formations. Neural network classifiers are not very popular as they are rather complex and they require specific knowledge on the theory of neural systems. Their complexity relates with decisions on network family, network architecture, on the way the data are introduced during the training and the point where the training should stop. They considered reliable classifiers since they have the ability to learn during training.

Del Frate et al. (2000) applied the Multilayer Perceptron (MLP) network family with a topology of 11 inputs (i.e. the calculated features describing the dark formations), one output and two hidden layers with 8 and 4 neurons respectively. Their data set was 600 ERS images in low resolution from which they extracted 139 dark formations 71 oil spills and 68 look-alikes. Using the leave-one-out approach the method misclassified 18% of the oil spills and 10% of the look-alikes.

Neural networks were used also as classifiers for oil spill detection by Topouzelis et al. (2007). They used a MLP network with topology 10:51:2, i.e. 10 features as inputs, 51 neurons in the hidden layer and 2 output nodes. The topology and the input features were chosen using a genetic algorithm. The genetic algorithm had chosen the selected 10 from a base of 25 inputs and the proper topology after searching 100 generations using 7 bit chromosome. Detailed information regarding the selected topology and the feature selection is given by Stathakis et al. (2006) and Topouzelis et al. (2008). Their dataset consisted of 24 high resolution SAR images containing 159 dark formations, 90 look-alikes and 69 oil spills. They randomly split the available data set into equally sized parts one for training and one for testing. The oil spills accuracy reported on the test data was 91% (detected 31 oil spills out of 34) and the look-alike 87% (detected 39 of out 45).

Another classification methodology, based on fuzzy logic, was implemented by Keramitsoglou et al. (2006) and by Karathanassi et al. (2006). Fuzzy classifiers work with ranges of values, solving problems in a way that more resembles human

logic. The input variables in a fuzzy based methodology are mapped into by sets of membership functions. They require specific knowledge on the theory of fuzzy systems but they considered reliable classifiers since they try to resemble human logic and they can be reproduced easily. They estimated the probability of a dark formation to be oil spill using an artificial intelligence fuzzy modeling system. Their method developed using 9 ERS-1/2 low resolution images and was tested on 26 images. Five features used as inputs, in general different from those used before. The method responded perfectly on 23 of 26 images, resulting in an overall performance of 88%. They also proposed a classification method based on fuzzy classification rules. Their methodology was based on an object oriented image classification technique, in which on the first step homogeneous image objects are extracted in any chosen resolution and in later stage are classified by means of fuzzy logic. They used 13 features as inputs on 12 ERS-1/2 high resolution images. They reported 99% overall performance.

Comparison between the different classifiers in terms of classification accuracies is very difficult. Mainly because oil spill detection approaches use different data sets, have different dark formation detection techniques, extract arbitrary number of features and in the end use different classifiers. Therefore, the reported classification accuracies cannot be directly compared. As the quantity of the SAR data increases rapidly there is a big need for semi or fully automatic methodologies to detect and identify dark formations as oil spills, fast and accurate. There are several methodologies proposed in the literature but their results are under discussion and they cannot really be compared. The main reason is that each study is using its available data set, which in most of the cases does not contain verified examples. Therefore, there is a need for a common database with verified oil spills and look-alikes which will be widely available in the scientific community. This database should contain a wide range of verified oil spills (in age, shape and brightness) and verified look-alikes, in different wind conditions, by several SAR sensors, polarizations and modes. Also, a categorization is needed for the verification means (e.g. airplane, vessel) and the time gap between the image acquisition and the verification. Only then the different methodologies will be comparable and their improvements measurable. Moreover, under this perspective the three main parts of the methodologies (i.e. dark formation detection, feature extraction and classification) can also be examined and compared in terms of accuracy and processing time.

There would be five critical factors which should be taken into account in affecting the offshore oil spill early warning by classification of SAR Images: the scarcity of the data in terms presence of oil spills, the imbalanced training set (there are more negative examples i.e. look-alikes that positive examples i.e. oil spills), the validity of the data selection (there is no guaranty that the examples used at the development phase are representatives of the examples that will arise after development), the feature selection procedure and the highly dynamic environment in terms of dataset, feature selection and classification algorithm. Another issue is the accuracy estimator, i.e. the performance of a method can be also added as a key

factor. These issues have to be very carefully studied before designing a new methodology or applying a new dataset to existing methods.

8.1.2 Early warning indicators

Another way to alert offshore oil spills is to use early warning indicators. Different approaches for the development of indicators may be grouped into:

- Safety performance-based indicators
 - Event indicators
 - Barrier indicators
 - Activity indicators
 - Programmatic indicators
- Risk-based indicators
 - Technical indicators
 - Organizational indicators
- Incident-based indicators
- Resilience-based indicators

The main function of a measure of safety performance is to describe the safety level within an organization, activity, or work unit. Safety measurements have been used for a long time as one means of assessing the safety performance. For offshore installations, process plants, and other areas of major hazards the accidents are so rare, that direct measures of safety (outcome measures) are inadequate. In the early '80s, research started on assessing the effect of organizational and other factors on safety, and the term 'indicator' was introduced in the safety field (Osborn et al., 1983a; 1983b; Olson et al., 1984; 1985). Terms like safety indicators, safety performance indicators, programmatic performance indicators, indirect performance indicators, etc. were used. This initial work on safety indicators started with a set of factors assumed to have an effect on safety, and one objective was to demonstrate this relationship through e.g. correlation. When the work was extended to cover underlying causes (i.e. the effect of organizational or programmatic factors), then safety performance measurements were not only useful to describe the safety level, but also to be used as early warnings.

Risk-based methods (or risk analysis based, PSA based, QRA based, etc) differ from safety performance-based methods in that they utilize a risk model as a basis. This is usually an existing risk model, but the development of a risk model (either a complete new model or an extension of the existing model) may also be part of the method (Øien, 2001a; 2001b). The main function of the risk indicators developed by this method is risk control, which means that direct indicators are adequate (and preferred) if there is sufficient data to be obtained in the data collection period chosen (e.g. each month or each three months). The organizational part of the method is normally foreseen used, only for significant risk factors with insufficient data. However, in the case of development of early warning indicators the

organizational risk indicators are of particular interest, which means that the organizational part should be used even if there is sufficient amount of data for direct risk indicators.

Incident-based methods (or incident/accident analysis based methods) identify early warning indicators by an in-depth study of one or more incidents or accidents. The focus is on identifying those less than adequate factors that contributed to the incident/accident, and the measuring of these factors, i.e. with the use of indicators. The presumption is that if these contributing factors had been adequate, then neither the particular incident/accident being analyzed nor similar incidents/accidents would have occurred (Øien, 2008).

Resilience refers to the capability of recognizing, adapting to, and coping with the unexpected (Woods, 2006). Resilience Engineering is a specific approach to manage risk in a proactive manner. It is about engineering resilience in organizations and safety management approaches, by providing methods, tools and management approaches that help to cope with complexity under pressure to achieve success (Hollnagel and Woods, 2006).

The safety performance-based method is very favorable when it comes to practicality, simplicity and documentation. The indicators are also very relevant as early warnings. The main weakness is that the risk significance is unknown, which is also the case for the relative importance between the chosen influencing factors. The risk-based method provides indicators that are very relevant for major accidents, it is easy to determine the risk significance (including relative risk importance between the various risk influencing factors), and it is not dependent on any accident investigation since it is also independent of any occurred events. One of the favorable inherent features is that it models potential scenarios, and need not wait for accidents to happen. The main weakness is that it is rather resource intensive, especially if organizational risk indicators are developed, which is desirable since they are most relevant as early warnings. The incident-based method provides indicators that are very relevant for major accidents, especially if the event investigated was a major accident or it had major accident potential. It is also very easy to communicate, since it is based on a factual incident or accident. This is also its main weakness, i.e. that it depends on the occurrence of a relevant incident or accident, and that the accident investigation needs to be very thorough and well documented. In addition, the risk significance and relative importance of the underlying causes in general are unknown. The resilience-based method's main advantage is that it focuses on positive signals, and not only on failures, for which there may be lack of data (i.e. the 'controller's dilemma'). It does not depend on information from occurred events and the indicators are relevant as early warnings. The main drawback is that the risk significance and relative importance of the influencing factors (or general issues) are unknown.

It is clearly advantages and disadvantages with all the methods, and they are also different in terms of resource intensiveness and the need for contribution from management and/or operating personnel, and in the scope and depth of analysis. This suggests that it should be flexible with respect to the choice of methods, and

preferably use more than one method, since they are also complementary, at least to a certain degree. Thus, the main conclusion is that it is favorable to have the possibility to use several different methods for the establishment of early warning indicators.

8.2 Classification in offshore oil spill

Classification methods are used, in practice, to group simulation units into clusters, and each cluster should represent a certain type of unit characteristics (Richard et al., 2001). Ranking is a process that orders objects based on a proposed set of criteria. Sometimes, ranking can be considered to be a special process from supervised classification (Ertekin and Rudin, 2011). Classification and ranking are of necessity and importance to support the decision making and in practice of oil spill monitoring, spill alert and response, helping reduce the set up and running cost and improves efficiency (Fernando et al., 2004). For example, it is usually time-consuming and costly to set up monitoring stations or trips in an offshore area potentially affected by oil spills (i.e., an area near offshore platform). Regions classification is able to categorize the stations or locations of monitoring trips and identify the ones which can sufficiently represent significantly different characteristics from each. However, a marine system is usually characterized by a large variety of meteorological, hydrological, and ecological features, which provides the basis for the classification and also makes it more challenging when the inherent complexity and uncertainty.

A ranking is a relationship between a set of items such that, for any two items, one is either 'ranked higher than', 'ranked lower than' or 'ranked equal to' the other. In mathematics, this is known as a weak order or total preorder of objects. Sometimes the ranking can be seen as a special case of classification. Ranking extends conventional multiclass classification in the sense that it does not only predict candidates to groups but instead gives an ordering of all candidates. Besides, it is well-known that a number of other learning tasks can be formalized within the setting of ranking (Furnkranz *et al.*, 2008).

Recently, classification techniques employed in offshore oil spill are only focusing on determination of the occurrence of a spill, and the type of spilled oil. Fingas (2001) describes the guidelines for estimating oil thickness using visual surveillance by the appearance of oil varying from silvery-sheen to dark brown. However, visual detection of an oil spill is usually not reliable as oil can be confused with other substances. Several natural and atmospheric phenomena produce dark areas in images similar to oil spills, e.g. sea weeds and fish sperm. These dark areas are usually referred to as look-alikes, whose presence makes the detection of oil spills a challenging task (Migliaccio and Tranfaglia, 2004; Brekke and Solberg, 2005). Therefore, classification techniques are usually employed to process the remote sensing information to determining an offshore oil spill (Ivanov and Zatyagalova, 2008; Topouzelis, 2008; Topouzelis *et al.*, 2009).

Challenge remains in how to alert levels of an offshore oil spill such as regular leaking, slight spill, moderate spill, major spill, and disaster, which requires ranking techniques with considerations of not only remote sensing but also onsite monitoring and analysis. Another challenge is how to screen response technologies once an oil spill happens. Recent practices in screening technologies for offshore oil spill responses are mainly based on experiences which may cause high uncertainties to operation. Therefore, classification techniques with additional consideration of multi-features in eco-environment and social-economy of the region are necessary to further supports technologies screening.

8.3 Simulation of oil spills

When oil is spilled, whether on water or land, a number of transformation processes occur; many of these processes are referred to as the behavior of the oil. The first process is weathering, a series of processes whereby the physical and chemical properties of the oil change after the spill, of which the most important are evaporation and emulsification. A second group of processes are related to the movement of oil in the environment. Offshore oil spill simulation combines the knowledge of both these sets of processes and provides the user with information on future locations of the oil as well as information on the state of the oil. Weathering and movement processes can overlap, with weathering strongly influencing how oil is moved in the environment and vice versa. All processes depend very much on the type of oil spilled and weather conditions during and after the spill.

Generally, the transport and fate of spilled oil in water bodies are governed by physical, chemical, and biological processes that depend on the oil properties, hydrodynamics, meteorological and environmental conditions. The processes include advection, turbulent diffusion, surface spreading, evaporation, dissolution, emulsification, sedimentation and the interaction of oil slick with the shoreline. When liquid oil is spilled on the sea surface, it spreads to form a thin film—an oil slick. The movement of an oil slick is governed by the advection and turbulent diffusion due to current, waves and wind action. The slick spreads over the water surface due to a balance between gravitational, viscous and surface tension forces, while composition of the oil changes from the initial time of the spill. Light fractions evaporate, water-soluble components dissolve in the water column, and immiscible components become emulsified and dispersed in the water column as small droplets. The formation of oil-in-water or water-in-oil emulsion depends upon turbulence, but usually occurs within days after the initial spill. These complex mathematical treatments for idealized problem are not suitable for applications to real field problems.

In **Figure 8.1**, a schematic representation of the transport and weathering processes are shown, as well as time periods for which each of these processes are important (Rasmussen, 1985). It is clear from these time scales that the oil undergoes significant modification during the first few hours following a spill.

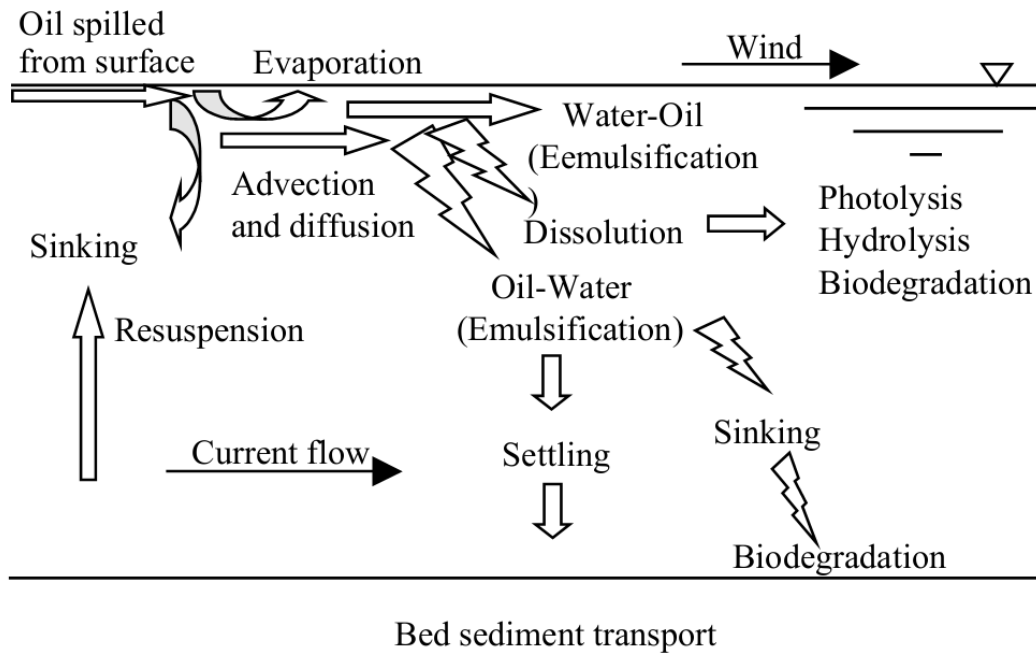


Figure 8.1 Transport and fate of oil slick in seas
(Source: Shen and Yapa, 1988)

As soon as crude oil is spilled onto the surface of the sea it will normally spread out rapidly to form a thin slick of oil and this will drift under the influence of wind, wave and current. Spreading of the oil slick is the horizontal expansion due to gravity, inertia, viscous and surface tension forces in the early stage of the oil slick transformation. When an oil slick reaches a shoreline, it may deposit in dead zones. The deposited spilled oil may be re-entrained into the sea current. Gundlach and Hayes (1978) proposed a method for classifying shorelines according to their vulnerability, which is the index reflecting the environmental sensitivity of the shoreline to the oil pollution. For beaches of different vulnerability, Torgrimson (1980) suggested the use of half-life values to describe the rate of re-entrained after it landed at a shoreline location.

8.3.1 Spreading and Drift

As soon as oil is released on water, the oil begins to spread by gravity, wind, and current, with the process resisted by inertia, viscosity, and surface tension, until the slick reaches a thickness of ~0.1 mm or less. The surface transport process, or spreading, can affect other weathering processes such as evaporation, dispersion, and emulsification (Figure 8.1). The environmental impact of oil spills largely depends on the spreading area. The coastal protection and cleanup operations also

require information on the spill size. Because of the influence of the winds and wind-induced surface currents, the oil slick may move downward with respect to the wind direction. This movement, called drift, results in a displacement of the center of the oil slick and contributes to the nonsymmetrical spreading. The drift speed is around 2.5~4.5% of the wind speed as measured in various laboratory studies and field studies (Reed et al., 1999; Brebbia, 2001). The drift velocity and the trajectory of the oil slick can significantly affect the coastal protection plan.

8.3.2 Evaporation

Evaporation is the primary cause of rapid volume reduction of spilled oil. The loss of light composition by evaporation results in an increase in the viscosity and density of the residual oil. Evaporation occurs immediately after the spill (Mackay et al., 1980). Evaporation is the process that the lower-molecular-weight volatile component of the spilled oil mixture comes from the surface slick into air. Evaporation is usually the most important weathering process, which can account for the loss of 20~50% of many crude oils and 75% or more of refined petroleum products (Brebbia, 2001; Michel et al., 2005). The evaporation rate of oil depends primarily on its physicochemical properties and is increased by spreading, high temperature, wind and waves. The composition and physicochemical properties of oil can change significantly with the extent of evaporation. For example, if about 40% of the oil evaporates, its viscosity could increase by as much as a thousand fold.

8.3.3 Natural dispersion

Natural dispersion is the process of forming small droplets of oil that are incorporated into the water column by wave action or turbulence. Natural dispersion is the net result of three processes: (1) globulation, which is the formation of oil droplets from slick under influence of breaking waves; (2) dispersion, which is the transport of the oil droplets into the water column as a net result of the kinetic energy of oil droplets supplied by the breaking waves and the rising forces; and (3) coalescence of the oil droplets with the slick (CONCAWE, 1983).

Natural dispersion reduces the volume of slick on the sea surface and the evaporative loss, but it does not lead to changes in the physicochemical properties of the spilled oil in the way those other processes (e.g., evaporation) do. If droplets are small enough, natural turbulence will prevent the oil from resurfacing. The rate of natural dispersion is an important factor for the life of an oil slick on the sea surface. In practice, natural dispersion can be significant, accounting for a major part of the removal of oil from these a surface. The effect of natural dispersion depends on both the oil properties and the amount of sea energy.

8.3.4 Emulsification

Under the influence of wave action, water droplets may become entrained into the oil slick to form water-in-oil emulsions. Such emulsions are highly viscous and resistant to treatment by chemical dispersants. The formation of emulsions makes mechanical recovery difficult. The processes which govern emulsion formation are not well understood, so an empirical approach has been taken to estimate rates of emulsification. The process of emulsification is affected by the wind speed, the thickness of oil slick, environmental temperature, etc. (Rasmussen 1985). Water droplets are entrained into the oil layer and remain in the oil slick in unstable, semi-stable, and stable forms. Emulsification can change the physicochemical properties of oils dramatically, especially for viscosity. The emulsified oil can contain up to ~70% water. More significant, the oil viscosity can increase as much as a thousand fold, making the emulsion very difficult to clean up. Once stable emulsion forms, other weathering processes are also affected. The evaporation and biodegradation slow, and the spreading and dissolution almost cease. Whether the emulsification occurs depends on the oil properties. Light, refined oils generally will not emulsify since they do not contain the right hydrocarbon components to stabilize the water droplets. Crude oil will emulsify when the wax and asphaltic content reach 5%. Some oils will emulsify only after they have been weathering to an extent. Emulsions are characterized as stable, meso-stable, and unstable when the maximum amount of contained water is 60–80%, 40–60%, and 30–40%, respectively (Sebastiao & Sores, 1995). Most emulsification models are derived from the formulation proposed by Mackay & McAuliffe (1988) to predict the water content, viscosity, and density of the emulsion.

8.3.5 Other Weathering Processes

Other weathering processes include dissolution, photo-oxidation, sedimentation, and biodegradation. Dissolution occurs immediately after the oil spill, and the amount is usually much less than that from evaporation. Some of the oil components, which are subjected to evaporation, can also dissolve into the water column from a surface slick. The volume loss of spilled oil by dissolution is negligible for any practical purposes, but the environmental consequences of dissolution can be significant. Although the concentration of these compounds in the water column will rapidly be diluted to very low levels, they can exert a toxic effect on marine organisms (Cohen et al., 1980). Photo-oxidation can change the composition of spilled oil, but it is not considered to be an important process because it affects less than 1% of the oil in the slick. Sedimentation is the adhesion of oil to solid particles in water; it has little effect in removing oil in open-sea conditions. Biodegradation is a slow, long-term process, and there is no general mathematical model to describe the biodegradation rate of crude oil in a marine environment. Because of these limitations, these processes are generally not considered in the mass balance or physicochemical property changes of the oil weathering model.

8.3.6 Integrated simulation models

After an oil spill, oil particles can stay in the water column for a long time and pollute the underlying water environment. In the last three decades, many investigators have studied the transport and fate processes of oil spills based on the trajectory method (Mackay et al., 1980; Huang, 1983; Shen et al., 1986; Shen and Yapa, 1988; Yapa et al., 1994; Spaulding, 1995; Lonin, 1999; Chao et al., 2001). Among these oil spill models, many of them focus on the surface movement of oil spills. There has been little published research on the vertical distribution of oil droplets. It is important to note that the advection forces are independent of each other so that the wind and waves can act in the direction same or opposite to the tide. The amount of time that each particle remains on the surface layer is, in turn, determined by the balance between the buoyancy and the vertical diffusion rate. Therefore, droplets of higher buoyancy spend proportionately more time on the surface layers and are advected further due to the surface currents. The spreading of the oil slick is a three-dimensional (3-D) process controlled by the droplet size distribution and shear diffusion processes (Wang et al., 2008).

In the last three decades, many investigators have studied the transport processes of oil spills based on the trajectory method (Huang, 1983; Mackay et al. 1980; Spaulding, 1995). Those methods have been applied in river-lake system (Shen et al., 1986; Shen and Yapa, 1988; Yapa et al., 1994); and seas (Lonin, 1999; Chao et al., 2001; Wang et al., 2005; Wang et al., 2008). Some commercial oil spill models, such as, COZOIL (Reed, 1989), NOAA (Galt et al., 1991), OILMAP (Howlett et al., 1993), WOSM (Kolluru et al. 1994), have been used to determine the oil movement and distribution in the water body. However, transport of oil spills has been conducted considering tidal currents simultaneously in only few researches. Furthermore, oil spills processes in a field of strong tide and tidal currents have not been investigated.

8.4 Systems optimization

Optimization tools are utilized to facilitate optimal decision making in the planning, design and operation in environmental management. The use of optimization tools as the most important component of decision support systems are not confined only to the quantity aspect of resource, but also the mitigation of pollutants in a regional scale, operation of treatment plants and scheduling, designing of optimal strategies for treatment process, minimizing system cost or maximizing profit etc. (Mayer and Muñoz-Hernandez, 2009).

Optimization has been studied extensively by the process systems engineering community in the recent years. General reviews on this topic are given by Reklaitis (2000), by Kallrath (2002), and by Verderame et al. (2010). Although most of the existing optimization models have only one objective function to maximize the economic performance, some use a multi-objective optimization

scheme to account for such additional objectives as environmental damage (Bojarski et al., 2009; Guillen-Gosalbez & Grossmann, 2009; Duque et al., 2010), service level (You et al., 2010), financial risk (Rodera et al., 2002; You et al., 2009), responsiveness (You & Grossmann, 2008, 2009 & 2010), and flexibility (Ierapetritou & Pistikopoulos, 1994). The methodology of process planning has been used in a wide spectrum of applications in process industries, including chemical production (Verderame & Floudas, 2009), refinery operations (Neiro & Pinto, 2005) new production development (Maravelias & Grossmann, 2001), pharmaceutical manufacturing (Gatica et al., 2003), and water network (Laird et al., 2006).

Very limited efforts, however, have been extended to deal with the decision-making problems in oil spill response. Most of the literature in oil spill modeling focus on the simulation of oil transport and weathering process (Brebba, 2001; Reed et al., 1999), and a few of them have addressed the decision problems in oil response planning and on-site actions. A review of the planning models for oil spill response is given by Iakovou et al (1994). For example, Psaraftis and Ziogas (1985) developed an integer programming model for optimal dispatching of oil spill cleanup equipment with the objective to minimize the total response costs. Wilhelm and Srinivasa (1997) developed an integer programming model for prescribing the tactical response of oil spill cleanup operations with the objective of minimizing the total response time of equipment. Limited literature exists that addresses the integration of oil properties, the weathering model, and the planning model (Ornitz & Champ, 2003). Gkonis et al. (2007) presented a mixed-integer linear programming model that considers the oil weathering process, an important factor for decision making in response operations. None these planning models, however, has taken into account coastal protection planning, which is usually required for massive oil spills. Moreover, only a single objective is used in the existing literature; and the time span of the entire response operations, which is the measure of the responsiveness, has not been considered by the existing optimization models.

8.5 Integrated decision support systems

Management of emergencies resulting from natural or man-made disasters requires enough information as well as experienced responders in both technical and co-ordination matters. It generally means making the best decision at the right moment, which requires a great amount of information (Hernandez and Serrano, 2001). In offshore oil spills, different affected sites have different characteristics depending on various features such as pollutants' properties, hydrological conditions, and a variety of physical, chemical, biological processes, etc. Thus, the response methods selected for different sites vary significantly, and the decision for a suitable method at a given site often requires expertise on both remediation technologies and site conditions (Geng, et al., 2001).

When an offshore area is affected by an oil spill, decisions about the types and durations of response operations are required after considering a range of factors. These factors include the environmental sensitivity, conservation value,

amenity value, and economic importance, and the logistics and costs of possible cleanup practices. Some vulnerable and/or sensitive parts of the world's coasts have been assessed with regard to their vulnerability to an oil spill, and contingency plans have been devised to guide actions and cleanup operations. For the majority of coasts, however, no contingency plan exists, and available response options must be reviewed and decisions made in very short times, if interventions are to have any chance of being successful. In such instances, decision makers have to assess the relative importance of all the factors (Kapucu and Ozerdem, 2011). The extensive literature on the effects of oil spills and remedial clean-up treatments on offshore/shoreline ecology may be capable to provide data to inform such decisions. Despite the existence of a large body of experience, challenges still remain in what point should response actions for offshore oil spills, so that natural ecological processes can complete the recovery of affected offshore area (Sell et al., 1995).

Decision support systems, which are series of computer-based systems for solving semi-structured problems, allow decision makers to simulate many steps of the process of decision making, to investigate the alternative decision scenarios, and to improve the decision making effectiveness. Although there is no unique definition or standard components of a decision support system, the purpose of a DSS is to increase both the efficiency and effectiveness (Power, 2002). The decision making is a complex process, influenced by many factors, both human and non-human. Recently, many DSSs have been developed aiming for emergency responses to flood (Sanders and Tabuchi, 2000; Castellet *et al.*, 2006; Mirfenderesk, 2009), forest fire (Jaber *et al.*, 2001; Asunción *et al.*, 2005; Bonazountas *et al.*, 2007), tsunami (Kumar *et al.*, 2010; Steinmetz *et al.*, 2010), etc. However, the effectiveness of these DSS is still challenged by the complexity and uncertainty which widely exist during these emergency responses.

Compared with the DSSs for emergency responses to flood, hurricane, and tsunami, the DSSs for offshore oil spill responses is still immature. In recent years GIS have been increasingly used in conjunction with oil spill modeling tools as a mean of integrating and pre-processing spatial data inputs to the numerical modeling and for post-processing and visualization of the modeling outputs. The integration of GIS and environmental modeling is now widely accepted as desirable, if not essential. Of considerable discussion and research have been levels of coupling achievable or desirable between GIS and environmental models (Li, 2001).

Although a few models have been developed for oil spill response and countermeasures, they usually separately consider response operations and the oil weathering process where interactions significantly exist (Reed et al., 1999; Brebbia, 2001; Fingas, 2001; Ornitz and Champ, 2003). Meanwhile, oil spill cleanup activities change the volume and area of the oil slick and in turn affect the oil transport and weathering process, which also dynamically affects the oil spill response and countermeasures. Therefore, it is critical to integrate the response planning model (i.e., optimization model) with the oil transport and weathering model, although this integration has not been addressed in the existing literature (You and Leyffer, 2011). Furthermore, although classification of response technologies, simulation of oil spill

weathering, and optimization of response operation can provide effective help to the decision making, there is still lack of DSS that employs these processes in offshore oil spill response and countermeasures.

8.6 Challenge of decision making in Newfoundland and Labrador

Most areas of Newfoundland and Labrador are located in the north region, which makes the offshore NL appearing strong harsh environment and cold region characteristics. Response options in cold and harsh environments vary depending on seasonal oceanographic and meteorological environments. The behavior of oil spilled in cold, ice covered waters is governed largely by the ice concentrations in the case of broken ice and the process of encapsulation and subsequent migration in the case of solid ice. Each season presents different advantages and drawbacks for spill response. During freeze-up and break-up, drifting ice and limited site access restrict the possible response options and significantly reduce recovery effectiveness. Mid-winter, although associated with long periods of darkness and cold temperatures, provides a stable ice cover that not only naturally contains the oil within a relatively small area but also provides a safe working platform for oil recovery and transport (Turner, 2010).

Crude oils and oil products behave quite differently if spilled in the cold and harsh environment such as offshore NL, due to the physical and chemical properties of the oil spilled. These properties influence the selection of response equipment and methods applicable for spill cleanup. Knowledge of the ultimate fate and behavior of oil should drive countermeasure decisions. The fate and behavior of oil in ice-covered waters is governed by a number of important weathering processes have a direct bearing on oil recovery operations. Weathering is the combined effect of the processes taking place when oil is spilt to the sea (evaporation, water-in-oil emulsification, drift, spreading etc.) and will influence the fate and behavior of the oil. The physical distribution and condition of spilled oil under, within or on top of the ice plays a major role in determining the most effective response strategies at different stages in the ice growth and decay cycle. Before oil spill response plans are developed or approved, it is important to understand the chemistry and physical behavior of the oil and how its characteristics change over time, once the oil is spilled.

At the same time, oil spill models are very sensitive to errors in the initial input data, such as the details of the release and the wind and current forecasts. Furthermore, the mathematical calculations used to simulate oil movement are likely based on empirical approximations and assumptions and are subject to time step and grid limitations. Trajectory model uncertainty refers to changes in the forecast as a result of these errors. Unfortunately, quantitative assessment of the errors in trajectory modeling is difficult and limited. In addition, oil spills are notorious for occurring in areas where the environmental data are temporally and spatially incomplete. This leads to a forecast process that often relies on the

forecaster's subjective judgment and approximated input. The ranking of uncertainty as low, medium, and high for trajectory forecasts and the model inputs presented here are subjective. But the forecaster's subjective judgment can be an invaluable resource, and, at least as anecdotal data suggest, it may be better than a model alone at estimating errors. Therefore, it become significantly challenging in oil spill early warning and modeling in offshore Newfoundland and Labrador, especially in winter.

In most countries, mechanical recovery of spilled oil is the first and preferred response option. A containment boom is normally used in combination with an oil recovery skimmer. In ice-infested waters, an additional challenge for oil skimmers is their ability to process ice, meaning the skimmer should be able to deflect smaller floes and slush ice in order to have access to the oil. Broken ice conditions occur during short periods in the spring and fall. Oil spreads less and remains concentrated in greater thicknesses in broken ice than in ice-free waters. However, as the amount of broken ice in the water increases the efficiency of conventional mechanical recovery systems is reduced (DeCola et al., 2006).

When responding to an oil spill in cold and harsh conditions, the first step is to identify the oil's physical properties particularly, the pour point. If the pour point is 5 to 10 degrees above the water temperature, there is a strong possibility that the oil has already solidified. Nets and other collection devices may be required for recovery. If the pour point of the oil is below the water temperature and if currents and wind conditions allow, then booms and skimmers may be applicable for use. Most mechanical containment and recovery methods are technologies developed for open water conditions. Mechanical response in broken ice is limited by the ability of the skimmer to encounter and remove spilled oil. This is based on the type of spill (subsea blowout vs. above ground blowout) as well as the amount of broken ice. Efficiencies vary and are based on the amount and type of oil spilled, meteorological and oceanographic conditions. Available estimates from mechanical response in broken ice vary from 1% to 20% depending on the degree of ice coverage and if responding during freeze-up or spring break-up. This compares with estimates of 5 to 30% for open ocean response without broken ice (MMS, 2008).

Environmental conditions in the harsh environment are an obvious impediment to the efficacy of most spill response technologies. Typical harsh conditions impacting on oil spill response operations include the presence and type of sea ice, extreme cold, limited visibility, rough seas, and wind, leading to impact on the fate and behavior of spilled oil, and thus may reduce the effectiveness of response technologies such as booming, herding, and skimmer (Owens et al., 1998; Brandvik et al., 2006). Therefore, it is important to conduct offshore oil spill responses in harsh environment in a timely manner, and thus requires an optimization of limited resources and man power for the recovery. However, there is still no such DSS to support offshore oil spill response and countermeasures in Newfoundland and Labrador.

8.7 An Decision-support Framework for Oil Spill Preparedness and Response in Offshore Newfoundland and Labrador

The integration of the technologies screening, oil weathering simulation, and optimization approaches is the key component of the proposed offshore oil spill DSS. The details about such integration are shown in **Figure 8.2**. In an offshore oil spill, parameters including temperature, wave height, wind speed, spill viscosity, slick thickness, etc. are used to represent site conditions, feasibilities of available technologies, and the proposed membership functions. The an integrated rule-based fuzzy adaptive resonance theory mapping (IRFAM) approach (Li et al, 2009; Li et al., 2011; Chen et al., 2012) is applied to screen the available technologies corresponding to the site conditions and the series alternatives can be consequently determined accordingly. Then the operational parameters of the selected technologies such as man power requirements, operational costs, and efficiencies are determined with probabilistic uncertainties and randomized with stochastic simulation. Meanwhile, according to the uncertain site conditions, the weathering simulation is conducted based on random number. The simulation results, the randomized operational parameters, and the resources/limitations (e.g., man power, finance, and regulation) are forming the constraints of the optimization model. Then according to the Monte Carlo simulation based fuzzy programming (MCFP) approach (Li et al., 2012) and the multiple-stage simulation based mixed integer nonlinear programming (MSINP) approach (Li et al., 2012), a simulation-based fuzzy stochastic dynamic programming (SFSDP) approach is generated and solved for one trial (e.g., trial l) until the number of trials achieves the preset number (e.g., N). Finally a series of decision alternatives are generated according to the optimization results. A decision alternative may include the combination technologies (e.g., number of machines) in each operational stage, allocations of man power and finance, corresponding cost and environmental effects, etc.

As shown in **Figure 8.3**, the proposed decision system includes: 1) a updating database of natural and social conditions, pollution prevention technologies, control technologies, clean-up technologies, and expert experiences; 2) a diagnostic module for oil spill risk levels determination via sampling and monitoring, geomatic analysis, risk assessment, and corresponding strategies of spill prevention, followed with an alert system to indicate the oil spill; 3) a Monte Carlo simulation based integrated rule-based fuzzy adaptive resonance theory mapping (MC-IRFAM) module for screening available technologies for offshore oil spill clean-up based on the specific condition of NL; 3) a simulation based optimization fuzzy stochastic dynamic programming (SFSDP) approach based on the simulation for oil spill weathering, simulation-based fuzzy stochastic dynamic programming for dynamically optimizing the combination of technologies and the allocation of resource in each planning strategy.

8.7.1 Database for background information and technologies

Different contaminated sites have different characteristics depending on pollutants' properties, hydrological conditions, and a variety of physical, chemical, and biological processes. Thus, the methods selected for different sites vary significantly. The decision for a suitable method at a given site often requires expertise on both clean-up technologies and site conditions. Management of emergencies, resulting from natural or man-made disasters, requires sufficient information as well as experienced responders both in technical and co-ordination matters. In this way, a great amount of information should be used to improve the management of the emergency, which generally means making the best decision at the right moment. In this regard, developing a database including all oil pollution records with accurate geo-referenced locations and all available clean-up technologies should be compiled. This database includes the attributes of each record such as spill volume, oil type, location, sector, source, cleanup percentage in each case, and environmental impacts. So, any new case can use the previous experience.

8.7.2 Diagnosis and alert approach for offshore oil spill

One major functionality of the diagnosis for rapid responding to an oil spill event is provision of real-time, medium-term and long-term alert information. The approach is based on capitalization of GIS data, remotely sensed data and other monitoring technologies like deployed sensors and observant systems. The management system will receive information from the diagnosis as follows:

- The detection and then location and spread of oil spills over both large and small areas.
- The thickness distribution of an oil spill to estimate the quantity of spilled oil.
- A classification of the oil type in order to estimate environmental damage and to take appropriate response action.
- Timely and valuable information to assist in response and clean-up operations.
- Stored and time-stamped, real-time evidentiary data on any spills and response efforts.

Medium- and long-term alert refers to the information about risk identification, assessment and monitoring. Subsequently the Environmental Sensitivity Index (ESI) map functioning as long-term alert for oil spill risk and trajectory simulation results over this map yields medium-term risk alert. The real time detection and monitoring sensors provide short-term alert for oil spill. There are three levels indicated by the alert system: green, orange, and red. The green level indicates a minor offshore oil spill and correspondingly pollution prevention strategies are then applied. The orange level indicates a moderate offshore oil spill

and correspondingly control strategies are then applied. The red level indicates serious oil spill and correspondingly clean-up strategies are then applied, supporting by the technology screening and simulation based optimization.

The Diagnosis and alert module is dynamically linked with the simulation based optimization module to provide real-time interaction of in diagnosis, alert, and response to offshore oil spill in NL.

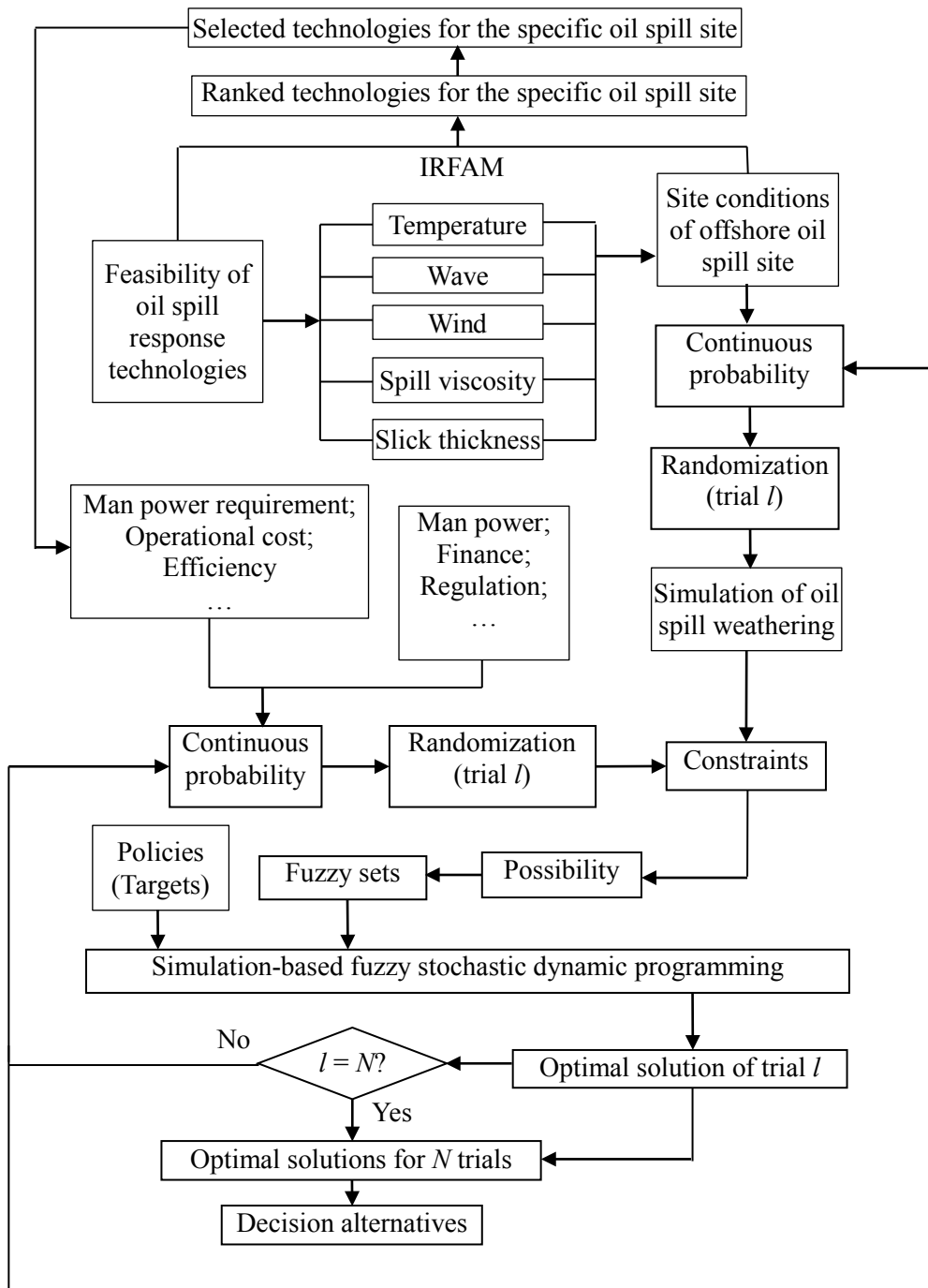


Figure 8.2 The integration of the technologies screening, simulation of oil weathering, and optimization approaches

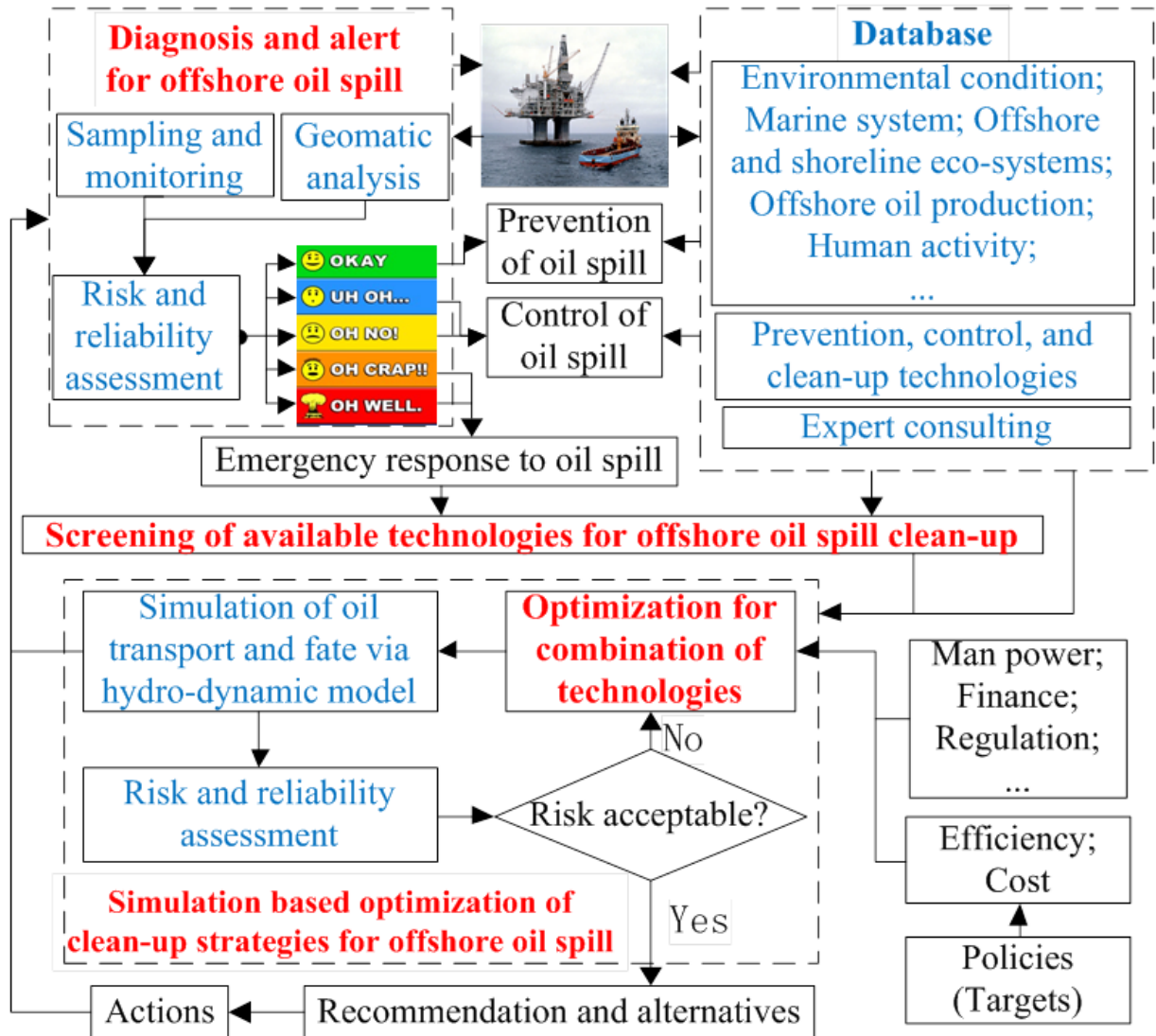


Figure 8.3 Frameworks of an integrated DSS for supporting offshore oil spill response and countermeasures in harsh environments

8.7.3 Technology screening for offshore oil spill

Once an oil spill is determined by the diagnosis, the screening process is then applied to determine the available technologies according to the situation of oil spill and polluted marine system based on the developed database and the IRFAM model (Li et al., 2011). This system is developed by integrating fuzzy set theory and rule-based operation with a conventional Adaptive Resonance Theory (ART) Mapping model. Five ART modules are included to carry out the unsupervised learning for cluster centroid calculation, supervised learning for criteria combination, and fuzzified original input classification. This system can efficiently handle the screening under uncertainty and complexity. By setting the criteria corresponding to the situation of the pollution and the condition of offshore NL (e.g. spill amount and temperature) available technologies are screened from the database for optimization.

8.7.4 Simulation based optimization for supporting oil spill management

8.7.4.1 Simulation of oil transport and fate

In the initial stage of the emergency management system, the simulation of pollutant transport and fate is firstly processed based on the hydro-dynamic process, mechanical spreading, evaporation, dissolution, and shoreline deposition. The simulation results show the situation of pollution in the affected area in spatio-temporal base, followed by risk and impact assessment.

8.7.4.2 Risk and reliability assessment to the offshore and shoreline systems

Risk analyses can be characterized as hazard-based or risk-based. A hazard-based analysis examines possible events regardless of their low (or high) likelihood. For example, a potential impact would not lose significance because the risk has been reduced due to an increase in the level of control, such as engineering standards. A risk-based analysis, on the other hand, does take into account the likelihood of the event occurring or the measures that can be taken to mitigate against its potential impacts.

The reliability assessment helps monitor, assess, and correct deficiencies of the operational production of offshore oil in NL. Monitoring includes electronic and visual surveillance of critical parameters in offshore oil production identified during the fault tree analysis design stage. The data are constantly analyzed using statistical techniques, such as Weibull analysis and linear regression, to ensure the system reliability meets requirements. Any changes to the offshore oil production system, such as field upgrades or recall repairs, require additional reliability testing to

ensure the reliability of the modification. Reliability data and estimates are also key inputs for diagnosis of and alert for offshore oil spill.

8.7.4.3 Optimization for supporting offshore oil spill management

Based on the results from simulation and risk assessment, screened technologies, resources and constraints (e.g., budgeting, man power, policy and regulation), the optimization is applied to provide the best combination from these screened technologies with allocation of existing resources. The ABFSIP is developed to process this optimization and provide decision support for the oil spill site clean-up strategies. The ABFSIP consists of a fuzzy-stochastic-interval linear programming (FSILP) model to handle the coexistence of uncertainties and an agent based model to handle dynamic in the system. This method can effectively tackle uncertainties that are presented in terms of probability density functions, fuzzy membership functions, and discrete intervals and incorporate a variety of uncertain information into a general framework. The agent based model provides optimizing agents living in dynamic simulations. These agents would be to run the optimization process against several different static scenarios and then have the agent constantly use the optimum parameters found for the scenario that most resembles the current one. Through the developed model, interactive relationships between different system objectives/constraints will be effectively reflected, potential conflicts and compromises between different system components will be highlighted, and complex features of the study system will be reflected.

The optimal solution for each oil spill clean-up strategy is obtained via the completion of each routine of simulation - risk assessment - optimization. If the risk from the assessment is acceptable, the simulation based optimization is stopped and provides the optimal solutions for all strategies of the offshore oil spill clean-up, otherwise, the simulation based optimization will repeat until the risk meets the requirement. When the clean-up actions are applied, the diagnosis is kept running to evaluate the efficiency of the actions. If the efficiency underperforms, corresponding changes and rerunning may be needed for the system.

8.7.5 Feasibility analysis for development of oil spill management system

This research tends to develop a management system of diagnosis, alert, and emergency response to oil spill in offshore NL, by integrating the existing databases and models with the newly developed technology screening module and the simulation based optimization module. The system will incorporate the existing and available database, risk assessment model, hydro-dynamic simulation model for the specific conditions of offshore NL or marine system in cold regions. The screening module will be adapted from the IRFAM model previously developed by the researcher, by calibrating the criteria for screening based on the NL offshore condition. The sub-module of ABFSIP is partially developed by the researcher, and

can be easily revised for the purpose of offshore oil spill management. Finally, the developed modules will be dynamically integrated by the artificial neural networks (ANNs).

8.8 Summary

Considering significant impacts being caused by offshore oil spill, it becomes urgent to provide strategies of offshore oil spill response and countermeasures. A few models have been developed for oil spill response and countermeasures based on decision support system (DSS). Meanwhile, many models have been developed to diagnose and alert the oil spill based on the geomatic analysis. There are also developed models out of geomatic analysis, like OSIS, or oil spill risk analysis (OSRA) model and GNOM). However, these systems usually screen response technologies based on only experience and suggest operations without supporting of numerical optimization, and few of them involve approaches to handle uncertainties which widely appear in and highly affect to oil spill response. Furthermore, although approaches based on the coupling of optimization and simulation can effectively increase the efficiency and reduce the time of response, none has been involved in the existing offshore oil spill DSS.

Recently, classification techniques employed in offshore oil spill are only focusing on determination of the occurrence of a spill, and the type of spilled oil. However, visual detection of an oil spill is usually not reliable as oil can be confused with other substances. Several natural and atmospheric phenomena produce dark areas in images similar to oil spills, e.g. sea weeds and fish sperm. Challenge remains in how to alert levels of an offshore oil spill such as regular leaking, slight spill, moderate spill, major spill, and disaster, which requires ranking techniques with considerations of not only remote sensing but also onsite monitoring and analysis. Another challenge is how to screen response technologies once an oil spill happens. Recent practices in screening technologies for offshore oil spill responses are mainly based on experiences which may cause high uncertainties to operation. Therefore, classification techniques with additional consideration of multi-features in eco-environment and social-economy of the region are necessary to further supports technologies screening.

When an offshore area is affected by an oil spill, decisions about the types and durations of response operations are required after considering a range of factors. These factors include the environmental sensitivity, conservation value, amenity value, and economic importance, and the logistics and costs of possible cleanup practices. Some vulnerable and/or sensitive parts of the world's coasts have been assessed with regard to their vulnerability to an oil spill, and contingency plans have been devised to guide actions and cleanup operations. For the majority of coasts, however, no contingency plan exists, and available response options must be reviewed and decisions made in very short times, if interventions are to have any chance of being successful. In such instances, decision makers have to assess the

relative importance of all the factors. The extensive literature on the effects of oil spills and remedial clean-up treatments on offshore/shoreline ecology may be capable to provide data to inform such decisions. Despite the existence of a large body of experience, challenges still remain in what point should response actions for offshore oil spills, so that natural ecological processes can complete the recovery of affected offshore area.

Although a few models have been developed for oil spill response and countermeasures, they usually separately consider response operations and the oil weathering process where interactions significantly exist. Meanwhile, oil spill cleanup activities change the volume and area of the oil slick and in turn affect the oil transport and weathering process, which also dynamically affects the oil spill response and countermeasures. Therefore, it is critical to integrate the response planning model (i.e., optimization model) with the oil transport and weathering model, although this integration has not been addressed in the existing literature.

Compared with the DSSs for emergency responses to flood, hurricane, and tsunami, the DSSs for offshore oil spill responses is still immature. In recent years GIS have been increasingly used in conjunction with oil spill modeling tools as a mean of integrating and pre-processing spatial data inputs to the numerical modeling and for post-processing and visualization of the modeling outputs. The integration of GIS and environmental modeling is now widely accepted as desirable, if not essential. Of considerable discussion and research have been levels of coupling achievable or desirable between GIS and environmental models. However, although classification of response technologies, simulation of oil spill weathering, and optimization of response operation can provide effective help to the decision making, there is still lack of DSS that employs these processes in offshore oil spill response and countermeasures.

Crude oils and oil products behave quite differently if spilled in the cold and harsh environment such as offshore NL, due to the physical and chemical properties of the oil spilled. These properties influence the selection of response equipment and methods applicable for spill cleanup. Knowledge of the ultimate fate and behavior of oil should drive countermeasure decisions. The fate and behavior of oil in ice-covered waters is governed by a number of important weathering processes have a direct bearing on oil recovery operations. Weathering is the combined effect of the processes taking place when oil is spilt to the sea (evaporation, water-in-oil emulsification, drift, spreading etc.) and will influence the fate and behavior of the oil. The physical distribution and condition of spilled oil under, within or on top of the ice plays a major role in determining the most effective response strategies at different stages in the ice growth and decay cycle. Before oil spill response plans are developed or approved, it is important to understand the chemistry and physical behavior of the oil and how its characteristics change over time, once the oil is spilled.

At the same time, oil spill models are very sensitive to errors in the initial input data, such as the details of the release and the wind and current forecasts. Furthermore, the mathematical calculations used to simulate oil movement are

likely based on empirical approximations and assumptions and are subject to time step and grid limitations. Trajectory model uncertainty refers to changes in the forecast as a result of these errors. Unfortunately, quantitative assessment of the errors in trajectory modeling is difficult and limited. In addition, oil spills are notorious for occurring in areas where the environmental data are temporally and spatially incomplete. This leads to a forecast process that often relies on the forecaster's subjective judgment and approximated input. The ranking of uncertainty as low, medium, and high for trajectory forecasts and the model inputs presented here are subjective. But the forecaster's subjective judgment can be an invaluable resource, and, at least as anecdotal data suggest, it may be better than a model alone at estimating errors. Therefore, it becomes significantly challenging in oil spill early warning and modeling in offshore Newfoundland and Labrador, especially in winter.

In order to better support offshore oil spill response and countermeasures, new decision making approaches and systems are desired for providing more effective support to stakeholders or decision makers at different levels such as: 1) general policy makers (e.g., regulators and oil producers) for long-term policy making and trade-off, risk and reliability analyses of the offshore oil spill management; 2) project/production managers and spill responders in designing of contingency plans and/or planning of oil and gas production and transportation in medium-term arrangements; and 3) operators in making on-site decisions and carrying out response and cleanup actions. Risk-based or simulation-based optimization models that can timely determine the best combination of technologies and allocation of resources at different response stages should be developed in order to achieve a most time-efficient and cost-effective response to an oil spill. This would be especially valuable for the areas where unpredictable weather conditions and harsh environments prevail.

In NL, it is particularly urgent and critical to improve the management strategies and decision making effectiveness in offshore oil spill response and countermeasures. To help address this concern, this study has proposed a general decision making framework with the following features: 1) integration of oil spill databases, early warning, risk assessment, technology screening, weathering and movement simulation, and response optimization; 2) quantitative reflection of system uncertainty (probabilistic and possibilistic) and complexity (dynamics and factor interactions) during modeling, response and countermeasures; 3) coupling approaches for interlinking system components (e.g., risk-classification, risk-optimization, simulation-optimization); and 4) special considerations of environmental conditions, resource availability, and time/site constraints during offshore oil spill response in the harsh environments prevailing in NL offshore areas.

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

As the major energy source worldwide, oils have been ever increasingly produced and consumed, so is the risk of spills involved. Oil spills are raising more concerns across the world including Newfoundland and Labrador (NL) because of the significant negative and long-term impacts on the marine environment and eventually human health, as well as the difficulties in spill prevention, control and remediation. This study attempted to get insight of the current methodologies and technologies in oil spill response and countermeasures, identified the existing knowledge gaps and technical challenges, and proposed a new strategic and decision making framework and provided the recommendations for improving oil spill response capacity and effectiveness in NL offshore areas. Particularly the cold weather and harsh offshore conditions in NL and their effects on oil spill response and countermeasurements were reviewed and discussed. The main achievements of this study include:

- Collection and analysis of background information on major oil spills and the associated environmental and economic impacts;
- Review of oil spill relevant policies and regulatory requirements as well as emergency response protocols in different countries;
- Review of the current status and trend of research and development of oil spill monitoring, early warning, emergency response, cleanup, and impact/risk assessment techniques;
- Identification of challenges in oil spill countermeasure in the cold regions and under harsh environments (especially in offshore Newfoundland and Labrador) and knowledge and technical gaps;
- Formulation of a general decision making framework of oil spill monitoring, diagnosis, early warning and response; and
- Recommendations on future strategies and technology development as well as next-phase research needs and methodologies.

The main research findings and conclusions are summarized as follows:

An oil spill is a release of liquid petroleum hydrocarbon into the environment due to human activities. It often refers to marine oil spills, where oil is released into the ocean or coastal areas, including releases of crude oil from tankers, offshore platforms, drilling rigs and wells, spills of refined petroleum products (e.g., gasoline, diesel) and their by-products, heavier fuels used by large ships such as bunker fuel, and the spill of any oily white substance refuse or waste oil as well. Oil spills are catastrophic, and often have significant long-term adverse environmental and socio-economic consequences.

As the major energy source worldwide, oil products has been ever increasingly manufactured and consumed, so is the risk of spills involved. Despite

significant progress in reducing spillage through a variety of technological and regulatory prevention measures along with better industry practices, oil spills continue to occur. On the daily basis, hundreds to thousands of spills are likely to occur worldwide in many different types of environments, on land, at sea, and in inland freshwater systems. The spills involve many different types of oil ranging from various types of crude oil to a large array of refined products, from heavy persistent fuels to lighter, less persistent, but very toxic lighter fuels. Multiple sources of spillage are involved, such as from tankers, offshore platforms, drilling rigs and wells, as well as through the a variety of processes of transportation, refining, storage and utilization of refined petroleum products and their by-products. The reasons are also diverse including structural failures, operational errors, weather-related events, earthquakes, human errors and negligence, and even vandalism or terrorism. The biggest contributor to oil pollution in the World's oceans (some 45%) is operational discharges from tankers, although natural seeps are considered as of great magnitude, and the single most important source of oil that enters ocean. Oil spills in most occurrences (72%) are with small scales and the overall amount of these small spills accounts for less than 1% of the total spillage. The largest spills (over 30 tonnes) rarely occur (0.1% of incidents) yet involve nearly 60% of the total amount spilled. Over the history, some major oil spills such as the Exxon Valdez oil spill in 1989 and the recent Deepwater Horizon oil spill in 2010 have captured global attentions due to the catastrophic impacts.

Offshore oil spills can cause enormous economic loss and harm to ecological systems, public health, and communities. These impacts have been reviewed in this study along with a variety of factors that determine the costs of oil spills such as type of spilled oil, physical, biological and economic characteristics of spill location, weather and sea conditions, amount spilled and rate of spillage, and effectiveness of clean-up as well as complex interactions among these factors. The economic impacts to some extent can be reflected on the total amount of liability and compensational funds which were regulated according to the legislation. The socioeconomic impact can also be evaluated due to the interruption of commercial, recreational fisheries and coastal tourisms. Environmental impacts have been reviewed in terms of mortality and community deterioration of seabirds, fish, shellfishes, benthos and wetland vegetation; however, the related costs of such damages are hard to directly measure and challenges exist in cost estimation particularly considering the associated long-term effects. The public health can also be compromised due to oil spills and transference to food chains. Epidemiological studies have been reported about the relationship between exposure to spilled oils and the appearance of acute physical, psychological, genotoxic and endocrine effects in the exposed individuals. Surveys have been conducted in the oil spill affected communities and shown the increased post-spill rates of generalized anxiety disorder, post-traumatic stress disorder, and depression as well as emotionally upsets due to intrusive recollections of spills such as unexpected negative pictures and thoughts.

The oil industry and regulatory authorities at different levels of jurisdictions including Canada and Newfoundland and Labrador have established series of

policies, laws, and regulations to ensure the safe and environmentally sound activities related to oil spill prevention and response. These commitments demand preparedness and continuous improvement throughout every phase of exploration and production where oil is produced, transported, stored and marketed. All regulatory regimes under study acknowledge that the speed and effectiveness of a response operation can be greatly enhanced through improved planning, training and coordination of a response system. Extraordinary coordination of international, federal, state and local resources is required for a spill. Particularly at an international level, the International Maritime Organization (IMO) is usually responsible for coordinating different countries, including the assistance of international actions. The fast development and growing exploration efforts (especially in the Arctic regions) of oil and gas industry lead to some new and more complex challenges upon the existing cumbersome legislation and implement processes as well as the unclear effectiveness of the regulations.

Most oil spills are accidental and thus unpredictable. Spills can happen on land or in water, at any time of day or night, and in any weather condition. Prevention is considered as the most critical area in all jurisdictions, with considerable efforts being placed to ensure the risk of a spill is as low as reasonably possible. However, once a spill occurs, the best approach for containing and controlling the spill is to respond quickly following a contingency plan and in a well-organized manner. A contingency plan (or management strategy) looks at all the possibilities of what could go wrong and details upon actual events, including the contacts, resource lists, and strategies to assist in the response to the spill. The management of offshore oil spills may appear complicated because it provides many details about the numerous steps required to prepare for and respond to spills. It also covers many different spill scenarios and addresses multiple situations that may arise during or after a spill. Despite its complexity, a well-designed contingency plan should be easy to follow and usually includes hazard identification, vulnerability analysis, risk assessment, and response actions. The plan can help minimize potential harm to human health and the environment by ensuring a timely and coordinated response. A sound contingency plan can assist response personnel in their efforts to contain and clean up oil spills by providing information that the response teams will need before, during, and after spills. Developing and exercising the plan provides opportunities for the response community to work together as a team and establish the interpersonal relationships to secure a smooth and functioning response.

The ability to detect and monitor oil spills at sea is becoming increasingly important. A variety of oil spill monitoring and analysis techniques have been reviewed in this study. Vessels, airplanes and satellites are major tools to conduct on-site monitoring. Although vessels are only able to detect oil at sea within very limited area, they remain necessary for oil sampling. Satellites monitoring can be used for a first warning, and aircrafts are more suitable to be applied to identify the polluter, extent, and type of a spill. Specifically, remote sensing for oil spill includes optical sensors, laser fluorosensors, microwave sensors, and slick thickness sensors. A common passive sensor is an infrared camera or an infrared/ultraviolet system,

which is economical but with the inherent weaknesses including the inability to discriminate oil on beaches, among weeds or debris and under certain lighting conditions as well as in water-in-oil emulsions. The laser fluorosensor is widely applied because of its unique ability to identify oil in a complex matrix. Equipments that measure relative slick thickness are still under development. Passive microwave has been studied for several years, but many commercial instruments are lack of sufficient spatial resolution. In recent years, some state-of-the-art technologies have been developed and applied for on-site monitoring, such as small remote-controlled aircraft, and underwater detection and tracking, and ship-borne radar for automated detection of spilled oil. There are growing interests and research efforts in these areas particularly making them available and feasible in field implementation.

During any uncontrolled release of oil, the physical properties (e.g., viscosity, density, specific gravity, flash point, pour point, distillation, and interfacial tension) of the spilled oil and their changes due to weathering must be available to support impact assessment and response actions. Meanwhile, the fate and behaviour of the spilled oil are strongly determined by their chemistries. Oil analytical techniques are a necessary part of the scientific, environmental, and engineering aspects of oil spills. There are different methods to classify the chemical compounds present in crude oil that allows to analyze their properties. The primary method for oil analysis, as well as for many chemicals in the environment, is gas chromatography (GC). Other analytical methods are also used for oils, such as high-performance liquid chromatography (HPLC), thin-layer chromatography, and some spectroscopic techniques like infrared spectroscopy, Raman, and nuclear magnetic resonance (NMR) spectroscopy and also mass spectrometry. Recently, environmental scientists have also considered fingerprinting the diamondoid hydrocarbons as a promising forensic technique for oil spill studies. These naturally occurring compounds are thermodynamically stable, and therefore, they may have potential applications both in oil-source correlation and differentiation for those cases where the traditional markers (e.g., terpanes and steranes) are absent due to removal in the refining processes. In addition, marine biological resources are sometimes monitored and analyzed to guide response options and clean-up activities, or to assist in media and public relations management. Biological monitoring includes responses at sub-individual and individual level (e.g., physiological and epidemiological markers, biomarkers of exposure/effect and/or biological responses in ecotoxicological assays), as well as monitoring studies at population or community level (population dynamic and/or community structure parameters). In terms of habitats, monitoring may be divided into three broad habitat areas - surface water, water column and seabed.

The response strategy of oil spills involves different stages aiming at the minimization of size of the affected area and damage to vulnerable resources. This can be achieved by operations launched to contain, recover, and/or eliminate the oil on the water and near or on the shoreline. The physical/mechanical, chemical and biological technologies and equipment have been reviewed in detail from the perspectives of types, characteristics, configuration, operation, performance and

limitations. These techniques are primarily used as the emergent responding defenses that have limited operational time-window. Chemical methods such as in-situ burning, oil dispersion, solidification and surface washing have received growing attentions on not only the effectiveness and advantages, as well as the toxicity and biodegradability of involved materials. Bioremediation and natural attenuation are two commonly referred biological methods requiring relatively long operational time. These response and cleanup methods have also been compared comprehensively in terms of mechanisms, when to use, target oils and areas, characteristic of effective products, limiting factors, waste generation, and environmental impacts.

Considering significant impacts being caused by offshore oil spill, it is important and necessary to provide both long-term effective strategies and on-site sound decisions for offshore oil spill response and countermeasures. Mathematical modeling has play a growing and critical role in this area and the main techniques include: 1) Warning and assessment - to assess spills in an early stage and provide warning messages and levels. The current techniques are mainly based on analyzing the monitoring information such as Synthetic Aperture Radar (SAR) images and using geographical information systems (GIS) as well as statistical analysis. Some quantitative methods based on risk and performance assessment have received growing interests in research and practice. 2) Classification and ranking - to determine the type of a spill and the levels of warning and impacts with assistance of visual detection. Models to screen response technologies are also available but lack of power to incorporate dynamic information with experts' knowledge. 3) Simulation - to model ocean hydrodynamic conditions and oil weathering processes and to forecast spill trajectory in order to provide the emergency responders with information about the state of the spilled oil and the spatial and temporal distributions of the oil slicks. The oil transport and fate in the ocean are governed by physical, chemical, and biological processes (advection, diffusion, spreading, evaporation, dissolution, emulsification, degradation, sedimentation, etc.) that depend on the oil properties, hydrodynamics, and meteorological and environmental conditions. Consequently it is challenging to accurately and dynamically simulate all these processes and the complex mathematical treatments for idealized problems sometimes are not suitable for applications to real field problems. 4) Optimization - to seek the optimal decision sets of planning and operation in oil spill response given limited resources and time. Although optimization models have been widely used to support decision making in diverse fields, limited efforts have been reported to address the decision problems in oil response planning and on-site actions. 5) Decision support systems (DSS) - to comprehensively consider multi-dimensional factors, to integrate different modeling efforts, to evaluate alternative decision scenarios, and to help responders make response decisions in an more efficient and effective manner. Compared with the emergency responses to natural disasters (e.g., flood, hurricane, and tsunami), the research and development efforts in DSS for supporting offshore oil spill response are very limited and much desired. Particularly there is a lack of

integration of early warning, risk assessment, spill simulation, and response optimization into a general decision making framework.

In Newfoundland and Labrador (NL), impacts of oil spills have been reviewed in terms of economic impact, liability for damages and environmental effects. The economic and environmental impacts were mainly estimated from the assessment using modeling techniques and focused on the south coast of NL where oil transportation predominates. Companies drilling in NL are responsible for preventing, mitigating and managing any oil spills from their operations. The Canada Oil and Gas Operations Act and the Atlantic Accords provide regulatory supervision in terms of a blowout. With estimated undiscovered potential of 6 billion barrels of oil, Newfoundland and Labrador (NL) accounts for about 40% of Canada's conventional light crude output with promising prospects. Increasing risk of spills in the northern Atlantic and Arctic oceans have been widely recognized due to the expansion of oil and gas industry and the openings of new transportation passages as a result of global warming. NL has a harsh environment characterized by strong wind, low visibility, low temperature, rough seas, and ice coverage, which poses unique challenges for oil spill response. For example, the waves are too strong to allow containment of oil slick with booms from October to next March. The occurrence of visibility restricted to less than 1 km could be as high as 30% from May to July. The daylight hours in winter are less than 9 hours in various areas. The water surface can experience considerable amounts of ice during the winter months (e.g., over 70% ice coverage at Labrador Shelf in February). Oil spill is more problematical in such harsh conditions because of the simple and highly seasonal ecosystems and the logistic challenges of cleaning up spills in remote regions. The low temperature will also make hydrocarbons persist, making ice-edge communities particularly vulnerable.

In the aspect of oil spill detection, numerous difficulties are encountered. For example, ice is never a homogeneous material but rather incorporates air, sediment, salt, and water, many of which may present false oil-in-ice signals to the detection mechanisms. Snow on top of the ice or even incorporated into the ice adds complications. During freeze-up and thaw in the spring, there may not be distinct layers of water and ice. There are many different types of ice and different ice crystalline orientations, making oil spill monitoring in harsh environment more challenging. Crude oils and oil products behave quite differently if spilled in the cold weather/water and harsh conditions, due to the variations of their physical and chemical properties. These properties influence the selection of techniques and equipment applicable for monitoring and sampling.

Oil spill forecasting and modeling in NL also face challenges due to the harsh environments. Oil spill models are very sensitive to errors in the initial input data, such as the details of the release and the wind and current forecasts. Furthermore, the mathematical equations used to simulate oil movement are likely based on empirical approximations and assumptions and are subject to time step and grid limitations. Trajectory model uncertainty refers to changes in the forecast as a result of these errors. Unfortunately, quantitative assessment of the errors in trajectory

modeling is difficult and limited. In addition, oil spills are notorious for usually occurring in areas where the environmental data are temporally and spatially incomplete. This leads to a forecast process that often relies on the forecaster's subjective judgment and approximated input. Therefore, it become significantly challenging in oil spill early warning and modeling in offshore NL, especially in winter. In harsh environments, it is also extremely important to respond to offshore oil spills in a timely manner, and thus requires more reliable and effective decision making schemes considering limited access time/sites, equipment and man power. Unfortunately there is still no integrated DSS to incorporate modeling processes and support offshore oil spill response in NL.

The harsh environments prevailing in NL offshore also significantly hinder the application of oil spill countermeasures and reduce the effectiveness. Presence of ice is a key factor affecting the ability to respond to a spill. The fate and behavior of oil in ice-covered waters is governed by a number of important weathering processes have a direct bearing on oil recovery operations. The physical distribution and condition of spilled oil under, within or on top of the ice plays a major role in determining the most effective response strategies at different stages in the ice growth and decay cycle. Before oil spill response plans are developed or approved, it is important to understand the chemistry and physical behavior of the oil and how its characteristics change over time in harsh environments. Spill response operations in ice and open water are fundamentally different. These variances must be recognized when determining the most appropriate strategy for dealing with oil in specific ice conditions and seasons, including freeze-up, winter, and break-up. Because of the vastly different ice environments and oil-in-ice situations, over-reliance on a single type of response will likely result in inefficient, ineffective clean-up after an actual spill. Also, each season presents different advantages and drawbacks for spill response. During freeze-up and break-up, drifting ice and limited site access restrict the possible response options and considerably reduce recovery effectiveness. Mid-winter, although associated with long periods of darkness and cold temperatures, provides a stable ice cover that not only naturally contains the oil within a relatively small area but also provides a safe working platform for oil recovery and transport. In fact, presence of ice is not the only environmental factor affecting spill response. Temperature affects the consistency of oil and the speed at which it degrades. Winds and the resulting wave action are another two factors. High energy from wind and waves can help oil to disperse naturally, but it also breaks up a thick slick into multiple thinner slicks, which are more difficult to be addressed. In addition, waves are less effective at naturally dispersing oil in broken ice. Besides, most of the established countermeasures require the support of aircraft, vessels, and trained personnel to properly deploy and operate them. Remote locations and lack of infrastructure can impede these systems considerably. The cumulative impact of such limiting factors can make marine spill response operations near impossible for long periods of time in offshore NL.

In NL, it is particularly urgent and critical to improve the management strategies and decision making effectiveness in offshore oil spill response and countermeasures. To help address this concern, this study has proposed a general decision making framework with the following features: 1) integration of oil spill databases, early warning, risk assessment, technology screening, weathering and movement simulation, and response optimization; 2) quantitative reflection of system uncertainty (probabilistic and possibilistic) and complexity (dynamics and factor interactions) during modeling, response and countermeasures; 3) coupling approaches for interlinking system components (e.g., risk-classification, risk-optimization, simulation-optimization); and 4) special considerations of environmental conditions, resource availability, and time/site constraints during offshore oil spill response in the harsh environments prevailing in NL offshore areas.

9.2 Recommendations

9.2.1 General Recommendations

1) Impact Assessment. More considerations regarding the economic impacts due to the damage of environment are expected. The liability and compensation funds usually make decisions on the assumptions that environment can eventually restore itself after the spills, while this has been proven to be inappropriate and may cause underestimation of the impacts. In terms of environmental effects of oil spills, further efforts are expected on long-term monitoring of the affected ecological systems after the spills, which could provide critical evidences for the regulatory decision and policy making. It is also necessary to establish detailed intervention protocols that include some mechanisms to detect and control the possible harmful health effects that exposure to the spilled oil can induce. For example, timely collection of biological samples is important in order to establish the levels of individual internal exposure effects at the acute and chronic level, especially those related to genotoxicity. This will permit not only determination of the risk that exposure may involve, but also evaluation of whether protective devices used by the individuals in each case adequately fulfilled their function, or on the contrary they did not exert the required protection and therefore require to revision. More efforts should also be extended to the sociocultural and psychological impacts of oil spills which desire further studies to reveal a more comprehensive picture on how the impacted community suffered from the spills and provide information to the social service system to improve their works with the affected communities.

2) Regulations and Coordination. The fast development and growing exploration efforts (especially in the Arctic regions) of oil and gas industry lead to some new and more complex challenges upon the existing cumbersome legislation and implement processes as well as the unclear effectiveness of the regulations. As a result, further studies and efforts are desired in developing more effective legislation and response strategies. The organizational cooperation is one of the key

factors in determination of success in oil spill response operations. It is notably important to ensure more effective coordination and clear allocation of authorities and responsibilities between the key stakeholders/responders responsible for oil spill prevention and response.

3) Monitoring and Analysis. To improve the monitoring performance, incorporation of more updated information and new technologies is needed. The oil spill monitoring programs/systems in future should be in an integrated manner, for example, covering conditions of hotspots (e.g., oilrigs, sunken ships and seepages), ship routes, production/shipping operations, ecological databases, and meteorological and ocean conditions. Also, a key challenge in detection of oil spills in some satellite monitoring is the accurate discrimination between oil spills and look-alikes. Most low wind situations can be handled by analysing the surroundings of a slick, but natural films cannot always be properly distinguished from oil spills based on a satellite image alone. Additional information about algal blooms, for example, can be derived from multisensory studies and prior knowledge about the likelihood of observing alga in a given area at a certain time of the year. In terms of oil spill analysis, the promising environmental forensic techniques (e.g., oil fingerprinting and biomarking) as well as biological monitoring at multiple response levels and habitat areas should be given priority of support.

4) Preparedness and Response. Development of well-designed local, regional, and national contingency plans is always of necessity and importance to guide responsible organizations and personnel to prepare for and respond to oil spills. It is also important to study previous spill incidents to learn how the oil has affected the environment, what clean-up techniques work, and what improvements can be made, as well as to identify the gaps in technology. Because oil spill response is constantly evolving and each oil spill help generate a better preparedness for future incidents, contingency plans are thus constantly improved, ensuring enhanced protection of human health and the environment. Better understanding of the consequences of a spill and response actions is important to assess the limitations and effectiveness of response strategies and options, to refine response methods and technologies, and to improve response capabilities. For example, a response gap can be identified when the activities that may cause an oil spill are conducted during times when an effective response cannot be achieved, either because technologies available will not be effective or because their deployment is precluded due to environmental conditions or other safety issues.

5) Countermeasures. Although physical and mechanical methods (e.g., booms and skimmers) are widely used, it is desired to further understand their recommended employment for certain type and scale of oil spills according to the configurations and to develop more effective joint application schemes suitable for different spill situations. The effectiveness and toxicity of chemical agents used in oil spill cleanup have received growing attentions and research efforts are expected particularly through large-scale and/or field tests to better understand the limitations and long-term effects in real-world conditions. Bioremediation and

natural attenuation are environmentally friendly and cost-effective for the mitigation of oil spills but requiring relatively long operational time and lacking of in-depth studies on their treatment effectiveness and enhancement techniques under different environmental conditions. It is also recommended that more research efforts should be made on the scale-up and real-world application of these techniques and their merits to long-term remediation as well as the suitability in harsh environments.

6) Modeling. Considering the more important role of mathematical modeling in oil spill response, future research and development efforts are recommended focusing on the following areas: 1) Quantitative methods such as risk-based and safety performance based assessment to evaluate impacts and indicate warning levels; 2) response technology screening methods with the improved features with which they can more effectively incorporate dynamic information with experts' knowledge, reflect system uncertainties and complexities, and quantity intrinsic value of the environment; 3) integrated simulation models capable of accurately and dynamically simulating ocean hydrodynamics, oil weathering and spill trajectory in a more realistic conditions and more effectively supporting field applications; and 4) optimization models being able to address the decision problems in oil response planning and on-site actions. Particularly, risk-based or simulation-based optimization models that can timely determine the best combination of technologies and allocation of resources at different response stages should be developed in order to achieve a most time-efficient and cost-effective response to an oil spill. This would be especially valuable for the areas where unpredictable weather conditions and harsh environments prevail.

7) Decision Making. Integrated decision support systems with abilities in comprehensively incorporating early warning, risk assessment, spill simulation, and response optimization into an general decision making framework. In order to more effectively support offshore oil spill response and countermeasure, new approaches that can effectively tackle the coexistence of uncertainty and complexity need to be developed for providing support to stakeholders or decision makers at different levels such as: general policy makers (e.g., regulators and oil producers) for long-term policy making and trade-off, risk and reliability analyses of the offshore oil spill management; project/production managers and spill responders in designing of contingency plans and/or planning of oil and gas production and transportation in medium-term arrangements; and operators in making on-site decisions and carrying out response and cleanup actions.

7) Others. Successful spill response hinges on more than the immediate availability of the best technology. Other important non-technical issues should also be considered when planning spill response programs and operations: encouragement of more flexible regulations so that all possible response tools can be considered for use from the outset of a response; development of long-term education and public outreach programs to explain the advantages and disadvantages of different response strategies; and application of multi-disciplinary

knowledge as part of net environmental benefit analysis to assess the relative merits and shortcomings of different response strategies and alternatives.

9.2.2 Special Recommendations for the Harsh Environments in NL

This study has reviewed and identified the key knowledge gaps and technical challenges associated with oil spill response and countermeasures in the offshore areas of Newfoundland and Labrador (NL), which are featured with harsh environments (e.g., strong wind, low visibility, low temperature, rough seas, and ice coverage). Consequently significant research and development efforts should be supported focusing on a variety of challenges related to the harsh conditions as discussed in this report such as:

- Baseline conditions and comprehensive monitoring methods of marine ecological systems and water quality;
- Social-economic and ecological impacts as well as health risks caused by oil spills due to the expansion of petroleum and shipping industry and the openings of new transportation passages in the Arctic ocean;
- Vulnerability and risk of the remote and/or ice-edge communities affected by oil spills;
- Chemistry and physical behaviors of spilled oil on/in/under ice and how its characteristics change over time in harsh environments;
- Effects of presence of sea ice on oil weathering and movement as well as the feasibility and effectiveness of monitoring, modeling, response and cleanup techniques;
- Persistence and degradation changes of spilled oil due to low temperature;
- Effects of wind and waves at different energy levels on weathering, movement and containment of oil slicks;
- Influences of reduced visibility in oil spill monitoring and response effectiveness and technical feasibility;
- Uncertainties associated with the weather and ocean conditions and the impacts on spill modeling and response decision making;
- Logistic issues and possible solutions of cleaning up oil spills in remote regions;
- Advantages and drawbacks for spill response due to seasonal changes as well as the adaptation techniques;
- Adaptation of long-term contingency plans, management strategies, on-site response decision to harsh environmental conditions as well as climate changes;
- Reliability and effectiveness of decision making schemes and approaches considering limited access time/sites, equipment and man power in harsh environments; and
- Integration of monitoring, assessment, simulation and optimization into offshore oil spill response decision support systems.

It is also recommended for an exploration and review in greater detail of the structures, responsibilities, roles, and capacities of the responsible parties in NL including petroleum producers (e.g., Exxon Mobile, Husky, Chevron and Suncor), regulators (e.g., C-NLOPB), and response organizations (e.g., ECRC). A greater collaboration between these parties should be promoted for preparing, responding and practicing in advance of a spill event. Besides, comprehensive studies are also suggested focusing on the issue of liability, including whether the thresholds should be adjusted to reflect current economic and environmental realities.

Offshore operators are required by the Atlantic Accords to put aside a fraction of project revenues towards research and development as well as education and training activities in NL. These benefit plans may emphasize on addressing challenges concerning the unique features of the harsh conditions in NL offshore areas. Investigations on how the existing technologies for oil spills monitoring, forecasting and response perform in these conditions should be conducted to fill the knowledge and technical gaps. Meanwhile, more research and development expenditures should be paid into the innovation of novel technologies customized with the specific characteristic of NL offshore oil spills.

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