A Review of Recent Innovations and Current Research In Oil and Chemical Spill Technology

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Prepared by:

and

The Ecology Lab Pty Ltd

Marine and Freshwater Studies
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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summary</td>
<td>1</td>
</tr>
<tr>
<td>1.0 Introduction</td>
<td>8</td>
</tr>
<tr>
<td>2.0 Scope of This Review</td>
<td>9</td>
</tr>
<tr>
<td>3.0 Recognised Limitations in Spill Response Technology</td>
<td>10</td>
</tr>
<tr>
<td>4.0 Recent Innovations in Spill Response Technology</td>
<td>12</td>
</tr>
<tr>
<td>4.1 Spill Preparation, Testing and Training</td>
<td>12</td>
</tr>
<tr>
<td>Local-scale Sentry Systems</td>
<td>13</td>
</tr>
<tr>
<td>Innovations in Wide-scale Remote Sensing Systems</td>
<td>14</td>
</tr>
<tr>
<td>Innovations in the Detection of Submerged Oil Slicks</td>
<td>19</td>
</tr>
<tr>
<td>Innovations in the Detection of Oil In and Under Ice</td>
<td>20</td>
</tr>
<tr>
<td>Innovations in the Identification of Oils</td>
<td>20</td>
</tr>
<tr>
<td>4.2 Spill Detection, Surveillance, Tracking and Measurement</td>
<td>13</td>
</tr>
<tr>
<td>Innovations in Wide-scale Remote Sensing Systems</td>
<td>14</td>
</tr>
<tr>
<td>Innovations in the Detection of Submerged Oil Slicks</td>
<td>19</td>
</tr>
<tr>
<td>Innovations in the Detection of Oil In and Under Ice</td>
<td>20</td>
</tr>
<tr>
<td>Innovations in the Identification of Oils</td>
<td>20</td>
</tr>
<tr>
<td>4.3 Improved Electronic Spill Prediction and Response Management Systems</td>
<td>21</td>
</tr>
<tr>
<td>Innovations in Oil Spill Trajectory and Fates Models</td>
<td>21</td>
</tr>
<tr>
<td>Innovations in Data Assimilation to Improve Trajectory and Fates Modelling</td>
<td>24</td>
</tr>
<tr>
<td>Innovations in Electronic Spill Management Software</td>
<td>27</td>
</tr>
<tr>
<td>4.4 Containment Devices</td>
<td>29</td>
</tr>
<tr>
<td>Innovations in Performance Testing</td>
<td>30</td>
</tr>
<tr>
<td>Innovations in Containment Technology</td>
<td>30</td>
</tr>
<tr>
<td>Other Containment Innovations</td>
<td>33</td>
</tr>
<tr>
<td>4.5 Oil Recovery Devices</td>
<td>34</td>
</tr>
<tr>
<td>Innovations in Performance Testing</td>
<td>34</td>
</tr>
<tr>
<td>Innovations in Fast Water Oil Recovery</td>
<td>35</td>
</tr>
<tr>
<td>Innovations in Oil Recovery in High Wave Conditions</td>
<td>36</td>
</tr>
<tr>
<td>Testing and Development of Skimmer Performance for Problem Oil Types</td>
<td>38</td>
</tr>
<tr>
<td>Innovations in Pumping and Handling of High Viscosity Oils</td>
<td>40</td>
</tr>
<tr>
<td>Innovations in Emulsion-Handling</td>
<td>40</td>
</tr>
<tr>
<td>4.6 Innovations in Oily-waste Treatment, Handling and Recycling</td>
<td>40</td>
</tr>
<tr>
<td>4.7 In situ Burning of Oil Spills</td>
<td>42</td>
</tr>
<tr>
<td>4.8 Chemical Oil Spill Treatment Agents</td>
<td>42</td>
</tr>
<tr>
<td>Research on Chemical Dispersants</td>
<td>43</td>
</tr>
</tbody>
</table>
Decision Support for Dispersant Application ................................................................. 45
Surface Washing Agents ............................................................................................... 46
4.9 Shoreline Clean-up ................................................................................................. 48
Bioremediation ............................................................................................................... 48
4.9 Wildlife Impact Management and Minimisation ..................................................... 50
Oiled Wildlife Care Facilities ....................................................................................... 50
Innovations in Oiled Wildlife Protection ....................................................................... 54
4.10 Developments in Chemical Spill Response ........................................................... 55
5.0 Funded research efforts by International agencies ..................................................... 58
5.1 Minerals Management Service (Department of the Interior, USA Government) .... 58
   Environmental Studies Program ................................................................................ 58
   Oil Spill Response Research Program ...................................................................... 60
5.2 Environment Canada (Canadian Government) ........................................................ 61
5.3 European Commission ............................................................................................ 62
Acknowledgements ....................................................................................................... 63
References ...................................................................................................................... 64
Links to information available on the World Wide Web ................................................ 75
Figures
Figure 1: Location of instrumentation for the Texas Automated Buoy System ............. 26
Figure 2: Prototype of the Bay Defender under test at OHMSETT ............................... 31
Figure 3: NOFI Current Buster in towed sweep configuration during field and tank tests 32
SUMMARY

This review aims to summarise recent innovations and current world-wide research in the areas of oil and chemical spill response technology. It does not attempt to synthesise information on the extensive commercially available technologies except where research addresses the limitations to such equipment and technologies. The scope of the review is limited to spills affecting marine and estuarine water relevant to Australian conditions. Data were collected from a wide range of sources with focus on post 1998 international conference proceedings, trade notes and publications as well as information published on the World Wide Web, particularly by primary research organisations. The text contains web links presented as numbered hyperlinks which, while correct at the time of writing (July 2003), may become inactive in the future.

Some of the general findings of the review are summarised below.

Spill Preparation, Testing and Training

Contingency plans are now required by responsible parties but vary among jurisdictions and have potentially conflicting structures. The US EPA has developed a Selection Guide for Oil Spill Applied Technology to provide decision making information to support rapid selection of suitable responses for given circumstances and guidance on their implementation and monitoring. The guide seeks to be a source of best available information on a wide range of countermeasure techniques, with regular updating and distribution via the world-wide web.

Free software developed by the USEPA (The Oil Spill Response Drill Generator) aims to assist the testing of plans by allowing users to enter locally specific information, weather conditions and appropriate objectives to be tested. The program generates the initial scenario as well as time and response dependent developments that are introduced as the response develops. An evaluation checklist is provided to track responses and aid assessment and feedback by an assessor.

Spill Detection, Surveillance, Tracking and Measurement

Several early warning systems (SPAWAR, OSPRA and Genesis Alert) have been marketed that extend the detection capabilities of local-scale systems using linked sensing buoys and improved detection of thin oil layers by absorbance of electromagnetic pulses. Local-scale sentry systems using floating buoys have inherent range limitations of < 1 m, are subject to damage by ships and require large numbers of buoys to effectively cover a broad coastal area or harbour. Of the range of existing technologies, only infrared and ultraviolet cameras supported by automated image processing technology are considered practical and cost effective.

Research on wide-scale remote sensing systems has focussed on expanding the operational limits of infrared, ultraviolet and satellite sensors. Satellite-based Synthetic Aperture Radar (SAR) systems function in cloudy conditions and provide broad coverage but can be limited by wind, sea state, the limited resolution of SAR images, the restrictions in revisit times and hence global coverage currently available. The issues of long image processing times and “false positive” images that have deterred the use of satellite image as real-time oil spill detection systems are being addressed by attempts to more fully automate image processing and issuance of warnings. The European-based ENVISYS system combines hardware, software and communications systems to improve detection and verification of spills and provides GIS-based information to allow assessment of options and risks. Successful field trials have not proceeded to commercial operation, but the technology may be transferred to a new joint project, OCEANIDES.
A Canadian system, Ocean Monitoring Workstation, which has been in operation since 2000, processes data from two satellites to automatically detect oil slicks within a short time (tens of minutes) of each overpass. The system provides geo-referenced maps to facilitate analysis, tracking, forecasting and cleanup.

Satellite sensor detection of oil slicks in Australia is currently hampered by limited numbers of overpasses, long image delivery times and lack of automation and routine monitoring. The planned launch of technologically advanced SAR sensors should offer faster revisit times, improve resolution and reduce the frequency of false-positive images. However, inherent shortcomings of the sensor system, such as the requirement for a restricted range of wind conditions and the inability to measure the weathering state or thickness of slicks has generated increased interest in development of advanced sensors for use from air-craft.

A current European research project (RAPSODI) aims to integrate and develop a wide-scale sensing system by combining current airborne sensors (SAR, SLAR, IR, UV and microwave radiometry) with space mounted SAR. Canadian efforts over the past several years have focussed on development of new airborne sensors. Unfortunately, development has not successfully extended beyond prototype stage to date.

Recent research in Australia has applied the use of airborne systems using hyperspectral sensors (CASI-2) to detection of oil slicks. The sensor proved capable of defining the shape of slicks with high contrast at sub-metre resolution. The system also differentiate various oil types, measured the thickness of slicks and differentiated oil slicks from “false targets”.

### Detection of Submerged Oil Slicks

Although there are currently no proven remote sensors that can detect submerged oil, approaches utilising high frequency echo sounders, side-scan sonar, range-gated fluorosensors have been trialled experimentally. Sonar, laser fluorosensors and hyperspectral scanners show promise in this application.

### Oil Spill Trajectory and Fates Models

A catalogue of available decision support software was published in April 2000 and promises to be updated. It details information on specific software systems, including two-dimensional trajectory and fates models, three-dimensional models, response evaluation models, response training and evaluation simulators, cost and accounting systems and various other aspects of spill prediction and response management.

Many existing two-dimensional fates models have been updated or refined, with improvement in the specificity and accuracy of data on weather conditions, oil types and links to GIS systems to aid in spill tracking. Many models now include tools for quantitative assessment of alternative response strategies and risk statistics.

The advent of fully three-dimensional models represents a significant improvement in the development of oil spill fate models. These models more accurately estimate the transport, dispersion and in-water concentrations of biologically-available compounds that would be expected at various water depths, with some models incorporating estimations of exposure effects to indicate the potential biological impacts. The US EPA NRDA model uses extensive databases on abundance and distribution of aquatic biota to estimate their movements and mortality (based on corrected L_{50} data) and can quantify future stock losses for commercially important species. The three-dimensional models have proven useful in estimating the net environmental benefits from responses that involve a trade off of risks between surface and subsurface habitats and biota.
**Data Assimilation to Improve Trajectory and Fates Modelling**

Advances have been made in the developments of data capture and transmission systems required for accurate, near real-time data input to three-dimensional models. Examples include the use of shore-based HF Radar systems to measure surface currents and dispersion coefficients and relay them in near real-time for input into an oil spill trajectory model, the use of automated current buoy systems that measure data on currents, temperature, wind and waves and transmit the information in near real-time using cellular phone and satellite links. These data are posted to a public web site within a few hours of capture, enabling their use in an oceanographic model that supplies predictions of sea conditions in the following 24 hours.

Recent advances in satellite technology have improved the collection of altimeter data from satellites which supply sea height data required to predict oil spill paths in areas where sea circulation is dominated by geostrophic forces (density driven). CSIRO has developed procedures for processing of altimeter data for Australia from three satellites, which, combined with coastal tide gauge data allow average (over 5-days) current patterns to be estimated on an 18 km scale. The properties of this relatively new data source require further investigation. However, a number of studies have shown that the ability of pollution transport models to predict the path of real oil spills in areas where large-scale currents dominate are improved by assimilation of satellite-derived altimetric-current data.

**Electronic Spill Management Software**

Geographic Information Systems (GIS) are now widely used for spill planning and response because they support collation and preparation of spatially-referenced information on the location, nature and sensitivities of different resources in a way that can be rapidly accessed. Recent efforts in the development of GIS systems applied to oil spills have focussed on collection and pre-coding of information on individual coastal resources, including their sensitivity to oil and the most appropriate strategy for protection and clean-up. Some progress has been made in linking software systems that have been developed to integrate data sourcing, mapping analysis, communication, data logging and accounting requirements for the management of a crisis into one system. The On-Scene Command and Control System (OSC), an interactive system developed for the US Coast Guard that views, tracks and manages resources and forecasts the future development of an oil spill crisis has now been developed into CMSMAP, which is designed to log, track and control resource allocations and communications as well as produce forecasts for a wide variety of marine incidents. These include oil and chemical spills, shipping accidents, search and rescue efforts and evacuations. Other interactive databases such as AIMS have been developed that comply with the Command System format. The focus of these systems is on integrating communications with resource tracking. GIS is used to display and track resources geographically.

**Containment Technology**

The main focus of new designs for booms is the improvement of boom efficiency in current speeds greater than 1 knot. A number of innovative booms have been developed. The Ramp Boom has a fixed inclined plane forward of two inflatable booms. Tests have shown collection rates of 100% at 1 knot and 86.5% at 1.5 knots, but critical loss of oil still occurred before 2 knots. The Bay Defender utilises inclined plane and trailing hydrofoil components and has achieved efficiencies of over 40% at speeds up to 3 knots, but is not effective at recovering light oil. The NOFI Current Buster and Ocean buster are the only high-speed booms with proven capabilities that have reached commercial production. These inflatable booms operate in the apex of a sweep boom and provide an expansion chamber to reduce
the apparent current speed relative to the current or tow speed. Field tests for the Current Buster have resulted in 90% recovery of oil with towing and current speeds up to 4.5 knots. The Ocean Buster is a larger-scale version designed to operate at speeds up to 4 knots in rougher seas. Boom deflectors have been developed that can assist the performance of conventional booms in currents between 1.5 and 8 knots. One variant is the Current Rudder, which can be used to deploy booms remotely from shore or to control the leading edges of a side or trailing sweep boom. The Flow-Diverter can be used in currents over 5 knots and is designed to deflect oil slicks and patches across the flow or and away from sensitive resources.

**Performance Testing of Oil Recovery Devices**

Recent developments in performance testing for oil recovery devices include a review of test data for different skimmer types, development of performance standards for devices that remove floating oil, a two stage certification system for skimmers and protocols for performance testing of sorbents.

**Fast Water Oil Recovery**

There have been innovations in the testing and development of devices to recover oil in fast currents. Four types of oil collection devices have been tested that operate in current speeds of up to 5 knots in calm to choppy sea conditions. Inverse dynamic incline plane skimmers, high speed weir types skimmer and high speed circus skimmers all effectively collected oil at speeds up to 2 knots with calm water, but all systems had reduced efficiency with increasing current speeds and wave action. Only sheet sorbent boom systems were inefficient in test speeds less than 2 knots. Several manufacturers have developed new skimmer units that have improved performance in higher current speeds and wave action.

**Oil Recovery in High Wave Conditions**

A large device, the Mitsubishi Oil recovery Scoop is currently in use in Japan. Other research in Japan is underway to develop skimmers with improved performance in high wave action conditions.

**Skimmer Performance for Problem Oil Types**

A number of innovations have been made in the assessment of skimmer performance, and development of new skimmers better suited to problematic oils. Research carried out in Norway by SINTEF has developed standard test protocols for oleophilic rope-mop skimmers against different oil types, with an emphasis on oils that have been weathered to form viscous emulsions. SAIC Canada, in collaboration with Environment Canada, has developed test protocols for the performance of sorbent materials and oleophilic skimmers to collect canola oil from water. A Canadian company has developed a specialised skimmer for problematic extreme viscosity oils such as bitumen and Orimulsion which works by refloating the bitumen particles into a viscous layer for sufficient time to be collected using a conventional boom and mechanical-feeder type skimmer.

**Pumping and Handling of High Viscosity Oils**

Modifications have been made to one of the most widely used heavy oil transfer pumps (GT-185) involving the addition of stream or hot water injection to outlet and inlet ports, resulting in a 40 fold improvement in the capacity to pump heavy oils such as bitumen.

**Emulsion Handling**

Testing of the injection of emulsion-breaking chemicals have shown that they can be used to reduce the water content of water-oil emulsions, and thus can extend the storage available
for on-water containment; however the decanted water may have unacceptably high concentrations of Total Petroleum Hydrocarbons (TPH) for on-site release. Therefore, this technology requires further investigation before it is widely adopted.

**Oily-waste Treatment, Handling and Recycling**

No notable improvements have been made to the use of vessel-based oil/water separation devices and land-based separators remain the only practical option for large spills in open water. Similarly, few recent advances have been made in the collection of oil that strands on shore. Investigations have been carried out to compare various treatment regimes in comparison to the option of applying no treatment and allowing natural degradation processes to operate. These have generally considered both the efficacy of the treatment and the impact on recovery of the system. In general, intensive recovery efforts have commonly yielded negligible results. Burial of sediments in situ, which has been considered an acceptable option for small quantities of oil grounded on sand, gravel and boulder-cobble shores may substantially delay degradation of stranded oil. Evaluation of hydraulic washing for oiled substrata has established that cool or luke-warm water is effective and does not cause mortality of resident fauna. A sand washer recently developed by the Lamor Corporation uses hot water and is acceptable only where sand can be sterilised.

**In Situ Burning of Oil Spills**

Active research is underway in the USA to test efficiency of in-situ burning as functions of oil type, temperature, weathering, emulsification and production and dispersion of airborne contaminants. The ability of fire booms to survive burn-offs has also been tested. The effects of burning on atmospheric and water emissions have also been the subject of research and the concentrations of particulates in air have been measured for crude oils and diesels, allowing construction of tables that outline safe distances for fires of different type and volume.

**Research on Chemical Dispersants**

Recent research has focussed on testing oil and dispersant combinations that are more representative of actual field conditions in order to eliminate discrepancies of past tests whose outcomes have been dependent of test conditions. Wave height and water temperature are two factors found to be important in deriving accurate oil-to-dispersant ratios. A database has been developed specifically to address the problem of dispersing heavy oils.

The Neat Sweep dispersant delivery system is one of the most significant hardware innovations for vessel-towed application of dispersants. This commercially available system combines a sweep boom, which concentrates oil patches into a narrow swath of more uniform thickness, with an automated spray delivery system. The system significantly increases treatment rates and reduces the waste of dispersants common to conventional spray systems.

**Decision Support for Dispersant Application**

The use of dispersants remains controversial. Legislation in most jurisdictions requires that a proponent demonstrate Net Environmental Benefit to justify the use of dispersants. However, in Australia and internationally, there have been few efforts toward development of decision support systems for the application of dispersants. Most efforts have been carried out in the USA, where modelling and field studies have been carried out to determine appropriate conditions under which the use of dispersants would result in a preferential environmental outcome. Most of these studies have concluded that the use of dispersant would actually reduce the net environmental harm.
Surface washing Agents

A review of surface washing agents concluded that most were effective in field trials, but their use can result in unacceptably high dispersion of oil into the water column. Although surface washing agents have met testing and documentation requirement in the USA, no manufacturers or suppliers have submitted documentation required for their use in Australia.

A standard guide has been developed by ASTM International that advises spill responders on cleaning agents that can be use for shoreline cleanups, but does not cover chemicals formulated as dispersants.

Shoreline Clean Up and Bioremediation

A number of programs have investigated natural or enhanced biodegradation as a viable clean-up strategy. Research in the USA has found that populations of oil-degrading bacteria are ubiquitous, but their populations tend to be larger near anthropogenic oil inputs. Screening tests for the effectiveness and toxicity of bioremediation agents have been developed for a variety of habitats and temperature regimes, but sources of inoculating cultures differ. Field bioenhancement trails have had mixed results, due in part to the variable response of the agents under different physical conditions. The weight of evidence suggests that the combination of fertilisation and physical treatment (such as tilling) to enhance oxygen supply can increase biodegradation rates, but fertilisation in the absence of physical treatment is unlikely to increase oil degradation rates.

Wildlife Management and Minimisation

Stimulated by legislation-generated funding, a large number of care facilities have been developed in the USA, particularly in California, to rescue and rehabilitate aquatic birds, sea otters and other marine mammals. Networks of care facilities, care professionals and volunteers have developed in the USA and other countries, and some have been active in the development of improved animal handling and treatment and co-ordination of spill response. Much of this research focuses on species found only in the USA or northern hemisphere and may not be readily transferable to Australian fauna. By comparison, care facilities and research efforts are very limited in Australia, due to a lack of funding.

Protocols for the care of oiled birds and marine mammals have been developed by the Oiled Wildlife Care Network (OWCN) in the USA. In Australia, protocols for the care of oiled birds have been developed but these require revision based on international experience. National guidelines for the development of oiled wildlife contingency plans have been issued as a contents guide, with recommendations that the States and Territories prepare plans appropriate to their jurisdictions.

The International Alliance of Oiled Wildlife Responders is to be launched as a new professional association that aims to establish international standards and guidelines for oiled wildlife response globally.

Developments in Chemical Spill Response

Compared to oil spill response technology, the development of equipment, techniques and systems to handle non-oil chemical spills have received less attention. Three-dimensional models have been developed that consider the wider range of physical states (powders, crystals, blocks, colloids, etc) and behaviours (dissolution, reaction, evaporation, etc) presented by chemical spills and these have been applied to assist decision makers to monitor spills for environmental and personnel safety. Other systems have been developed to provide rapid access to materials safety data.
Funded Research Efforts by International Agencies

Support of research into oil spill response technology has been concentrated in the USA, Canada and some European countries. A review of the current research programs by various countries suggests that the USA and Canada continue to be the focus of research.

In the USA, The Minerals Management Service, a bureau of the Department of the Interior, provides multiple-million dollar recurring funding to support programs of research covering various aspects of spill response technology.

Environment Canada supports a range of projects focussing on the properties, behaviour, and effects of spilled hazardous materials.

Until recently, funding for research to improve oil spill response technology in Europe has been provided by the European Commission, through the Joint Research Centre. However, the current round of research programs does not list any projects directly related to oil spill response.
1.0 INTRODUCTION

On an international scale, oil spills into the marine environment are relatively frequent events (Fingas 2001). The majority of these spills are small. However, incidents that require protracted and intense clean-up efforts continue to occur (www.spillpoint.com).

Knowledge of oil spill behaviour and an armoury of procedures and equipment to limit and respond to spills have developed greatly over the past three decades (Fingas 2001, IMO 2002). Despite this, control and cleanup of oil spills on the sea continues to be a significant challenge due to the highly variable nature of spills and the large number of complicating factors introduced by the environment into which they occur.

No two spills will be exactly alike. They differ in terms of the physical and chemical nature; volume, release rate and duration; location relative to sensitive habitats, and other resources; environmental conditions such as winds, waves, currents and temperature; access for responders and equipment; dangers to responders and local residents; harm to wildlife and a host of other factors. Consequently, to be effective, spill responders require an array of tools for:

- Spill detection, measurement and tracking;
- Forward prediction of the trajectory and fate of the spilled oil;
- Decision support, response selection and consequence testing;
- Monitoring the efficacy of response actions;
- Communication and tracking of personnel, equipment and consumables;
- On-water containment, treatment and recovery;
- Shoreline protection and clean-up;
- Storage and handling of recovered oil and oiled waste;
- Wildlife protection and treatment of affected wildlife;
- Cost accounting and documentation

Existing knowledge in all of these areas is incomplete and further investigations will be required to improve this state of knowledge (IMO 2002).
2.0 SCOPE OF THIS REVIEW

The objective of this report is to review recent innovations and current world-wide research efforts in the area of oil and chemical spill response technology. The scope is limited to technology relevant to spills into or affecting marine and estuarine waters and has relevance to Australian conditions. As Australia’s National Plan to combat pollution of the sea covers a wide range of geophysical conditions, information relevant to cold-water, temperate and tropical zones were reviewed. This review does not attempt to review the extensive body of information on commercially-available equipment that uses existing technology, except to highlight any recently noted limitations that have been recognised with this technology as a benchmark for defining the impetus for development and the performance of new and emerging technologies.
### 3.0 RECOGNISED LIMITATIONS IN SPILL RESPONSE TECHNOLOGY

The focus of the Second International Oil Spill Research and Development Forum was the development of priorities for future research and development (IMO 1995). Twenty seven priority issues were identified during debate of each area of response and then prioritised by vote-ranking (Table 1).

**Table 1: Twenty seven research priorities identified and prioritised by the 2nd International Oil Spill Research and Development Forum (1995).**

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<td>1</td>
<td>Determine consequences and trade-offs of alternative clean-up countermeasures</td>
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<td>Studies of natural removal rates and processes for oiled shorelines</td>
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<td>Develop criteria for environmental conditions where bioremediation is recommended</td>
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<td>Standard approval tests for dispersant toxicity/efficacy</td>
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<td>Guidelines for safe conditions for near-shore dispersant use</td>
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<td>6</td>
<td>Provide user-friendly information from R &amp; D programmes</td>
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<td>7</td>
<td>Develop standard measurement and analytical techniques for oil-fate processes</td>
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<td>Development of rational data sets to be monitored during spills</td>
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<td>Establish the contribution of different bioremediation treatments</td>
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<td>Involve users in R&amp;D project specification</td>
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<td>International guidelines for oil-spill source identification</td>
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<td>Development of advanced communications technology</td>
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<td>Need for a standard reporting system for oil spill incident databases</td>
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<td>Develop surveillance and recovery techniques for submerged oils</td>
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<td>Improved methods for oil-spill recovery in fast currents</td>
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<td>16</td>
<td>Studies into fish tainting associated with fish farms</td>
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<td>Agreed standardized format for oil-spill training</td>
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<td>Understanding of interaction between oil and mineral fines</td>
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<td>Develop simple models aimed at user needs</td>
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<tr>
<td>20</td>
<td>Improved user-friendliness of oil spill models</td>
</tr>
<tr>
<td>21</td>
<td>Develop means to enhance natural range of burning for oil spills</td>
</tr>
<tr>
<td>22</td>
<td>Guidelines for remote sensing requirements</td>
</tr>
<tr>
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<td>------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>23</td>
<td>Evaluate fire-resistant booms in realistic circumstances</td>
</tr>
<tr>
<td>24</td>
<td>Evaluate natural film-forming chemicals for shoreline protection</td>
</tr>
<tr>
<td>25</td>
<td>Improved accuracy of oil-spill behaviour models</td>
</tr>
<tr>
<td>26</td>
<td>Validation of prevention and mitigation measures, through prototype testing</td>
</tr>
<tr>
<td>27</td>
<td>Assemble global database of oil spills</td>
</tr>
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</table>

In terms of the need and scope for progress to be made, the overwhelming indication was that participants were heavily focussed on the need to solve practical problems and enabling responders to make better decisions about the suitability of current response strategies. The area of research that received outstanding support at that time was determination of consequences and trade-offs associated with different clean-up strategies, with emphasis on shorelines. Other well-supported themes were the need for improved integration of the various clean-up techniques, and the need to develop specialised equipment and techniques to respond to spills under difficult conditions, such as fast-water containment and recovery devices.

Since that time, there has been a substantial body of research, field trials and practical application of innovative approaches conducted internationally, much of which addresses one or more issues identified at the abovementioned forum. However, the Third International Oil Spill Research and Development Forum and other recent reviews of spill response capabilities indicate that further work is required, especially in relation to handling of heavy fuel oil, operations in difficult and hazardous conditions, improved methods of shoreline clean-up, development of alternative countermeasure and development of improved salvage technology, especially in relation to recovery of oil from sunken vessels (IMO 2002, Burns et al. 2002). The persistence of a gap between oil spill research and practical application of developed technologies has recently been argued and possible reasons explored (Goodman 2002).

A quantitative assessment of the impact of oil spill technology improvement in selected areas of response (mechanical recovery, dispersant treatment and in-situ burning) has recently been made by estimating the cost savings that could have been made if currently available technology were applied to historic, well-documented spill events. Costs were estimated in terms of shore-line clean-up effort and expense, socio-economic and environmental damage taking account of whether current technologies could have been applied in the specific circumstances of each spill. The analysis indicated that a substantial net cost saving should be realised due to advances that have been made but responses were still not possible for some of the past events (Etkins et al. 2003).
4.0 RECENT INNOVATIONS IN SPILL RESPONSE TECHNOLOGY

4.1 Spill Preparation, Testing and Training

Planning and preparation have long been recognised as vital for effective response to spills. Contingency plans are now required by responsible parties in most jurisdictions internationally, and guides to plans have been produced by a number of authorities (IPIECA 2000, 1). Contingency planning arrangements and structures vary among jurisdictions with the potential for confusion among responders. The most recent summary of oil spill response arrangements and resources worldwide was published earlier this year by the International Tanker Owners Pollution Federation Limited (ITOPF 2003). This document summarised the spill notification points, competent national authority, response arrangements, national and states response policies, equipment levels and international conventions followed in each country. One major area of conflict among contingency plans used in different jurisdictions has been the command structure that is followed. The Incident Command System is followed in the USA but has not been widely adopted internationally due to the perceived complexity of the structure.

One function of an effective contingency planning and spill preparation exercise is to identify and pre-evaluate potential response technologies. To aid this process, the US EPA has developed a Selection Guide for Oil Spill Applied Technology [2]. The guide provides decision making information to support rapid selection of suitable responses for given circumstances and guidance on their implementation and monitoring. This selection guide seeks to be a source of best available information on a wide range of countermeasure techniques, with regular updating and distribution via the world-wide web.

Exercises are used widely to test contingency plans and provide valuable training to personnel. In the USA and Canada legislation has been in place for over a decade which requires parties responsible for contingency plans to conduct regular field deployment and table-top exercises, with evaluation and feedback from independent evaluators. A recent review of the experiences gained under this environment has stressed the value of variety, challenge and an element of surprise in exercises as well as the importance of consistent scrutiny and follow-up by overseeing authorities (Taylor & Green 2001). Recent legislative changes in the USA brought in by the Spill Prevention Control and Countermeasure rule (2002) now include the provision for unannounced tests of spill contingency plans to be conducted by regulators, with the threat of economic and other sanctions where plans and preparedness do not meet requirements. These changes have been made to provide incentive for companies to strengthen commitments to preparation and planning.

Recent innovations to assist the testing of plans include the development of software to generate realistic scenarios for response drills. The Oil Spill Response Drill Generator software was developed by the USEPA and allows users to enter locally specific information, weather conditions and appropriate objectives to be tested. The program generates the initial scenario as well as time and response dependent developments that are introduced as the response develops. An evaluation checklist is provided to track responses and aid assessment and feedback by an assessor. The software is distributed free on request from the US EPA web site [3].
4.2 Spill Detection, Surveillance, Tracking and Measurement

When a spill occurs there is a need to detect the slick as early as possible and to gather useful spatial information on the slicks that will help responders. There have been a number of advances in the area of spill detection and measurement. These range from systems that automate the monitoring of harbours or restricted waterways through to advances in wide-scale remote sensing systems.

Local-scale Sentry Systems

A number of oil spill sentry systems have been developed following the principle that early warning of spills should improve the opportunity for a timely response and potentially minimize the quantity of oil that is released, and enhance the policing of illegal spills. The principal application areas are high risk-sites where spilled oil has a good chance of directly encountering the sensor, such as oil bunkering and refuelling sites, terminals, refineries, oil platforms, trafficable estuaries, discharge channels etc.

Floating “sentry” type systems have now been available for over a decade, using a variety of sensing technology. Most consist of a base station that monitors one or more floating sensors. An early system, which is currently marketed as the Leakwise interface sensor, measures the absorption of an electromagnetic pulse delivered to the water interface. The presence of oil is detected as a lower absorption rate. The sensor is triggered by oil on water layers exceeding 0.3 mm and is capable of measuring oil thickness. Leakwise was developed and is marketed by Agar Corporation [4].

SPAWAR Systems Centre, a division of the US Navy has more recently completed and tested an automated oil spill sentry system known as the Spill-Sentry that uses sensing buoys linked to a base station via cable, radio, or satellite communication. Thus, the buoys may also be deployed at offshore stations. Unlike the Leakwise system, the SPAWAR floats use a fluorometric sensor, which provides higher sensitivity and the ability to differentiate among oil types. The fluorometric sensor has been tested at the Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT), operated by the US Minerals Management Service and was found capable of detecting oil layers that are two orders of magnitude thinner (> 5 µm) than electromagnetic absorbance sensors for a wider range of oil types. Tests for problems associated with biofouling, detection of various hydrocarbons, water turbidity and wave tolerance have been published (Dakin 2001). Applied Microsystems Ltd (AML, Sidney, British Columbia) now market the system worldwide under the trade name Spill-Sentry [5].

Other similar systems that use fluorometric sensing are the OSPRA system, marketed by Spectrogram Corporation [6], and the Genesis Alert System, marketed by Baxter Technologies [7]. Anchored sensor platforms that are fitted with oil tracking buoys, which can be automatically released when oil is detected, have also been developed by Baxter Technologies. The oil tracking buoys relay their position by telemetry and report whether they are inside or outside of the slick. Sensors suitable for chemical pollutants and other water quality parameters have also been developed for the Genesis System.

One of the limitations of sentry systems using floating buoys is that they must encounter the oil in order to raise an alarm. Thus, their effective measurement range is limited to < 1 m and a large number of buoys are required for effective coverage of a harbour. Thus they tend to be expensive to install and maintain. They are also subject to damage from ships so it may not be practical to place them where oil is most likely to be encountered.
A review of remote sensor systems that would be suitable for all-of-harbour monitoring has recently been published (Goodman et al. 2003). This review focussed on systems that could:

- Be pole mounted and scanned to view a whole port;
- Automated to detect oil without human monitoring;
- Sensitive to hydrocarbons;
- Insensitive to other false targets common to harbour environments;
- Suitable for day-night and all-weather operations.

From the range of existing technologies, only infrared and ultraviolet cameras were considered practical, cost-effective and suitably supported by developed automated image processing technology.

**Innovations in Wide-scale Remote Sensing Systems**

Remote sensing devices which are capable of locating and defining details of spills from a distance have been available for over a decade. However, recent reviews have concluded that their application to emergency spill response has been limited due to logistical and technical restraints, and progress to overcome these limitations has been relatively slow (Fingas & Brown, 2000a, 2000b, 2002).

Research over the past few years has focussed on identifying and expanding the operational limits of currently available sensors.

Infrared sensors, which detect infrared radiation levels given off surfaces, have been developed into relatively inexpensive sensors for ship-board and aerial observation of oil slicks. These sensors are capable of detecting thicker parts of a slick only (> 100 µm) so are useful for guiding response to the thicker parts of oil. They must be combined with an ultraviolet sensor, which shows the thin oil sheens, for complete imaging of both the thick and thin portions of a slick. The combined image provides a useful guide to where to direct response efforts (Fingas 2000a).

The utility of shipboard navigational radar as an oil tracking tool has also been demonstrated in a wide range of sea states, during darkness, rain and fog and under wind speeds of 10 – 30 knots using specially-tuned radar systems (Tennyson 1988).

Brilis et al. (2001) and Fingas & Brown (2002) summarise the satellite sensors that have been available for observation of oil pollution in the open ocean. These include platforms that use passive sensors that detect in the visible, infra-red (IR), or ultraviolet (UV) range of the radiation spectrum (e. g. Landsat TM, & Spot), and platforms that carry active sensors, which both transmit and receive. Most of these systems, such as Synthetic Aperture Radar (SAR) operate at the microwave end of the spectrum.

All of these systems have provided some capability of detecting oil slicks from the background and can return varying levels of information on slick area, shape and distribution. However satellite sensor systems which operate in the visible spectrum using passive sensors are limited in practice because they will not function through cloud or fog cover or at night-time, thus are impractical for operational use under most circumstances (Fingas & Brown 2002). In contrast, satellite SAR systems are able to sense through cloud and to function day and night. This “all-weather” operation and the wide swath width provided by the available SAR satellites have been the major reasons why satellite-based SAR has been most commonly promoted for operational detection of oil slicks (Navas et. al 2001, Fingas &
Brown 2002). However, satellite SAR systems also suffer from significant limitations for operational slick sensing. Principal obstacles have been coverage, limitations due to wind and sea state as well as the limited resolution that is provided by SAR images.

There are presently three SAR satellites in orbit with global coverage: RADARSAT, ERS-2 and ENVISAT. These provide revisit times for most places on the globe that are impractically long and irregular for operational sensing of a given spill (Fingas & Brown 2002). RADARSAT has a repeat cycle of 24 days for coverage of a given area of latitude, while ENVISAT and ERS-1 have revisit frequencies of 35 days. Coverage opportunities have been improved by combining images from multiple satellites. Coverage also increases towards the poles so that daily coverage is available over northern Europe and Canada. This has made satellite SAR a more practical option for these regions (Navas et. al. 2003, [8]).

In the recent past processing of satellite signals to usable images has required processing on the order of days to weeks, making the information impractical for real-time spill response. SAR images are also known to return many “false positives” for oil slicks caused by natural phenomena which generate patches of similar appearance.

A number of European and Canadian initiatives have attempted to address these issues. The impetus has been to establish early warning systems with wide geographical coverage to detect the large number of smaller operational spills and occasional large spill from the high volume of shipping in these regions.

Kongsberg Satellite Services AS (formerly the Tromso Satellite Station) in Norway has for almost 10 years provided a near real-time oil spill detection service based on ERS, RADARSAT and Envisat SAR data for customers in Northern Europe. The information is distributed to customers electronically or by phone/fax or by direct communication with surveillance aircraft within 1-2 hours after the satellite overpass.

A number of more recent systems have been developed in an attempt to more fully automate the processing and issuance of alerts. ENVISYS was developed by a co-operative of European organisations co-ordinated by the Norwegian Computing Centre and funded by the European Commission [9]. ENVISYS is a hardware, software and communications system that was developed for environmental emergencies in general and included automatic detection of oil spills in near real-time from satellite SAR data. The oil spill functions included a detection module, which normally operates unattended, and uses improved processing algorithms to differentiate spills from false targets and sets off an alarm when a potential target is found; a verification module with visual processing tools that allow the operator to manually verify potential spills; a GIS-based assessment module that allows dangers to resources to be assessed and modelled; and an operations module, which includes an equipment database and tools to archive the development of the slick and send updated positional information to responders.

ENVISYS was developed to demonstration status and successfully field-trialled against experimental and real oil spills. Commercial operation for the European coastal countries was proposed to commence in 2001 but was unsuccessful in receiving support among member nations. A new joint project, OCEANIDES [10] was commenced in February 2003 under funding from the European Commission with the aim to “identify and assemble the knowledge required to establish a more harmonised and effective monitoring of European waters for illicit marine oil pollution”. The Norwegian Computing Centre, who co-ordinated ENVISYS are also a contributor to OCEANIDES and it is hoped that the ENVISYS technology will be transferred into this program (pers. comm. Rune Solberg, Norwegian Computing Centre).
The Ocean Monitoring Workstation (OMW) is a Canadian system developed for automatic processing of satellite SAR imagery over oceans. The OMW system is configured to process SAR data from RADARSAT and ERS-1 and 2 satellites and has been under field development and operation at the Canadian Centre for Remote Sensing since installed in 2000. OMW functions include rapid (tens of minutes) and automatic detection of oil slicks and conversion of slick images into detailed geo-referenced maps of the spill area for facilitation of analysis, tracking, forecasting and cleanup.

Vessel detection tools have also been developed, providing opportunities for identifying and locating polluting vessels. OMW can provide details on vessel location, estimates of ship size (beam length characteristics), and estimates of the speed and heading of a vessel. In a study conducted by the Canada Centre for Remote Sensing, the OMW was found to have an accuracy rate of 97% when compared to ship board GPS and Vessel Traffic Monitoring Systems (Henschel et al 1998). The system is effective for targets over about 20 m in length. OMW was developed and is currently marketed by Satlantic Inc based in Canada [11] under funding by several Canadian government agencies. Information on the application to Canadian waters can be found at the Environment Canada web site [12].

The principal Australian organisation that processes satellite data is Geoscience Australia [13]. Geoscience Australia currently process SAR data obtained from RADARSAT and ERS-2 and provide a priority service involving manual processing of data to produce images, which has a nominal delivery time of < 12 hr delivery following an overpass. There are presently no capabilities for automatic detection of slicks and routine monitoring is not in place for this purpose, although funding proposals for such a service have been put forward (pers. comm. Medhavy Thankappan, Geoscience Australia). One of the major limitations for Australian application of satellite SAR data at present are the excessive revisit times for available satellites. Current revisit times that were reported by Geoscience Australia for example latitudes are:

<table>
<thead>
<tr>
<th>Latitude</th>
<th>Satellite</th>
<th>Revisit frequency</th>
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<tbody>
<tr>
<td>Great Barrier Reef</td>
<td>Radarsat</td>
<td>4 hits per 24 d (at irregular spacings)</td>
</tr>
<tr>
<td></td>
<td>ERS-2</td>
<td>5 hits per 24 d (at irregular spacings)</td>
</tr>
<tr>
<td></td>
<td>Combined</td>
<td>1-7 days between images</td>
</tr>
<tr>
<td>Great Australian Bight</td>
<td>Radarsat</td>
<td>4 hits per 24 d (at irregular spacings)</td>
</tr>
<tr>
<td></td>
<td>ERS-2</td>
<td>6 hits per 24 d (at irregular spacings)</td>
</tr>
<tr>
<td></td>
<td>Combined</td>
<td>1-8 days between images</td>
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The planned launch over the next few years of technologically advanced space-borne SAR sensors by the European Space Agency (ASAR, Advanced Synthetic Aperture Radar), Canada (RADARSAT-2) and the National Space Development Agency of Japan (PALSAR, the Phased Array type L-band Synthetic Aperture Radar) should offer faster revisit times and improve the resolution and detail for slick detection (Brown & Fingas 2001, Fortuny-Guasch 2003). Each of these planned systems will be selectively steerable and provide ScanSar capability. ScanSar sensors offer higher resolution and data frequency and return polarized information which can potentially assist differentiation of oil from false targets. However, it
is expected that the life of existing SAR platforms will be coming to an end as these new platforms are launched so that there is unlikely to be an increase in available platforms in orbit.

Despite the long revisit times for satellite SAR in many regions, the data has proven useful for monitoring known slicks that persist from one satellite pass to another. For example, data from RADARSAT was used to monitor and map slicks caused by the recent sinking of the Prestige off the coast of Spain [14].

Post-processing of historic satellite SAR data has also proven to be useful for building intelligence on the frequency and distribution of illicit, operational oil spills (Jingxuan et al. 1999; Volckaert et al. 2000). In this situation, processing time is less critical than the all-weather, day and night coverage and wide beam-width provided by satellite SAR. For example, Jingxuan et al. (1999) analysed 5029 scenes covering south-east Asia between 1995 and 1998. A total of 5019 slicks of various sizes were detected, mapped and classified. The researchers were able to map out the distribution of slicks and identify trends in slick occurrence relative to the major shipping lanes. This information provides powerful guidance to the concentration of education and enforcement effort.

Improved image processing procedures for historic and near real-time satellite SAR have also been developed by a number of private organisations driven by commercial interest in natural oil seeps. For example, the Global Seeps Program is a commercially-based effort to screen all the world’s offshore oil producing basins < 3 km deep to develop a database of natural seep sources [15]. Presently acquired coverage for Australia includes Cape York to Papua New Guinea; the Arafura Sea and Timor Sea; the Canning Basin of the North West Shelf; the Perth Basin; the Great Australian Bight & western Bass Strait. Remaining sections of the Australian coast and the entire New Zealand coast are planned for phase 2. Other companies providing similar services are Enfotec [16] and Geochemical Solutions International [17]. Such information could be useful for identifying potential sources of spills of unknown origin, if slicks could be back-tracked to known locations of natural seeps. However, other evidence would be required for confirmation.

A number of limitations with Satellite SAR for oil spill detection have been recognised for some time. SAR systems rely on the detection of surface roughness, with rougher surface returning more of the microwave signal. Oil slicks can be detected (as dark areas relative to the surrounding water) if they dampen the short capillary waves generated by winds and waves. Detection is difficult or impossible for some oil types, and not possible for most oils outside of a narrow range of wind conditions (Hodgins et. al. 1996). In their review, Fingas & Brown (2000) provide a more detailed description of the limitations of space-borne SAR sensors.

With the recognition that multiple sensors are required to properly identify and detail slicks, the Joint Research Centre of the European Commission has recently funded RAPSODI, a three-year project with the goal of developing a wide-scale sensing system integrating and developing current airborne sensor technologies (SAR, Side looking aperture radar [SLAR], Infra-red [IR], Ultraviolet [UV] and microwave radiometry) with space-borne SAR. This project commenced in January 2000 and was to conclude in January 2003. To date, the project has completed field trials, following development of improved processing for spatial referencing, improved signal processing to increase contrast of slicks and to extend the suitable weather window, and removal of signal artefacts caused by aircraft movement (Navas et al. 2003).
Further information on RAPSODI can be found at [18]. Details of related European Commission projects that have been completed and the outcomes of this research are summarised in [19].

A joint industry research effort co-ordinated by Environment Canada has developed two scanning laser Environmental Airborne Fluorosensors (LEAF and SLEAF2), which provided superior discrimination of oil from other misleading targets, compared to SAR, in laboratory trials. The devices also proved capable of discriminating oil on shorelines, among debris, ice or vegetation [20]. However, significant problems have been encountered in taking the system from a laboratory prototype to a system that is robust on an aircraft, forcing this project to be deferred [21].

Slick thickness has proven difficult to measure accurately with existing satellite or airborne sensors (Fingas & Brown 2002). Two research programs have been carried out by Environment Canada to develop lightweight and reliable sensors for this purpose.

The Laser Ultrasonic Remote Sensing of Oil Thickness (LURSOT) sensor has been developed and tested to prototype stage. This device uses three lasers: one directs a pulse at the surface of the oil and the other two detect the return signal generated at the oil surface when the pulse travels through the oil and is partially reflected by the oil-water interface. One of the two receiving lasers is equipped with an interferometer allowing accurate calculation of the time required for the signal to pass through the oil. Fingas & Brown (2002) reported that the prototype proved reliable in laboratory studies and in preliminary air-borne trials. Full-scale field trials were planned for late 2002. However, these have been postponed due to staffing problems [22].

The range-gated fluorosensor has been developed to prototype status and found to provide a measure of the thickness of an oil slick in laboratory and field trials (Brown et al. 2000). This device works by actively inducing florescence of the oil in controllable waveband steps. Absorption of the returning signal is proportional to the thickness of the oil. Therefore, once calibrated against a particular oil type, the distribution of oil can be accurately mapped. Operational limits of the system remain to be determined, particularly against thicker slicks (Fingas & Brown 2002).

In their series of reviews of oil spill remote sensors, Fingas & Brown (2000, 2002) have maintained that sensors operating in the visible spectrum (400-700 nm) provide no mechanism for positive oil detection, based on earlier laboratory studies that used sensors with limited resolution of the spectra. However, application to oil spill sensing of airborne hyperspectral sensor systems, which passively sense hundreds of narrow wavebands within the visible to near-infrared range rather than a few wide bands, has recently been developed to provide high spatial resolution of oil spills. One hyperspectral system, Compact Airborne Spectrographic Imager (CASI), is an imaging spectrograph for the acquisition of visible and near infrared wavebands. This system has been operational for over a decade and continues to be developed for a wide range of environmental, agricultural and geological applications. The most recent version, CASI-3 has increased spectral resolution and wider waveband width so that increased coverage can be achieved within a given air-time [23]. Another airborne hyperspectral system on the commercial market is HYMAP [24].

These sensors offer a number of advantages over current airborne oil sensing systems, and thus deserve more attention from the spill response community:

- Fully developed for aircraft use, with signal processing to correct for aircraft position and movement;
- Lightweight and compact, so that they can be fitted into small survey aircraft;
• Measure a very wide spectral bandwidth (e.g., CASI-2 senses from 400-900 nm in 1.5 nm steps) providing much greater differentiation of the spectral signature of a target area;
• Have high spatial resolution for a relatively wide swath width compared to aircraft-based SAR (e.g., CASI-2 provides 90 cm resolution at 2,500 ft with 0.5 km swath width);
• Can penetrate to depths of 20-30 m in clean water to see the substratum or submerged oil.

Research on the spectral analysis of different oil types on the sea surface using the CASI-2 hyperspectral sensor has been conducted in a joint study in Australia by BallAIMS, Resource Management (Australia) and CSIRO to develop and field calibrate data processing techniques for oil slick sensing. Field trials were undertaken that involved the sensing of purpose-released slicks of known oil types. The sensor proved capable of defining the shape of slicks with high contrast and spatial resolution (sub-metre), differentiation of the spectral signature of different oil types (heavy oils to condensates) and continuous measurement of the slick thickness for thin to thick slicks. The detailed spectral content of the data also proved suitable for differentiation of mineral oil spills from other “false targets”. The sensor was also reportedly successful under a wide range of sea conditions [25].

Following these field trials, BallAIMS and Resource Management (Australia) applied the sensor and processing algorithms to large-scale airborne surveys to map out natural seeps over the offshore region of North Western Australia (McMurtrie et al. 2002). Research and field calibration was also carried out in this study to apply reverse trajectory analysis to determine the slick source (pers. comm.. Paul Quaife, Resource Management Australia). Resource Management Australia is coordinating ongoing research with this sensor.

**Innovations in the Detection of Submerged Oil Slicks**

There are currently no proven remote sensors that will reliably detect submerged oils (Brown et al. 2002). A number of systems have shown some promise. High frequency echo sounders and side-scan sonar have been trialled experimentally against chemically dispersed oil, simulated seabed blowouts and submerged Orimulsions® fuel (consisting of a bitumen/water suspension; Hay and Davidson 1984, Brandvik et al. 1996, Rye and Brandvik 1997, Hvidbak et al. 2000). All studies concluded that further work was required to reliably differentiate signal from noise. The range-gated fluorosensors developed by Environment Canada (LEAF and SLEAF2) described previously have the capability of scanning into the upper water column and studies are currently underway to determine the operational capabilities of this sensor against submerged oils (Brown 2003).

The 3rd R & D Forum on High Density Oil Spill Response (2002) recommended international co-operation on the further development and testing of sonar and laser fluorosensor technology for detection of submerged oil plumes [26]. Thus, this is expected to be an area of future development. Hyperspectral scanners such as CASI also show promise due to their wide spectral band-width, compact size, water penetration capabilities, and the advanced understanding of signal properties that have been developed for related applications. However, these sensors have not received attention from the oil spill response community (e.g. review by Fingas & Brown 2002).

Flow-through fluorometers, which measure the fluorescence of water samples, have been developed as sturdy units suitable for field measurement during oil spill response. They have been applied widely to in-situ measurement, particularly to determine the success of
chemical and mechanical dispersion efforts. Recent research has addressed the need to establish correlations between the values returned by the instrument with real concentrations of in-water concentrations. Comprehensive laboratory tests carried out at Environment Canada on chemically-dispersed oil using the most commonly used instrument (Turner Fluorometer fitted with either a long wavelength or short wavelength sensor) concluded that fluorometer values could be relied upon as a relative measure of concentration for a given source oil type only. Values could not be directly linked to the concentration of any specific PAH or the sum of the PAH components in solution because individual PAH compounds contributed varying levels of fluorescence. The choice of sensor was also found to be critical for some oil types. The long-wavelength optical kit was ineffective at detecting and quantifying in-water components of diesel fuels. The short-wavelength sensor was effective on diesel fuels but gave poor results for crude oils (Lambert et al. 2001, 2003).

Innovations in the Detection of Oil In and Under Ice

Australia’s maritime boundaries extend to subantarctic waters where ice coverage would be a complicating factor in an oil spill response. Ice coverage over open and enclosed waters and at land-water barriers is a seasonal reality within waters of Northern Europe, Canada and the USA and considerable research has been conducted in these regions to develop methods for detection of spilled oil slicks among ice. A recent review by Fingas & Brown (2000b) summarised the problems of detecting oil both among and within ice and outlined the current status of sensors. Detection of oil among ice was reported to be the best developed, with most of the problems and solutions being common to detection of oil on open-water without ice. One exception is that radar sensors are not useful for oil among ice because the ice dampens and distorts the small waves that are sensed by these systems. Infrared, combined infra-red/ultraviolet systems and laser fluorosensors are all capable of discriminating oil among ice. Detection of oil within ice (i.e. bound within the ice structure) remains problematic due to the wide variety of ice structures and interference caused by impurities. Acoustic sensors show promise but the acoustic properties of sea ice are highly variable. Radar-frequency methods, Impulse radar, UHF radiometry, optical methods, gamma ray detectors and sensing for the gas-off of volatiles have all been trialled without success.

Innovations in the Identification of Oils

Crude oils and petroleum products are complex mixtures of hundreds or thousands of organic compounds. The infinitely variable nature of oil mixtures results in a wide variety of behaviours that have a significant impact on the effective containment and clean-up efforts (Fingas 2000a). Thus, it is important that mystery oils be identified and characterised as soon as possible during a response. Significant advances have been made in laboratory-based identification equipment and procedures over the past decade, so that it is now possible to differentiate oils having a very similar nature (Wang et al. 2002). Analytical advances have recently been summarised in a review by Fingas (1999) and in a special session of the Arctic and Marine Oilspill Program (Wang & Fingas 2002). An evaluation of field kits capable of identifying petroleum hydrocarbons has also been published recently (Lambert et al. 2001). This revealed that the kits suffered from different limitations depending upon the oil characteristics, the sample matrix (oil, water etc) and concentration of dissolved hydrocarbons, among other things so that laboratory analysis following developed procedures were recommended for unambiguous identification and quantification of concentrations.
4.3 Improved Electronic Spill Prediction and Response Management Systems

Advances in computer technology have supported the development of a range of software tools designed to assist different aspects of spill response planning, training, and response. Computer simulations of the fate, transport and effects of oil spills, and specialised models for other aspects of spill-related decision support have increasingly become part of the oil spill response and planning activities over the past decade. Examples of this technology are now in place amongst government agencies, international petroleum production and exploration companies, large port authorities and shipping operators.

A variety of software to aid spill response and planning is now available from a number of suppliers. The International Maritime Organization has recently published an outline of available software as well as recommendations for improvements to assist spill response [27]. The latest catalogue published was completed in April 2000 and further updates are promised. This catalogue provides a good overview of the range of computer-based decision support systems that had been developed by that date to aid different aspects of spill response planning, preparation and response. The catalogue provides detailed information on specific software systems, including:

- Two-dimensional oil spill trajectory models, including simple trajectory models and more comprehensive fates models;
- Three-dimensional oil and chemical spill models, including models that estimate biological impacts;
- Response evaluation models that are designed to evaluate and compare the outcomes of alternative clean-up strategies, such as shoreline clean-up, mechanical clean-up, dispersant applications and in-situ burning;
- Electronic response equipment databases;
- Logistics databases and electronic inventories;
- Response costing and accounting systems;
- Response training and evaluation simulators;
- Search and rescue systems; and
- Various spill reporting and response logging systems.

Innovations in Oil Spill Trajectory and Fates Models

Response to an oil spill can be enhanced by forecasts of the short-term and longer term behaviour of oil spills. A considerable amount of work has been conducted internationally over the past decade to better understand and predict the movement of oil in the ocean. A review of spill modelling technology up to the mid-90’s demonstrated that two-dimensional spill trajectory and fates models were becoming increasingly capable of accurately predicting the fate of surface-bound oil (ASCE Task Committee 1996). The main mechanisms which govern the fate of oil slicks, namely spreading, evaporation, dispersion, emulsification, sedimentation and biodegradation, were understood to varying levels of confidence and had been described mathematically. The main limitation of these models at that time was seen as the availability of suitably accurate inputs to describe the advection and spreading of oil.

Since that time, the major advances in two-dimensional fates modelling have been in the refinement or replacement of weathering algorithms, especially for complex yet critical processes such as evaporation (Fingas 2001), water-in-oil emulsification (Fingas et al. 1999,
Fingas & Fieldhouse (2001) and sinking or over-washing of heavy oils (Fingas 2002d). Most of the commonly used models are also now capable of using information on specific oil types and prevailing environmental conditions (winds, temperature etc) to estimate the weathering of particular oils by partitioning the initial spill mass over time among different compartments (surface, subsurface, atmosphere, shorelines etc.). Other advances include improved “user-friendliness” and integration of geographic information systems as the user-interface, so that spill locations can be spatially related to the location of sensitive resources and other spatial information to assist responders (such as response facilities, navigational hazards, access routes etc.). Databases of oil input data, such as the ADIOS database served by Environment Canada, have also become widely available to support more rapid selection and execution of the models during a spill response.

A number of oil spill related models have been developed in the USA, by the Hazardous Materials Response Division of the US National Oceanic and Atmospheric Administration (NOAA/HAZMAT). These include:

- General NOAA Oil Modelling Environment (GNOME), a simple two-dimensional oil trajectory model that predicts how wind, currents, and other processes might move and spread oil;
- Trajectory Analysis Planner (TAP), which shows how spilled oil might move and spread within a particular body of water;
- Automated Data Inquiry for Oil Spills (ADIOS) program, which is an oil weathering model that runs on personal computers and incorporates an extensive database of crude oils and petroleum products [28].

The models are public-domain and are supported for US regions by NOAA/HAZMAT. However, with the exception of ADIOS, they are set up for modelling in that region only.

Many of the current generation oil spill models have incorporated tools for quantitatively assessing alternative oil spill response strategies. These include algorithms to calculate the effect of applying dispersants and deploying alternative boom and skimmer configurations allowing the implications of alternative response options to be tested before resources are committed (e. g. Howlett et al. 1993, Reed et al. 1995, 2000).

There have also been advances in the incorporation of uncertainties within input data to provide error-bounds to aid the more accurate interpretation of outputs from oil spill models. For example, wind forecast errors can be a major contributor to forecast errors in spill trajectory models. Models such as OILMAP and GNOME have facilities that attempt to account for these errors by calculating spill trajectories using multiple particles, which are each affected by random variation, within a user-defined range, on the “best estimates” of wind speed and direction (Lehr et al. 1999, 2003). This procedure results in a wider predicted spill path and thus provides a more conservative estimate on the locations that could be exposed. Current research by NOAA/HAZMAT is exploring more advanced error-estimation techniques to extend wind input data days beyond the available wind forecasts (Lehr et al. 2003). Similarly, uncertainties in oil specification parameters, including volumes, rates of release and intrinsic characteristics of the oil will cause errors in the predicted weathering rates. The ADIOS oil weathering model has been developed to take account of errors in these specifications by applying multiple simulations with random variations, within defined distributions, for the parameters that are in doubt. The model then yields a statistically-weighted range in the model outputs (Lehr et al. 1999). Another approach used is the stochastic modelling of spill trajectories and fates. This is most commonly applied to forward risk assessment, but can also be applied to spill response modelling. The procedure
involves the repeated simulation of a defined spill scenario, with random variation in defined input variables (eg French et al. 1999). The procedure allows important risk statistics to be quantified for a given spill scenario, such as the probability of contact with a location, the time it will take for oil to make contact and the potential volume that could be involved.

Significant improvements in modelling technology have been made with the development of fully three-dimensional oil spill fates models. Recently developed models support the simulation of the fate of entrained and dissolved oil components, allowing the full consequences of an oil spill to be better understood (e. g. Reed et al. 1995, ASCE 1996, French 2000, Korototenko et al. 2000, Reed et al. 2000, French McCay & Whittier 2003). These models include algorithms that more accurately estimate the formation of entrained oil and the release of dissolvable hydrocarbons into the water column from the slick and the entrained oil. Other algorithms then estimate the transport, dispersion and in-water concentrations of biologically-available toxic compounds (principally BTEX and PAH compounds) that would be generated at particular locations on the seafloor, or at particular depths within the water column. A number of 3D fates models have also been developed that include exposure-effects estimation to indicate the potential for biological impacts as a consequence of dispersed and/or dissolved oil exposure (e. g. French et al. 1996, Korotenko et al. 2000, Chandrasekar et al. 2003, Mearns et al. 2003). These models are based on estimates of in-water hydrocarbon concentrations and measures of sensitivity to toxicity for different biological components. While some models use information on the abundance, type, distribution and sensitivity to hydrocarbons of individual species, and thus require an extensive knowledge-base to be developed for a particular region, general relationships have also been developed that estimate the potential for toxicity when the specific sensitivity information for individual species has not been tested (French 2001). These general relationships are based on regressions of the dosage-response relationships for marine species to in-water concentrations of aromatic hydrocarbons.

The US EPA Natural Resource Damage Assessment (NRDA) model for coastal and marine environments is a three-dimensional oil spill model that is used in the USA to determine post-spill damage and compensation under the US Comprehensive Environmental Response Compensation and Liability Act (CERCLA) regulations. This biological effects model estimates movements of aquatic organisms (based on information on their abundance, distribution and mobility) and concurrent exposure concentrations and durations experienced by them. Mortality of the exposed organisms is calculated using acute toxicity data (LC₅₀) corrected for temperature and time of exposure, and assuming a log-normal relationship between percent mortality and concentration of mono- and polycyclic aromatic hydrocarbons. For commercially-valued fauna (e. g. commercial fish-stocks), the model also includes estimators to quantify future stock losses due to effects on the generation directly affected by a spill (French et al. 1996). To support application of the model within waters of mainland and territorial USA, extensive databases of species information have been developed for a range of habitats.

The three-dimensional physical fates and biological effects models in the CERCLA NRDA model have been developed into a globally-relocatable model for use on personnel computers, known as the Spill Impact Model Analysis Package (SIMAP; French 1998, French et al. 1999, 29). The model may be used to estimate concentrations and dosages (i.e. the concentration x duration) of aromatic hydrocarbons within the water column to yield general guidance on the potential for harmful effects (e. g. using a generic threshold concentration of concern). A full biological effects model can also be run to quantify impacts on populations of resident fauna, for which estimates for the abundance of any species of concern within the local habitats are required. OSCAR2000 is another three-dimensional oil spill model that
includes exposure models for fish, ichthyoplankton, birds and mammals [Reed et al. 2000, 30]. OSCAR2000 was developed in Norway.

The most valuable contribution of the three-dimensional models has been to allow investigation of the full impacts of given spill scenarios, beyond just the effects on surface features. Three-dimensional oil spill models have also proven to be highly useful for investigation of the net environmental benefits from responses that trade-off impacts on surface and subsurface resources. Mearns et al. (2003), for example, described the use of the three-dimensional oil dispersion model, HAZMAT (developed by NOAA) to compare the outcomes from spill scenarios in two shallow embayments (Santa Barbara Channel, USA, and Chesapeake Bay, USA), with and without the application of dispersants. The model was used to estimate the concentration of undispersed (slick) oil and dispersed oil that would contact shorelines and the shallow subtidal zone under each response regime. In each case, non-treated oil was predicted to wash onto shore and accumulate in the surf zone. However, dispersed oil was expected to remain offshore and disperse to below critical concentrations before exposing shorelines. Similar results were obtained in another modelling study that assessed biological outcomes of spills into the Gulf of Mexico and Pacific Outer Continental Shelf Region of the USA. Net Environmental Benefit Analysis (NEBA) was used to compare impacts on a range of habitats for spills 10 to 250 km offshore. Effective dispersion and a NEB were indicated for dispersant use regardless of launch site, water body or season (Trudel et al. 2003). A relatively simple dispersion model (the NEEBA model) has recently been developed and applied to investigate the net economic benefits of various response strategies (Koops et al. 2003). In this model, ecological responses and the overheads of different responses are collectively treated as costs.

Innovations in Data Assimilation to Improve Trajectory and Fates Modelling

While trajectory and fates models have now reached a level of useful sophistication, one of the limiting factors of their accuracy is the input data to describe transport of material, including forces causing the advection and dispersion of oil or chemical spills. Hydrodynamic models that operate in two-dimensionally averaged and three dimensions using barotropic forces (tidal flows, surface wind shear and seabed drag) are relatively well-developed for use in spill trajectory and fates models over tidally-dominated coastal waters. However, their value is limited in areas where other, less predictable forces dominate. A number of recently developed systems have attempted to address this limitation for specific areas of operation by integrating measurements of current flow and turbulence.

Texas A & M University have developed a high-frequency (HF) Radar system that provides real-time velocity coefficients for input into an oil spill trajectory model (Ojo & Bonner 2002). The concept has been applied to Corpus Christi and Matagorda, two bays located in the Texas section of the Gulf of Mexico. Surface currents and dispersion coefficients can be calculated at a spatial resolution of 1000 m. The HF Radar measures surface currents by Doppler effect while the dispersion coefficients are obtained from the velocity time series using the principle of Autocorrelation Functions for time series. The system has significantly improved the data available for both trajectory and dispersion simulations in this area. In contrast to expectations, spatial variability of dispersion coefficients within bays were found to be several orders of magnitude higher than between bays.

The Texas Automated Buoy System (TABS; [31]) is a project commissioned and currently maintained by the Texas General Land Office (TGLO) to provide the spill response community with critical information on offshore surface currents in near real-time. The system consists of a network of 7 current measuring buoys linked to a further 7 buoys
operated by the National Data Buoy Center, a division of the US National Weather Service [32] to provide spatially-varying information on the surface currents over the Texas Gulf of Mexico (Figure 1). The buoys transmit surface current and temperature observations via cell phone and commercial satellite digital links to a central server. One of the buoys is also fitted with an Acoustic Doppler Current Profiler (ADCP), to report vertical current structure, and a digital wind gauge. The buoys provide half-hourly current measurements four times daily under normal conditions and every two hours during a spill response. Data are posted to a public web site [33] within a few hours of capture. The web site provides links to other sources of oceanographic data and also serves the forecasts of an operational oceanographic model that currently supplies 24 hours prediction windows. This is currently a 3-D barotropic (wind and tide driven) version of the Princeton Ocean Model (POM), which uses the TABS current observations and wind fields from the NCEP global atmospheric model. A baroclinic version with links to regional and global scale baroclinic models is being developed to further improve the accuracy of prediction (Guinasso et al. 2001). Archived data is also used to build up a better understanding of the relationship between forcing conditions and hydrodynamic response. The system was designed by the Texas A & M Geochemical and Environmental Research Group [34] using the latest off-the-shelf current measurement and cellular telephone technology.

Software has been developed for Shell Brunei that assimilates, in near real-time (10 minute updates), data collected from a series of Acoustic Doppler Current Profilers placed over the Brunei Shelf Sea (Copeland 2002). The software integrates data from three ADCP stations and outputs current flow-field predictions for a 200 km by 100 km area at 1 km resolution, taking into account the requirements of mass and momentum conservation. Currents in this area are predominantly non-tidal, thus are less predictable using wind and tidal data. Results from the software allow time-series of past and present flow events, which are suitable to calculate historic or real-time spill trajectories with the addition of wind drift. A similar system has been developed for input to models serving the offshore oil and gas exploration and production fields in UK waters by Fugro GEOS (company brochure).
Figure 1: Location of instrumentation for the Texas Automated Buoy System (TABS)

Prediction of spill paths over open ocean areas away from suitable surface or in-water instrumentation is more problematic, especially where circulation is dominated by geostrophic current systems (i.e. those driven by density differences and the rotation of the earth) because these areas commonly encounter complex eddies and associated jets that form, progress and dissipate in a seemingly random fashion that cannot be predicted by localised hydrodynamic models. A number of three-dimensional global-scale and regional-scale models operating with baroclinic inputs (i.e. accounting for differences in the temperature and salinity of water at different horizontal and vertical locations) are in operation. However, a limitation of these models has been that they typically operate at relatively coarse scales which may not be adequate to describe circulation at the scale required for spill modelling.

Recent advances in satellite technology have assisted the estimation of geostrophic currents over open ocean areas. Satellite altimeter platforms (e.g. Topex/Poseidon, RADARSAT, ENVISAT, ERS-1, JASON-1) measure small differences in sea-heights allowing the locations of relatively high and low water to be mapped relative to expectations for sea levels derived from tidal models and other data. Localised current flows can then be interpreted from these sea height anomalies. In Australia, CSIRO Division of Marine Research have developed
procedures for processing altimeter data from up to three altimeter platforms (Topex/Poseidon and ERS-1 and ERS-2) at a time, and data from coastal tide gauges to interpolate currents on an 18 km grid every 5 days by a three-stage optimal interpolation. These are now served to the hydrodynamic circulation model used by the oil spill and search and rescue models under the Australian National Plan. A description of the data and validations is given at the CSIRO web site [35]. Implied currents are also served publicly from data from the JASON-1, TOPEX, ERS-2 and GFO sea height anomaly readings by the Global Ocean Observation Centre, a division of NOAA. These data are available globally on a 10 day average and a spatial scale of 25 km but have not been thoroughly validated (pers. comm. Joaquin Trinanes, NOAA.).

A number of models have been developed internationally to assimilate data derived from altimeters. Direct feeds from near real-time interpretations of the Topex/Poseidon altimeter data have been developed by CSIRO Marine Research Division as input to the GCOM3D model currently used by the Australian National Plan (Gilbert 2000). Meteo-France has developed a two-dimensional pollutant transport model (MOTHY) that is operational over the eastern part of the Atlantic Ocean and Mediterranean Sea. In a recent study, the ability of MOTHY to predict the path of real oil spills was compared with assimilation of alternative external data sources for large-scale currents: 1) seasonal current databases, 2) operational large-scale (global) models, and 3) sea height anomalies from satellite altimeter (ERS-1 and Topex/Poseidon). Best fit was obtained by assimilation of the altimeter data (Daniel et al. 2003). The HYDROMAP model, developed by Applied Science Associates has also been developed to assimilate geostrophic data from satellite or other sources for operations over any part of the globe (pers. comm. Tatsu Isaji, Applied Science Associates).

Other efforts at data assimilation are concentrating on more rigorous description of the starting location and shape of oil slicks as input to trajectory and fates models. The Swedish Coast Guard are using information on the spatial location and shape of slicks observed with an airborne surveillance system to input new starting point(s) into an oil spill trajectory model. Data collected by air-borne sensors is geo-rectified and transmitted to a response centre in real-time. Polygons describing slick locations, shapes and areas are displayed directly on a GIS where it can be combined with spatial resource data. The polygons are also directly importable within an oil spill trajectory model to define the present location of slicks. The model calculates the trajectory of particles originating from within this area [36]. An alternative approach has been developed by RISSHO University in Japan for the Sea of Japan. This system assimilates the observed location of oil slicks from RADARSAT-SAR observations during a simulation to correct the predicted path of slicks (Goto et al. 2001).

**Innovations in Electronic Spill Management Software**

Effective response to oil spills requires ready and timely access to critical information covering a wide spectrum of issues. These include information on the spill episode and spilled material, field surveillance, prevailing and forecast environmental conditions, environmental and socio-economic resources that are at risk, status of response equipment and personnel, legal and accounting details, contact details for external and internal response organisations and so on. Response will be more effective when essential information is prepared, collated and readily accessible in preparation of a spill episode (Douligieris et al. 1995). Throughout the response, a large amount of information must also be managed and documented in an auditable fashion. Thus, there is a need for organised information management systems to support an effective response.
Geographic information systems (GIS) are now widely used for spill planning and response because they support the collation and preparation of spatially-referenced information on the location, nature and sensitivities of different resources in a way that can be rapidly accessed (Laflamme et al. 2001). The ability to map and analyse complex spatial relationships between environmental observations and other mapped information then becomes a powerful advantage during a response (Brilis et al. 2001).

GIS systems are highly flexible and a wide range of applications have been developed to assist spill preparation and response. Databases of coastal resource atlases, alternatively known as oil-spill information management systems (OSIMS), that combine map-based information on many themes, are now widely used in most jurisdictions (Fingas 2000a, Harbaugh 2003). Other systems have been developed to identify and map potential sources of oil. For example, in their efforts to identify risks to the Pacific nations, the South Pacific Regional Environment Programme has identified and collated track data for trade and fishing vessels passing through the region, as well as logging the location of over 1080 shipwrecks that were sunk in the region during World War II (Gilbert et al. 2003).

Most recent efforts on oil spill related GIS development worldwide have concentrated on building up more spatially-accurate information, sharing of information across wider jurisdictions, and pre-developing sensitivity coding and formal response strategies for individual sites. For example, The US Department of Interior is co-ordinating development of a computerised Geographic Response Strategy (GRS) system that combines spatially-rectified aerial photographs, GIS maps and textual information from local knowledge and research on habitats and local sites. The system was first developed for Alaskan waters but will be extended to all US coastal and inland waters (Mutter et al. 2003). The unique feature of this system is that each habitat and site is being pre-assessed for sensitivity to oil and the most appropriate strategy for protection and clean-up. A number of other GIS programs have also been developed in the USA, many of which are more specific in geographic coverage and were originally developed independently. For example, the Gulf of Mexico is covered by The Tactical Response Plan, The Florida Marine Spill Analysis System and the Maritime Security Strategic Information System. While these systems continue to be supported and developed with increasingly sophisticated analysis tools, linkages are now being developed using state of the art web-GIS technology to share information and foster a more universal approach (Harbaugh 2003).

Research in Norway is developing a GIS and model-based ranking system for environmental sensitivity for use in contingency planning and spill response. The MOB system uses four major criteria for each of the mapped resources: Naturalness; Reparability, Conservation status & Vulnerability. Priority rankings are stored within a GIS with links to look-up tables describing specific information and response guidance for each resource (Drolshammer 2003).

Efforts in Canada have also focussed on development of a consistent and standardised application of coastal mapping and the development of sensitivity ratings for each local site and habitat. Environment Canada has developed the Atlantic Sensitivity Mapping Program (ASMP) for use in pre-planning and response and is currently extending the system to other regions of the country. The basis for the sensitivity ratings in ASMP is the Shoreline Cleanup and Assessment Technique (SCAT), which provides a formal procedure for applying standard, accepted definitions and shoreline segmentation procedures to describe shore-zone character, sensitivity and clean-up response strategies. Four distinct data templates are provided: Shore zone character; Shoreline protection; Shoreline treatment and Response & requirement summaries. These templates use 143 different attributes to provide a unique characterisation for each shoreline segment. The system incorporates digital terrain maps
and three-dimensional digital terrain models as well as powerful data interrogation tools to synthesise information in a usable format (Laflamme et al. 2001).

Developments in technology have also assisted improvements in GIS-based systems for spill planning and response. Examples include improvements in the accuracy of global positioning systems (GPS) with the removal of “selective interference” in 2000 (Brilis et al. 2001), the availability of increasingly more accurate and sensitive information from satellite platforms (Goto et al. 2002), the development of robust hand-held palm-type computers which can receive and send GIS information between the field personnel and computers serving coastal resource atlases (Gilbert et al. 2003) and developments in web-based GIS systems, which better support sharing of GIS information among widely separated user-groups as well as the general public (Goto et al. 2002).

Computerised databases are now widely used for organising the diverse information that must be accessed and stored for an effective response (Mutter et al. 2002). However, many of these systems use disparate software that may be difficult to link. A number of integrated software systems have been developed to integrate all of the data sourcing, mapping, analysis, communication, data logging and accounting requirements for management of a crisis in the one system. The On-Scene Command and Control system (OSC) was developed for the Unites States Coast Guard to manage all the incident command system forms, manage a database of spill response resources, serve the interface for the OILMAP oil spill modelling system, and provide a GIS system pre-loaded with marine charts and resource maps for viewing the spill simulations and field surveillance relative to resources of interest (Anderson et al. 1998). The system is interactive, in that any resources that are allocated (using an ICS assignment form) are displayed spatially on the GIS, tracked by modules for resource control and cost accounting, and logged for re-assessment during future progress meetings. More recently, the basic structure of OSC has been developed into the Crisis Management System Mapping and Analysis Package (CMSMAP). CMSMAP integrates an interactive Incident Command System to log and control resource allocations, a communication system to link geographically separated members of a response team, an interactive GIS and linked forecast models specifically developed for a wide range of marine incidents, including oil spills, chemical spills, shipping accidents, search and rescue and evacuations (Anderson et al. 2002). The system is currently in use by the Maritime and Port Authority in Singapore and the Hong Kong Pollution Control Department. The Oil Spill Response Incident Control System (OSRICS) is an interactive database system that was developed initially for fire response and has a focus on crew and resource management, automated reporting, and communication during an incident. Interactive forms that comply with the incident Command System format provide facilities to allocate response crews and other resources, set crew security schedules and log actions and costs. A GIS is provided to display resources geographically (Traveltech Pty Ltd; company brochure).

4.4 Containment Devices

Containment and diversion of oil slicks is usually achieved using booms. Commercially available booms have been developed for application to a wide range of conditions and vary in design, construction and materials but basically consist of a floating barrier suspended by tension members and used to enclose or divert the movement of oil.

Booms suffer from a number of limitations related to the type of oil and the environmental forces involved. Booms commonly fail to contain a proportion of the encountered slicks, even under calm conditions. The modes of failure are generally understood (Fingas 2000a) and include entrainment, submergence, planing and structural failure - caused by excess
current speed across the face of the boom; and splash-over, which is caused by excessive vertical movement of the boom due to wave action.

Innovations in Performance Testing

Recognising that much of the data to objectively judge the performance of different boom designs was not generally available in a public form, and was not assembled in a way that aids comparison, the U. S. Department of the Interior, Minerals Management Service funded an extensive review of test data available for different boom types (Schulze & Lane 2001). Both published and unpublished test data from 78 tests (1995-1999) were assembled, reviewed and condensed. Available comparative data was generally limited to the first loss tow speed (lowest speed at which oil escaped the boom). The review made recommendations for a larger number of tests to make performance more predictable over a wide range of deployment conditions. Suggested test data included:

- buoyancy to weight ratio;
- boom draft;
- test-oil viscosity;
- wave steepness.

First loss of oil occurred with all designs by 1 knot under calm conditions or at 25-50% lower current speeds in the presence of choppy waves. Because current speeds commonly exceed these limits in Australian waters, particularly within regions of the North West Shelf of Western Australia, the Northern Territory and northern Queensland as well as many of the coastal embayments and estuaries throughout the country, these limitations are relevant to Australian conditions. These performance constraints also limit the speed that booms can be towed to collect floating oil, even in areas with low current speeds.

Innovations in Containment Technology

The speed limitation of conventional booms, known as the critical velocity, has been recognised for some time and various configurations devised for use of booms in higher current speeds (Fingas 2000a, Swift et al. 2000). The 2nd International Oil Spill Research and Development Forum (IMO 1995) listed development of research into boom technology capable of operating in high-flow conditions as a priority area of research.

A number of boom designs have more recently been developed to operate with cross-boom current speeds that exceed 1 knot. Tank testing has been undertaken at OHMSETT test tank of an innovative boom system designed to maintain efficiency in higher current speeds (Wong et al. 2002). The Ramp Boom, developed by the University of Miami, is an inflatable boom designed to operate in the apex of a sweep-boom configuration. It has a forward buoyancy tube that supports a solid plate inclined 15° with respect to the water surface. This plate is trailed by three conventionally oriented booms with different drafts and separations. The plate acts as a submergence plane to force oil underwater. The positive buoyancy of the oil then forces it to rise and collect within range of one of the three collecting zones formed by the trailing conventional booms. Collection efficiency against both high and low viscosity oils was reported to be ~100% at 1 knot and 86.5% at 1.5 knots in the test tank. However, critical loss occurred before 2 knots (Wong et al. 2002).

Another prototype boom (Bay Defender) that has been developed by the University of New Hampshire to overcome the conventional limits of entrainment speeds has been tested at OHMSETT. This device also uses the submergence plane technology, but has a flexible
submergence plane that is trailed by a perforated flexible membrane supported aft by a second inflatable boom (Figure 2). A trailing hydrofoil is used to overcome the tendency of the inclined plane to rise out of the water at higher speeds. Tests of the inclined plane and hydrofoil configuration gave a recovery efficiency of over 40% at speeds of up to 3 knots. A number of problems were encountered, however. The device was not effective at recovering light oil because they tend to disperse rather than refloat and speeds of over 1 knot were required for oil to be driven down the submergence plane (Hansen 2002). This device is not yet at commercial production stage.

![Prototype of the Bay Defender under test at OHMSETT](image)

**Figure 2: Prototype of the Bay Defender under test at OHMSETT**

The NOFI Current Buster is another apex-end boom that has been developed for faster currents. The device has been evaluated in tank tests at OHMSETT (DeVitis et al. 2000) and has reached commercial production stage. This inflatable device consists of two sweep-booms that are shaped to form a smoothly-tapered chamber, which precedes an expanded section with a submerged flexible floor that acts as a collection chamber (Figure 3). The drop in velocity of the surface water/oil on entering the collection chamber causes the oil to collect at the surface, while water escapes from vents through the floor (~ 1.5 m below water level). The whole device is designed to connect to a sweep boom and can be towed or anchored in a flowing current. A lower membrane and inflatable cross-members are used to maintain the shape of the sweep boom at higher current speeds so that flow remains laminar both inside and outside of the chamber. Laminar flow outside of the chamber allows a vessel to operate directly alongside to recover oil using a pump or skimmer. The device is designed for rapid deployment and ease of control and recovered over 90% of encountered oil in calm waters at speeds up to 3.5 knots during tank tests at OHMSETT (DeVitis et al. 2000, Foreman & Talley 2002). Subsequent field tests in Alaskan and Canadian waters have reportedly yielded similar efficiency ratings with towing and current speeds up to 4.5 knots. A recent application of the boom system to recover diesel from a 159,000 L spill of diesel from sinking...
of the M/V Windy Bay in Alaska recovered an estimated 29% of the release (Marchant et al. 2003).

NOFI have since developed a larger version, known as the Ocean Buster, which is 3 times larger and designed to operate at speeds up to 4 knots in higher sea-state conditions. A scaled-down version is also under development for use in restricted waters. Further information is available at the NOFI web site [37].

Tests of two prototype vee-sweep booms that used horizontal and vertical netting to maintain a smooth profile of the sweep have also reportedly achieved collection efficiency at up to twice the conventional entrainment speed (Hansen 2002).

Another high-current booming system, known as SlySar (Surface Layer Separation and Retention) that has been under development for the past 3 years, is reportedly based on a novel arrangement of inflatable booms supporting perforated membranes that the developers claimed could theoretically be deployed at higher speeds (up to 5 knots) and in seas up to Beaufort scale 5. The equipment has been under sponsored development in the United Kingdom since 1999 and has now reportedly reached pre-production evaluation [38]. However, no details or performance indicators on this system have been released.

These specialised systems offer to extend the critical towing or current speeds suitable for booming operations, rather than meet all operational conditions. Most are prototypes that require further development, testing and commercial product development before they will be available to the oil spill response community. The Current Buster and Ocean Buster appear to be the only commercially available high-speed booms that have proven capability.

Other recent efforts have focussed on improving the outcomes of booming operations in higher current speeds with conventional booms. In an effort to streamline responses to spills in fast flowing waters (1-5 knots), the US coast guard have published and distributed on-line a field guide to fast water response that includes chapters on hydrodynamic considerations and booming techniques [39]. The field guide includes a decision matrix that identifies fast-water scenarios and provides diagrams and descriptions of recommended booming configurations. Examples are provided for both tidal estuaries and coastal waters relevant to Australian conditions. The guide also discusses issues of equipment, deployment and logistics for each scenario (Hansen 2001).
An ongoing programme of testing at the OHMSETT facility has identified a number of devices that can assist the performance of conventional booms in fast currents (Hansen et al. 2001, Hansen 2002). Boom deflectors (developed by Envirotech Nisku, Canada) consist of tubular aluminium floats with a vane fixed along the keel. They are attached at intervals along the boom with self-angling wings that are designed to set the vane at a fixed angle to the current flow and thus set the boom at a fixed angle to the current. Their main advantage is in simplifying deployment and improving control of boom angle because they negate the requirement for additional guy ropes and anchor points and achieve a smoother boom profile. Tests of these devices indicate they perform in currents between 1.5 and 8 knots and work best with semi-rigid boom.

The current rudder is another variant that proved successful in tank and field tests (Hansen 2002) and is now available commercially (Current Vane, ORC AB, Sweden). It consists of a series of vertical aluminium vanes set at a fixed angle and mounted in a frame suspended beneath a rigid floating beam. This is designed to be attached to the terminal end of a boom and acts to pull the leading edge out into the current and hold it at an angle of 10-15° to the flow. A trip line is fitted to retrieve the device remotely. It can be used to deploy booms remotely from shorelines where the current is parallel to shore, or to control the leading edge(s) of a side or trailing sweep boom. It requires a minimum current speed of about 1 knot to generate enough lift force and water depths greater than the vane height are required (two models are produced: 1.1 m and 0.55 m draft).

A variant on the hydrofoil device, the fast-water Flow-Diverter, has been developed, tank and field tested. It consists of two or more catamaran-like floats that have a wing-profile (Coe & Mackay 2003, Drieu & Hansen 2003). They are designed to be anchored with their bows facing towards approaching oil slicks. In contrast to the Current Vane and Boom Deflector, the Flow-Diver is designed for deflection of oil slicks and slick patches across the flow and into a collection area, or away from sensitive resources. Tests by the US Coast Guard have shown that Flow-Diverters can be used in currents over 5 knots.

Other Containment Innovations

Harbours are common sites for operational spills associated with shipping. However the use of booms as a precautionary measure around vessels that are refuelling or debunkering can be limited in practice due to difficulties in manoeuvring the boom in the restricted space, and the requirement not to impede other traffic. A range of mechanical devices have been developed by Copdel Inc in the USA which are designed to be positioned fore-and aft to form a barrier against oil escape between a ship and a hard wall wharf, or between two ships lying side by side. The Protecteur oil barriers are slid into place and extended to form a rigid barrier between the vessel and another hard surface using hydraulic that support solid rubber skirts. Their main advantages are that they can be deployed relatively quickly from a wharf to form a solid seal. However, they are specialised devices and would not assist where oil is leaking from the open side of a vessel. Containment of volatile oils in such close proximity to a ship may also increase the risk of a fire.

Air-driven pneumatic or bubble barriers and rising/sinking booms are other innovative systems that are suitable for permanent installation around sites of high source risk or of high sensitivity from oil spills. The pneumatic barrier sets up deflecting water currents as a barrier to oil, while the rising/sinking barrier consists of a negatively buoyant boom that is inflated in position to form a conventional inflatable boom. An example of a pneumatic barrier boom has been tested at the OHMSETT facility in June 2002 and successfully deflected oil at tested
current speeds up to 1.5 knots. Examples of these units are produced by Oil Stop in USA [41], Trident Oleanic Ltd in the UK [42] and Hydrotechnik in Germany [43].

Team One USA, a US-based vessel builder has developed an oil-spill response Paravane boom, which is designed for rapid response to small operational spills in high traffic areas. The paravane booms consist of a high tensile aluminium frame covered with a stainless steel mesh, forming panels into which bags of sorbent material are slotted. The paravanes are deployed from both sides of a fast utility vessel and are held back and out of the water while the vessel is moving to the site. Hydraulic rams are then used to lower the booms into an advancing vee-scoop configuration with the frame and panels held perpendicular to the approaching waters. The manufacturers claim that the boom/sorbent arrangement can be operated at speeds of 3 to 5 knots in the collection mode and that stabilizer arms on the booms dampen wave action. Further details are available from the Team One USA website [44].

4.5 Oil Recovery Devices

Oil recovery is usually affected by use of skimmers, sorbents and manual recovery (Fingas 2000a). A large number of skimmer types and models have been developed for different purposes and using different operating principles. Current skimmer technologies include devices relying upon the differential densities (centrifugal or vortex separators), buoyancies (inclines-plane skimmers, weir skimmers, suction/vacuum skimmers), and adhesion (oleophilic discs, ropes or brushes) of oil and water. These devices vary in their efficiency against different oil types and most work best when the oil is relatively thick and on calm waters. The efficiency of most devices is poor in waves greater than 1m and currents greater than 1 knot (Fingas 200a). Very viscous oil, ice and oil debris also limit the operation of most skimmer designs.

Innovations in Performance Testing

As for containment booms, a large body of test data exist for skimmer performance under controlled conditions that has not been readily available, or previously summarised in a concise format. The American Standards Technical Management Committee on Hazardous Substances and Oil Spill Response produced an extensive review of test data available for different skimmer types (ASTM Manual 34) [45]. The review covers 15 generic skimmer designs based on test data produced by government and non-government institutions. The review addresses skimmer performance in terms of oil type and condition; environmental conditions (winds, waves, currents, air and sea temperatures); slick thickness; and the presence of debris.

ASTM International, an international, voluntary standards development organisation, have published a standards guide developed by a committee of industry professionals (Committee F20 on Hazardous Substances and Oil Spill Response) for determining performance parameters of oil spill removal devices in recovering floating oil when tested in controlled environments against specific test oils [46]. Thus, it is intended for testing organisations.

Det Norske Veritas (DNV) and the Norwegian Pollution Control Authority have recently completed (in 2002), a certification scheme for oil spill skimmers intended for international application (Johannessen & Mjelde 2001, Johannessen et al, 2003). The certification scheme includes criteria for safety, functionality, quality and documentation as well as performance testing under controlled conditions. The objective of the projects has been to develop the...
technical framework for a comprehensive assessment of oil spill skimmers, on which to base future certification type approval systems.

The development has resulted in three main standards/procedures, specifying the certification program. The suggested skimmer assessment program is a type approval system, and is divided into two distinct stages, to be carried out separately. In order to be certified, any unit must be subjected to and approved according to both stages:

- **Stage 1** - Assessment of Safety, Functionality and Quality (qualitative assessment) specified in the document: *Standard for Assessment of Safety, Functionality and Quality (SFQ) of Oil Spill Skimmers*

- **Stage 2** - Assessment of Oil Spill Recovery Performance through physical performance testing in controlled conditions. The stage 2 assessments are specified in the document: *Standard for Performance Testing of Oil Spill Skimmers*

The test procedures include detailed guidelines for test execution and specification of oil properties and conditions at which testing should be carried out. The test procedure dictates that testing should be carried out in emulsions as well as fresh oil. A method for preparation of water-in-oil emulsions has been developed and described in: *Procedure for Preparation of Water-in-Oil Emulsions for Testing of Oil Spill Response Equipment.*

The Emergency Technology Centre (ETC) of Environment Canada has developed test protocols for performance testing of sorbents. Sorbent material are categorised and tested against a range of defined oil viscosities. Performance criteria include buoyancy, hydrophobic and oleophilic properties under dynamic conditions and oil absorbance rates in short (15 minute) and longer (24 hours) tests. A full description of the protocol is provided at the ETC website [47].

**Innovations in Fast Water Oil Recovery**

Collection of contained oil is problematic in fast flowing water or at high towing speeds, which are usually desirable for increased clean up rates of oil on water. Wave action is also a limiting factor (Fingas 2000a). A test protocol has been developed at the OHMSETT facility for controlled comparison of oil collection equipment in fast-water and waves and a series of performance tests has been published (DeVitis *et al.* 2000, Hansen *et al.* 2001, Hansen 2002). In these tests, collection devices were operated in current speeds of up to 5 knots and under wave profiles ranging from calm to choppy seas. Design concepts that were tested included:

1. Inverse dynamic incline plane skimmers (represented by JBF DIP600), consisting of a belt of polyvinyl chloride which is rotated along a plane inclined to the water surface and with the trailing edge positioned below water level. The belt is rotated at neutral speed relative to the approaching oil/water and assists deflection underwater. The oil rises under buoyancy and collects in a chamber set in the lee of the inclined plane.

2. High speed weir type skimmer employing pressure reduction baffles (represented by Vikoma FasFlo Skimmer). This device has three parallel chambers running perpendicular to the direction of water flow, which widen toward the stern. Water entering at the bow end at high velocity reduces velocity in the expansion chambers. Entry guide vanes induce laminar flow and concentrate oil near the surface where it is collected by a self-adjusting weir skimmer.

3. High speed circus (represented by Foilex, Blomberg High Speed Circus), composed of a circular aluminium collection chamber with a single opening placed side-ways to the current flow. Two rigid sweep arms direct water flow into the chamber and induce a
vortex that concentrates oil at the surface near the centre of the chamber where it is collected by a weir skimmer.

4. Sheet sorbent booms (represented by MYCELEX Sheet sorbent), composed of panels of oil-absorbent material streaming from a tensioning line, designed to encourage the through-flow of oil/water and maximize surface area and contact time with the oil. Various designs were trailed, including toboggan devices to limit submergence and planking of the sorbent material.

All systems except the sheet sorbent booms could efficiently collect oil in tests at speeds up to 2 knots with calm water. All systems suffered loss of efficiency with increasing current speeds and wave action. Choppy wave action proved unsuitable for the high speed weir skimmer and high speed circus.

The US Coast Guard’s Fast-Water Field guide (Hansen & Coe 2001) lists other design concepts for skimmers that have proven successful in field and/or tank tests at higher current speeds. These include the static-inclined plane skimmer (similar to the dynamic-inclined plane skimmer but using a fixed inclined plate without a moving belt) and the zero relative-velocity rope mop skimmer, which uses an oleophilic rope that is rotated along the water surface at the same speed as the approaching oil/water mix. The latter device was reported as the most effective in waves or in the presence of debris.

A number of manufacturers have developed new skimmer units that have improved performance in higher current speeds and wave action.

Lamor Corporation, based in Finland, has developed a range of skimmer configurations using stiff oleophilic brushes as either wheels or belts. The brushes are rotated through the oil/water interface, pick up the oil and lift it to a brush-cleaning device, where oil is directed to a sump. The brushes have higher surface area than conventional oleophilic discs or ropes of the same size, thus can achieve higher pick-up efficiency, with lower water content. Oleophilic brushes are also suitable for collecting a wider-range of oil types (light to heavy) than oleophilic discs, which are generally not suitable for light to medium oils (Fingas 2002a). A number of configurations are specifically designed for fast flowing waters (0.5-3 knots), such as rivers and estuaries. Inclined-belt configurations are available in various sizes that use a bank of V-shaped oleophilic brushes, which are rotated upwards to lift the oil from the oil/water interface. The manufacturers claim an effective current speed up to 3 knots for these configurations.

HUD aqua-skim, based in Hong Kong, has developed a range of oil and debris recovery vessels around a suction-forced skimmer that has no moving parts. Suction is generated by venturi effect of the approaching water. Tests of one configuration (the SMAVE skimmer vessel) at the OHMSETT facility yielded recovery rates for diesel oil that exceeded 98% at approach speeds up to 2.5 knots in calm waters and short choppy waves (US Department of Navy 2000, unpublished report provided by manufacturer).

Innovations in Oil Recovery in High Wave Conditions

Japanese research is currently underway to develop skimmers with improved performance in sea conditions with high wave action. Ueda & Hikida (2001) have reported preliminary research that concentrated on the design of baffle systems that create a calm area inside a recovery vessel, leading to the construction and testing of a prototype device. This work is still highly experimental.

A larger device suitable for ship-side mounting has been designed and built by Mitsubishi Heavy Industries, and is currently in use by the Japanese Port Construction Bureau (Figure
4). The oil recovery scoop employs an upward sloping baffle plate inside an open-mouthed enclosure. Wave energy entering the enclosure is dissipated by the baffle-plate in a similar way to waves dissipated on shore. The oil/water mixture then passes across a submergence plane, inducing the oil to collect in a sump, where it can be drawn off by a pump. The unit is designed for use with moderate to heavy oil, and can operate in the presence of debris, due to the use of an open-mesh conveyor belt and water jet at the front of the chamber. The manufacturers claim a throughput rate of 500 m$^3$/hour, subject to wave height and ship-speed [48].

![MITSUBISHI OIL RECOVERY SCOOP](image)

Figure 4: The Mitsubishi Oil Recovery Scoop. Image above shows construction details. Lower image shows the scoop operating from the side of a vessel.
Testing and Development of Skimmer Performance for Problem Oil Types

Performance of recovery devices is subject to the type of oil being recovered and uncertainties and difficulties have been highlighted for some problematic oils, including heavy, emulsified and vegetable oils (IMO 2002).

Several researchers have called for more extensive performance testing to better establish selection criteria for oil recovery equipment (Hvidbak 2003, Fingas 2002a, Singsaas et al 2001). For example, Hvidbak (2003) pointed out that weir skimmers fitted with high capacity pumps were attempted against the 200,000 cSt oil generated by the Erika spill. However, these proved to be ineffective and contributed to the very low recovery rate (< 5%) before landfall. Subsequent tank tests of weir skimmers carried out by SAIC/Environment Canada and Fleming Co in Denmark against a range of high viscosity oils showed these types of skimmers to be unsuitable due to the inability of oil to pass over the weir, especially where the oil was partially submerged. In contrast, mechanical feeder-type skimmers of several designs proved highly effective at recovering oil with viscosities up to 3 million cSt. These devices act by physically gripping the oil and lifting it clear of the water surface where it can be scraped off and delivered into a sump.

Effective devices included:

1. Various open or closed structure inclined belt types, which convey the oil to a scraper, which gravity feed into a tank or pump (e.g. Marco, ERE, Axiom HOBS, Tar Hawg, DESMI Belt Animal). Open-structure belts were found to be the most effective, as the closed structure belts tended to deflect the oil in wave action.

2. Rotating stretch metal net drum, a "snail’s shell", feeding - by the concentrating geometry of the stretch metal drum - into an auger, which feeds into a pump (e.g. Unisep, WP-1, Roto 70).
3. Twin counter rotating drums with positive guides, which lift and pressure-scaper feed the oil into an auger which feeds into a pump (e.g. KLK).

4. Conveyor belt with flap cups (corn elevator type) which gravity dump feed into a tank or a pump (e.g. EGMOPOL).

5. Rotating discs with rough teeth at the perimeter of the discs, gravity/scaper feeding to a pump (e.g. Vikoma Sea Devil).

Research carried out in Norway by SINTEF has developed standard test protocols for oleophilic rope-mop skimmers against different oil types, with an emphasis on oils that have been weathered to form viscous emulsions. This work investigated the influence of viscosity, elasticity, oil flow properties, adhesion and cohesion, as well as water-temperature on performance of this type of skimmer (Singaas et al. 2001). The rheolotic properties of the oils and emulsions significantly affected the performance of the rope-mop skimmers. Preliminary indicators for the predictability of skimmer performance based on the wax, asphaltene and naphthalene content were gained. Rope-mops proved ineffective on high-wax oil emulsions because the belt is repelled by the oil. Predictability for other oil-types was complicated and further study was recommended.

SAIC Canada, in collaboration with Environment Canada, has developed test protocols for the performance of sorbent materials and oleophilic skimmers to collect canola oil from water (Cooper & Obenauf, 2002). A total of 10 generic sorbents types and 2 skimmer designs (drum and belt-types) were tested against processed Canola Oil, diesel and medium crude oil. Results indicated that oil viscosity, rather than the type of oil was the most-significant controlling factor in oil/water pick-up rates. Pick-up rates increased with viscosity over the test range and Canola oil was collected by both the sorbent materials and skimmers at a similar pick-up rate as would be expected for a crude oil of a similar viscosity. The oleophilic skimmers were able to effectively collect Canola oil, although were most effective at slower rotational speeds than were suitable for the more viscous medium crude oil.

Heavy extreme-viscosity oils, such as bitumen and Orimulsion are further problematic because they may initially go into suspension as entrained droplets occupying the upper 2-3 m below the sea surface. A Canadian company (Environmental Recovery Equipment) has developed a specialised skimmer (The ERE PNP Refloater) for application to spills of such oils that works by agitating and aerating suspended Orimulsion® fuel. This development followed a series of studies carried out by INTEVEP and BITOR to develop the forced adhesion and floatation principle (Hvidbak & Masciangioli 2001).

Splashing and agitation are created by a submersible high output centrifugal pump. A vertical discharge tube sends the flow vertically up above the water surface where it strikes a diffuser plate that diverts the flow to hit a splash cover that houses the whole assembly. The splash cover reflects an air and bitumenous particle mixture and sends it back down towards the water surface at high speed, to force air into the water column. The violent agitation and strong aeration causes efficient floatation of the suspended bitumen particles which form a coherent layer of viscous bitumen on the surface of the water. There they are contained by a conventional boom and recovered by a mechanical-feeder type skimmer. Tests in Environment Canada’s test tank demonstrated that submerged bitumen was effectively refloated and the refloated bitumen remained buoyant for sufficient time to be collected using a conventional boom and mechanical-feeder type skimmer (Hvidbak & Masciangioli 2001). Further details on the refloater are available at [49] and [50].
Innovations in Pumping and Handling of High Viscosity Oils

The pumping of highly viscous oils and emulsions is a significant challenge. The capability of most pumping systems to transfer viscous oil is commonly limited because the pressure delivery requirements cannot be met by the available pumps, or the required pressure to overcome frictional resistance exceeds the limits of the transfer hoses or connectors (Hvidbak 2001). Thus, while a range of skimmer designs of the mechanical-feeder type are available to recover extreme viscosity oil, their suitability is currently limited by the inability of conventional pumps to transfer this oil from the skimmer (Hvidbak 2003).

A joint project between the Canadian Coast Guard and Breco Innovation (Navenco, Canada) was initiated in October 2001 to develop and test a new high and extreme viscosity steam water lubrication system for a positive displacement Archimedes’ screw pump (Cooper & MacKay 2002). Two of the most widely used heavy oil spill transfer pumps on the spill response market (GT-185 and DESMI DS/DOP-250) had previously been tested on refloated bitumen originating from a tank test spill of Orimulsion® at 14 – 18 °C. Both pump types had difficulties transferring the product from pump inlet to pump discharge. Modifications were developed for the GT-185 pump that involved the addition of steam/hot-water injection on both the inlet and outlet sides. Tests jointly sponsored by Canadian Coast Guard & Environment Canada, were carried out at the Environment Canada test facility in Ottawa in February 2002 of the modified GT-185 pump on refloated bitumen in the 2-3 million cSt viscosity range. A maximum capacity of 14 m³/h was achieved through 12 m of 100 mm (4”), more than 40 times greater than the unmodified pump.

Innovations in Emulsion-Handling

A large amount of water is often recovered with oil by skimmers, especially in waves. This water is collected both as free water and water associated with emulsified oil. The problem this creates is that the water may occupy a large proportion (up to 70-80%) of the storage space available on-site, which can limit the capacity to recover enough oil before storage is exhausted and generate significant additional logistics in transporting the recovered fluid away for treatment (Buist et al. 2002). A series of studies initiated in 1998 by SL Ross Environmental Research have investigated the use of direct injection of emulsion-breaking chemicals within collection systems in order to separate the oil and water from the emulsion on site. Tests carried out at OMSETT in 2001 showed that emulsion breaking was effective with injection at various points within the skimming/pumping circuit, and increased with increasing mixing energy. The tests showed that emulsion breakers could be used to increase the capacity of on-site containment. However, a negative outcome that was demonstrated in these tests was that the Total Petroleum Hydrocarbon (TPH) concentration in the decanted water was increased. Hence treatment of the decanted water may be required before it could be released, which could eliminate any advantage to offshore processing. A review of the use of surfactants for environmental applications (Fingas 2000b) has pointed out that the sub-lethal and long-term toxicity of emulsion breakers have not been reported in the literature.

4.6 Innovations in Oily-waste Treatment, Handling and Recycling

Due to the high water content of oils collected by skimmers, collection efforts usually result in large volumes of water and oil stored in temporary containment devices. While gravity separation can allow water to be decanted from below the floating oil-layer after a period of settlement, the decanted water will contain elevated concentrations of hydrocarbons. For example, experiments at the OHMSETT facility found that water decanted from stationary tanks into which an oil/water mixture had been introduced contained 100 to 450 ppm total...
oil for highly viscous oils and 1400 to 3000 ppm for low viscosity oils after short-periods of settlement (< 1 hour). Lower rates could be achieved with longer periods of undisturbed settlement. However, the oil content of the decanted water remained unacceptably high after days of settlement (Buist et al. 1999). In practice, most oils form stable oil/water emulsion after on-water weathering so gravity separation will be ineffective for recovering the emulsion bound water without treatment (Strom Kristiansen et al. 1995, Fingas et al. 2002).

High throughput and high efficiency oil/water separator devices developed for ship-board use are capable of reducing the oil in water content to less than 50 ppm at an offshore response (e.g. Nordvik et al. 1994). However, these have not been widely applied at the scene of offshore oil recovery operations due to a number of logistical and performance problems. These include their high weight, inefficiency when on a rolling and pitching platform, with high viscosity emulsified oils and with high oil in water content and inability to handle debris. A case for overcoming these problems to enable use of separators on vessels of opportunity was presented in the mid-90’s (Schulze 1995). However, no reference to further advances could be located and a recent general summary of oil spill response technology (Fingas 2000a) suggests that on-land separators remain the only practical option for large spills in open waters.

Grounding of oil on shorelines typically results in large volumes of oil-contaminated substrate that must be treated or otherwise disposed of to avoid chronic contamination. Fingas (2000a) provides a summary of recommended shoreline clean-up techniques for different shoreline types. Burial of sediments in situ is one option that has been applied, and is categorised as acceptable for small quantities of oil on sand, gravel and boulder-cobble shores according to Fingas (2000a). This has raised concerns that oil may be mobilised at a later stage. A number of research projects have shown that oil buried in sediments above the water line degraded relatively quickly and that water-soluble components showed little mobilization over time due to binding to the sediments (e.g. Daniels et al. 1995). Conflicting results were given in a more recent internationally-funded experimental study that was conducted in a sub-arctic region (Svalbard, Norway) involving the experimental oiling of mixed coarse sediment beaches and comparisons of various treatment methods. In this study, mixing (by tilling) of the oiled layer of surface sediments in the upper intertidal zone did not clearly demonstrate short or long-term loss of oil and thus was not recommended for future use. However, relocation of oiled sand down into the surf-zone significantly accelerated the rate of oil removal (Sergy 1999).

Another procedure used for cleaning oiled substrates is hydraulic washing using various combinations of water pressure, temperature and mechanical disturbance. Studies conducted by Environment Canada and the US Minerals Management Service (Beak Consultants 1999) have systematically compared biological recovery rates for mixed coarse substrates when subjected to different combinations of water pressure, temperature and duration of treatment. Although effectiveness was positively related to all three factors, low-pressure washing with cool or luke-warm water was effective and did not cause mortality of resident fauna. High pressure and temperature treatment was not recommended.

A sand washing system has recently been developed by the oil-spill equipment company, Lamor Corporation. The Lamor Sand Washer is designed to separate oil from polluted sand. The sand is cleaned by mixing and moving the sand through hot or boiling water. Thus, the process would not be appropriate were sterilization of the sand was not an acceptable outcome. However, the system could be a viable option for cleaning of beaches with high public amenity. The washer incorporates a conveyor belt, water tanks and a built in burner fitted into a shipping container.
4.7 In situ Burning of Oil Spills

The development of in-situ burning for large open-water spills is being treated as a priority area of research in the USA. The Research and Development Center of the US Coast Guard has been co-ordinating an interagency effort to test the efficiency of in-situ burning as a function of oil type, temperature, degree of weathering, and emulsification, and delineate the production and dispersion of airborne contaminants [51]. Efforts over the past several years have included development and refinement of a stainless steel fire boom, so that it is lighter and less expensive. From 1997 to 1998, the new boom was tested using burning oil and wave generation within the coast guard’s test-tank facility. Specific in-situ burning procedures, including fire boom deployment, coordinated task force operations, command centre protocols, and aerial ignition using a helitorch, were developed during a series of 3 exercises conducted in Galveston, Texas during 1999-2000 (Bitting et al. 2001). Tests of boom survivorship were also conducted at the OHMSETT facility of 2 fire-booms and 4 heat resistant blankets that are designed to cover a conventional offshore boom (Cunneff et al. 2000). A number of these booms did not survive the tests under fire conditions.

The combustibility of oils on water is known to decrease with weathering and water content. Studies have been conducted to correlate the external heat flux that would be required to initiate and sustain combustion for two Alaskan crude oils under different levels of weathering and water content. Results showed that the correlation was simple, allowing the generation of a simple look-up chart for the tested oils (Kulkarni & Walavalker 2001).

In-situ burning has not receive wide acceptance as a viable response to oil spills due to concerns over atmospheric and water emissions. Results of over 45 mesoscale, in-situ burning experiments carried out by Environment Canada in association with US agencies have recently been summarised (Fingas et al. 2001). PAH compounds found in the soot were between 2-8% of the source oil, indicating a 92-98% reduction. Particulates in the air were found to be higher than acceptable clean-air standards within 500m for crude oils but further for diesels. Over 150 compounds were identified in the smoke and measurements over distance from the source fire were used to construct look up tables relating the safe distance for each compound relative to the oil type and fuel volume.

In-situ burning as a clean-up method for contaminated saltmarshes has also received attention in the USA, with a number of investigations examining the relationship between soil temperature and eventual regrowth and survivorship of the saltmarsh plants (e.g. Bryner et al. 2001, Mendlessohn et al. 2002). These studies have shown that burning is effective at removing the free oil and preventing chronic re-oiling, or the spread of oil. Regrowth is effective where the rootstock of plants do not become overheated. Another conclusion of these studies is that in-situ burning does not mitigate the contamination of the soil that has occurred prior to burning. For example, a recently published investigation of a response to a real spill into a saltmarsh involved the in-situ burning of the free oil and contaminated foliage (Williams 2003). Burning was found to have effectively removed the free oil but soil remained contaminated by elevated PAH. However, in combination with other treatments (tilling and fertilization), PAH degradation was effective over a few years.

4.8 Chemical Oil Spill Treatment Agents

Oil spill treatment agents can be categorised as any class of chemical that assists clean-up of oil. A summary of the different classes of treating agents, and the broad issues relating to each class has been provided by Fingas (2000b). Spill treating agents can be broadly separated into surfactant products, which have molecules with both water soluble and oil-
soluble components (dispersants, surface-washing agents and emulsion breakers/inhibitors); solidifiers, which act to fuse oil into solids or gels; recovery enhancers, which are formulated to increase the adhesion of some low elasticity oils and biodegradation agents, which are formulated to enhance the breakdown of oil into less harmful constituents by microbial action. Major issues common to all classes are effectiveness, application rates (and hence cost effectiveness) and potential for toxicity, either directly caused by the agent or by the increasing the partitioning of oil components into the water column.

Research on Chemical Dispersants

Oil spill dispersants have received the greatest research efforts and recent reviews have been provided by Fiocco (1999), Fiocco et al. (1999), Lunal & Lewis (1999), Fingas (2000b, 2002a) and Lessard & Demarco (2000). Fingas (2000b) also summarises research on other surfactants, including surface washing agents and emulsion-breakers. Despite extensive research on dispersants over the past 30 years, current areas of research remain the testing of effectiveness and toxicity due to difficulties of quantifying these factors in realistic situations suitable to potential field conditions (Fingas et al. 2001, 2002a, 2002b, Roberts & Stevens 2002).

In his recent review, Fingas has pointed out the large discrepancies from many of the past studies of dispersant effectiveness that have been carried out in large tanks (Fingas 2002b) and in field trials (Fingas 2002c) and outlined the major issues that must be overcome to make testing more effective. A general conclusion that can be drawn from these reviews is that measures of dispersability are subject to the test conditions so that great care should be followed in interpretation of results. One of the largest problems has been, and still remains, the difficulty of properly accounting for the mass balance of oil components partitioned at the surface, in the water column and adhering to other surfaces, which has lead to severe over or underestimation of dispersability. In addition, there are significant problems in transference of the results from tank and even field trials to real-spill situations. More realistic conditions, such as appropriate wave energy and spectrums and other environmental conditions will require better measurement and control. One specific issue that has received recent attention has been applying appropriate oil-to-water ratios in swirling flask tests (commonly used to test dispersant effectiveness) so that loss of surfactant from the oil over time, with subsequent resurfacing, can be properly measured under laboratory conditions (Fingas et al. 2002).

Some recent research efforts have focussed on testing of specific oil and dispersant combinations under conditions that are more representative of the environments in which they would be used. For example, Belore (2002) reported dispersability tests carried out under cold water conditions (0-1 °C) in wave tanks that were designed to specifically simulate winter conditions found off the New Foundland Banks. The locally produced oil, previously believed to be non-dispersible (due to a high wax content and tendency to readily emulsify) proved to be readily dispersible by a locally stocked dispersant and optimal oil-to-dispersant ratios were derived. Page et al. (2002) describe results of another dispersant effectiveness test using a wave tank, this time set-up to simulate a warm shallow embayment. The wave tank apparatus allowed simulation of wave conditions relevant to the site of interest (Corpus Christi Bay) and apparatus were used to monitor the mass-balance of the oil throughout the tests.

Another potential problem associated with the effectiveness of dispersants is that they may be held in storage for many years before use. Dispersant effectiveness testing in the late 1980s by the Warren Springs Laboratory in the UK (Albone et al. 1988 cited by Fingas 2000b) indicated aging did not deteriorate the tested dispersants. Results of more recent research by the Cawthron Institute in New Zealand using the Warren Springs test protocols indicated
that age-related deterioration was an issue with some of the dispersant formulations held in New Zealand (Roberts & Stevens 2002). However, follow-up studies have reportedly indicated that this apparent deterioration was an artefact of the test conditions (pers. comm. Trevor Gilbert, AMSA).

Dispersants have long been considered ineffective upon heavy oils. However, more recent research has shown that the dispersability of an oil by a given dispersant cannot be confidently predicted by chemical analysis of the oil and that some heavy oils have been effectively dispersed in laboratory conditions (Fingas 2000b). Testing of various dispersants against oils handled in New Zealand, including heavy fuel oils, by the Cawthron Institute in New Zealand has also shown that effectiveness was a product of the oil and dispersant combination. Corexit 9500 was effective against heavy fuel oil (Stevens 2003). There have been ongoing efforts to test the suitability of different oil type and dispersant combinations, under standardised conditions by Environment Canada and the US MMS, which has lead to the development of a database of laboratory effectiveness ratings for a large number of oils handled in that region against Corexit 9527 and 9500, as well as comparative ratings for other newer dispersant products. Recent tests have included tests on deep water oils from the Gulf of Mexico (Fingas et al. 2000;[52]).

Regardless of the effectiveness of dispersants under laboratory conditions, dispersant application has commonly been limited in practice due to difficulties in applying dispersants to slicks, because slicks rarely present themselves as uniform and contained bodies of oil that can be easily targeted, and because effective field application of dispersant requires the delivery of the product with an optimal velocity and droplet size (Fingas 2000a, 2002a).

One of the most significant innovations in hardware for dispersant application has been development of the Neat Sweep dispersant delivery system for vessel-towed deployment. This consists of an inflatable vee-sweep boom that support a bank of dispersant spray heads set over the open apex of the boom. The action of the vee-sweep is to direct the encountered patches of oil into a narrow swath of more uniform thickness. The dispersant is delivered by hose from the tow vessel and released under pressure through purpose-designed spray heads that spray directly downwards from a fixed optimum height to treat the concentrated oil stream. Sensors in the boom apex monitor dispersant application rates and automatic controls adjust the delivery rate. This system was tested at the OHMSETT facility and was found to offer a number of important advantages (Nolan et al. 2001):

- The vee-sweep herds a broad swath (hundreds of meters) of smaller oil slicks, which vary in thickness, into a narrow (3 m) band of oil that is uniform in thickness. Thus, significantly increasing the treatment rate over conventional vessel-mounted systems while reducing the normal pattern of over- and under-dosing of the slicks that would occur from spraying over patchy oil;
- The system overcomes problems of oil herding away from a vessel, which occurs with bow-mounted or side-mounted sprays, and can occur with fire-monitor systems;
- Dispersant can be applied at full concentration directly onto the oil, which reduces the amount of dispersant that would be wasted through evaporation and miss-targeting;
- The system provides monitoring and feedback on the effectiveness of the dispersion;
- Dispersant is applied hundreds of meters behind the vessel, reducing the risk of exposure to response personnel;
• The system allows for large payloads to be delivered because the dispersant is carried on the towing vessels. Combined with the more efficient delivery, this provides for significantly increased endurance;

• The wide swath-width makes vessel operations an effective option for slick areas that would usually require aircraft to treat, thus removing the safety risk of aerial spraying operations.

The system is now available commercially, and is manufactured by Elastec in the USA [53].

Decision Support for Dispersant Application

In comparison to the effort in testing of dispersants, application of dispersants to oil spills, especially in coastal marine ecosystems, has been rare around the world over the past decade due to concerns of toxicity to submerged habitats. Legislation exists in most countries and local jurisdictions that require government approval before dispersants can be used. In some countries, such as Sweden, Finland, Germany and other Baltic states of Europe, the use of dispersants is banned and no stockpiles are held (Fingas 2002a). Fingas (2002a) also reports that no applications for dispersant use have been made for several years in Canada and stockpiles and spray equipment have largely been disposed of. Where dispersant use is allowed, there is usually a requirement for a judgement to be made, and argued to the relevant authority, that there is a net environmental benefit of applying dispersant. For example, guidelines that have been produced for the use of oil spill dispersants in New Zealand provide a formal framework for reaching the decision to apply or not apply dispersants (Stevens 2000). Authorities that control the use of dispersants in the states of Australia also require a strong case to be made that there is a net environmental benefit from dispersant use and this general requirement is embodied in state and local plans. This decision must usually be made quickly during an actual response due to the short window of time available before natural weathering increases the viscosity of most oils to an untreatable stage. However, there has been little effort in Australia and many other countries to prepare information or tools to properly make such a decision.

Controversy associated with dispersant use is largely the legacy of the relatively high toxicity generated by early generation dispersants, despite the bank of evidence that demonstrates modern formulations of dispersants alone, or oils dispersed by modern formulations, have lower or similar toxicity than that generated by untreated oils (Fingas 2000a, 2002a, Brady et al. 2002). The persistent issue of concern is whether the application of dispersant will generate harmful concentrations of hydrocarbons within the water column, potentially affecting sensitive biota.

In contrast to other countries, chemical dispersion has continued to be treated as a viable option in the USA. This is reflected in the increased research focus of US-based researchers on better understanding of the physical and chemical processes associated with chemically dispersed oil under realistic conditions, as well as improved methods to predict and assess dispersion in real-time.

Recent considered assessments of locally-specific aspects of dispersant use, including operational issues (effectiveness and limiting factors of the local environment) and environmental issues (net environmental benefits from applying or not applying dispersants for local resources) have been carried out by Marine Safety Victoria to support development of dispersant use protocols for marine waters of Victoria (Brady et al. 2002). The assessment reviewed published knowledge of toxicity and effectiveness of dispersants and related it to knowledge of the sensitivity of temperate Australian habitats. A more comprehensive
assessment has been carried out for marine waters of California, USA (Trudel et al. 2003). The assessment included a review of available data specific to the oil types handled in the region and application of a three-dimensional oil spill fates model to quantitatively estimate the exposure and effect on the various submerged and intertidal habitats. Net Environmental Benefit analysis was then used to compare outcomes with and without chemical dispersion for a range of spill scenarios. Both of these studies concluded that greater net environmental benefits could be gained by the cautious application of dispersants, with due consideration to the potential for effective dilution of dispersed and dissolved oil prior to arriving within shallow sensitive habitats. A number of other modelling studies have been conducted in the USA to pre-define the net environmental benefit of applying or not applying dispersant (French McCay & Payne 2001, Mearns et al. 2003, Trudel et al. 2003). All of these studies indicated that a net benefit can result from the application of dispersant, even those in relatively shallow inshore waters. This pre-developed knowledge provides a sound basis for the decisions required in an oil spill response. Marine Safety Victoria has recently commissioned dispersant modelling to investigate the consequences of dispersant use within and on approach to Western Port, Victoria, for this purpose.

Information supporting the careful use of dispersants in real spill situations has been published. For example, improved rates of long-term (23-29 years) post-spill recovery of oiled mangroves in Florida and Puerto Rico have been attributed to the use of dispersants at sufficient distance offshore to allow effective dispersion before the mangroves were exposed (Getter, 2003). Application of dispersants over the shallow intertidal areas was also beneficial to mangroves, but was harmful to adjacent submerged habitats (e. g. corals). In comparison, mechanical clean-up of mangroves was highly detrimental over the short and long-term.

In a recent practical application of dispersant within sensitive near-shore waters, the US Coast Guard/NOAA selectively applied dispersants in a response to an oil spill in the Galapagos Islands from the tanker, Jessica. One approach was to commence applying dispersants after the flood tide and throughout the ebb tide, based on observations that a strong near-shore current would carry the dispersed oil into deeper water. In this situation, the risks to seabirds from surface slicks was considered to be higher than to submerged habitats, given the controlled application of dispersant (Henry & Levine 2003).

The Texas Nearshore Dispersion Demonstration Project has investigated the theoretical, site-specific basis for applying dispersants, rather than purely mechanical clean-up, for spills affecting near-shore waters of the Texas Gulf, in preparation for planned field trials (Aurand et al. 2003).

Surface Washing Agents

Surface washing agents are distinguished from dispersants by having a higher hydrolipophilic-lipophilic balance, which gives better performance for washing of oil off surfaces and causes less dispersion of oil into the water column. Extensive testing of a wide range of dispersants and surface washing agents by Environment Australia has indicated that dispersant formulations provide poor surface washing ability while surface washing agents are usually poor dispersants (Fingas 2000b). This is a beneficial situation, because surface washing agents are most commonly used to wash oil off shorelines and other substrates in near-shore or enclosed waters, where they can be collected by skimmers or sorbents. The low dispersal rates reduce the in-water concentrations of hydrocarbons that are generated (Fingas 2000b). Limited trials of the effectiveness of surface washing agents have been performed in standardised laboratory settings and field trials. These studies are reviewed by Fingas (2000b) who concluded that most of these agents are highly effective at washing oil off
surfaces. However, caution is required with their use because they may also increase the penetration of oil into some substrates and can result in unacceptably high dispersion of oil into the water column.

Combined surface washing agent and fertilisers have been developed to aid cleanup of hard substrates and sediments. Cytosol is a commercial surface washing agent formulated from vegetable oil derived methyl esters and slow-release fertilisers (Wedel 2000). The product is designed to perform two functions. Firstly, the methyl esters act to break oil bonding to surfaces so that oil can be floated or washed off effectively with low-pressure cold water. This avoids the requirement for using high pressure hot water that will cause mortality to local biota. Secondly, the slow-release nutrients stimulate indigenous populations of oil-degrading bacteria to break down the residual oil (see section 4.9 Bioremediation). A series of field trials conducted by the US Coast Guard, US EPA and US Department of Agriculture have produced recovery rates of 60-80% depending on the oil and sediment (Wedel 2000). One of the limiting factors for use of surface washing agents is the relatively high application rates that are required. For example, Cytosol has a recommended application rate of 0.5:1 to 1:1 (Wedel 2000).

A more recent controlled study of Cytosol and another surface washing agent (Corexit 9580) carried out at the Shoreline Environmental Research Facility (SERF) in Texas (Page et al. 2000) also highlighted the complications that may be present at the site of a shoreline clean-up which must be considered during a response. The experiment was designed to specifically investigate the suitability of these products along open sand beaches of the Texas Gulf. Experimental applications of Cytosol and Corexit 9580 were applied to remove a weathered (24hrs) oil blend contaminating fine-grained sand in wave tanks. In the presence of wave action, Corexit 9580 was reported to effectively desorb the oil initially. However, reabsorption appeared to occur due to the fine sand released by the wave action. Cytosol was more effective at keeping oil desorbed. However, it also caused some dispersion of the oil into the water column in the presence of the simulated shore waves.

Pre-testing and approval for performance and environmental and personnel safety is required by authorities in most jurisdictions, including Australia, prior to the use of surfactant products. Effectiveness tests were developed in 1996 by Environment Canada and extended by the US EPA (Fingas 2000b). Testing of chemical treating products is on-going in a joint study of oil spill chemical treating agents by Environment Canada and the US Minerals Management Service [54]. However, no surface washing agents have recently been tested under this program. In Australia, The National Plan Advisory Committee (NPAC) Policy on New Chemical Products established a policy in 1997 that products must be pre-approved and listed on the National Plan Chemical Product Register prior to consideration of their use in Australian waters [55]. As a minimum pre-requisite, products must be listed on the US National Contingency Plan Chemical Product schedule and thus have met the testing and documentation requirements of that register. There were 22 surface washing formulations listed on the US register as of March 2003. However, to date, no manufacturers or suppliers have submitted documentation for pr-approval and register on the Australian schedule (pers. comm. Trevor Gilbert, AMSA).

ASTM International, an international voluntary standards development organisation, have recently (2000) published a standard guide for the use of chemical shoreline cleaning agents which can be purchased on-line [56]. This is a standard guide for shoreline applications that provides information to assist spill responders in the use of chemical shoreline cleaning agents as part of the oil spill cleanup response. The guide covers and distinguishes between shoreline cleaners that disperse oil into the water and those that disperse little oil into the water under low energy levels but not chemicals formulated as dispersants. The guide does
not provide criteria to assess the suitability of shoreline cleaners and assumes that conditions are suitable and that permission has been obtained from environmental regulators. The guide does not cover chemicals formulated as dispersants. Variations in the behaviour of different types of oil are also not dealt with in this guide and may change some of the parameters documented within the guide. It is noteworthy also that many of the guides on ecological considerations for dispersants that are referred to in the guide have been withdrawn (at the time of preparation of this review).

4 9 Shoreline Clean-up

Bioremediation

It is well established that oil stranded on shorelines above the tide zone will weather with time and some biodegradation will normally occur, although extremely slowly. In some environments, deposits of relatively unweathered oil are still being monitored 20-30 years following spill exposure (Wang et al. 2001, Prince et al. 2002). Studies to date have shown that the rate and extent of natural petroleum biodegradation are most strongly affected by the environmental conditions, especially temperature and the availability of oxygen, the physical and chemical composition of the oil and the type of petroleum degrading bacteria that are present (Bonner et al. 2002).

Natural biodegradation is known to occur through the action of mixed microbial populations. Many bacterial species capable of degradation of some hydrocarbons components have been isolated, although no one naturally-occurring species has been found capable of degrading more than about 10 compounds. Thus, a consortium of bacterial species will normally be required (Fingas 2000a). Further, natural bacterial populations can only utilize the light aromatic and saturate fractions of oils so that biodegradation is only effective on light to medium oils that have a high saturate fraction. Biodegradation of oil will result in a residue consisting of asphaltenes, asphalts and heavy aromatic fractions that will not degrade.

Some research has been undertaken in the USA to evaluate the ubiquity of indigenous populations of petroleum-degrading bacteria. Bonner et al. (2002) sampled sediments at both oil-contaminated and un-oiled, apparently pristine, shorelines along the Texas Gulf for hydrocarbon-degrading bacteria and enumerated populations in terms of total heterotrophs, saturate degraders and polycyclic aromatic hydrocarbon (PAH) degraders. Populations of oil-degrading populations were found to be ubiquitous, although PAH populations were higher where there were anthropogenic oil inputs.

Interest in enhanced bioremediation grew out of successes reported from the use of treatments tested on oil-exposed shorelines during the Exxon Valdez spill in 1989, and since that time, many commercially produced bioremediation agents have been developed. These can be classified into bioenhancement (or biostimulation) agents, that contain fertilizers, surfactants or other chemicals to enhance the activity of hydrocarbon-degrading organisms indigenous to the site of the response, and bioaugmentation agents that also contain inoculums of bacteria with proven biodegradation capabilities, which are not naturally occurring at the site. All of these treatments may have undesired consequences for the environment, such as triggering local eutrophication or interfering with the function of local bacteria. Most of the recent research on these agents has focussed on determining the efficacy and environmental consequences of their application.

Screening tests for the effectiveness and toxicity of bioremediation agents have been developed by Environment Canada and the US-EPA (Foght et al. 1998, Wang et al. 2000).
tests developed by Environment Canada have been specifically developed for cold (<10 °C) marine waters and cool (10-20 °C) fresh-water environments, while the US EPA tests have been developed for marine waters with a wider range of temperatures, thus would be more applicable to Australian conditions. Tests developed by these agencies also differ fundamentally, because Environment Canada developed tests based on synthetic consortia of bacterial cultures, which were originally drawn from geographically diverse sources representing different natural environments, but are then maintained under controlled conditions, while the US-EPA chose to use natural seawater micro-flora from locales and seasons of interest as their standard inoculums. Thus, the former approach aims at standardisation and reproducibility of different bioremediation agents in laboratory tests. The latter approach, although achieving lower reproducibility, aims to make results more realistic. These tests have shown that nutrient amendment stimulates degradation of saturates and some agents also show enhanced rates of degradation of PAH components in laboratory tests (Wang et al. 2000).

Results of bioenhancement trials that have been carried out in large tank and field trials have been mixed. For example, trials of two types of bioremediation agents: a slow-release inorganic fertilizer and an oleophilic organic fertilizer in mesocosms containing natural beach sands contaminated with Arabian Light Crude Oil indicated that limited to no additional biodegradation was achieved due to application of the agents (Swannel et al. 1995). One of these agents had earlier proven to be effective at enhancing biodegradation rates for a similar oil type in natural cobble beaches (Bragg et al. 1994), highlighting the importance of physical conditions present within different beach environments.

More recently, controlled experiments were carried out in a tidal estuary in Canada to compare remediation of weathered light crude oil contaminating sediments by natural attenuation (no treatment) and different blends of fertilizers and surfactants. The results demonstrated that biodegradation was not significantly enhanced by the fertilization treatment (Lee et al. 2001). In another study conducted on oiled beach sediments, the bioavailability of PAH was similarly unaffected by simple nutrient treatment, but did decline slowly over time, suggesting that depletion was due to weathering and sediment dispersion and not to bioremediation efforts (Hodson et al. 2002). Doe et al. (2002) found that the detoxification of oiled marsh sands (as indicated by toxicity to amphipods) was more rapid and complete in a treatment combining nutrient addition and sediment aeration, compared to no treatment. Detoxification was due to biodegradation of the polycyclic aromatic hydrocarbon (PAH) components. Regular tilling and irrigation has also been shown to significantly enhance the biodegradation of oil treated with the combined washing agent and bioremediation agent, Cytosol (Wedel 2000). Thus, the weight of evidence suggests that the combination of fertilization and physical treatment to enhance the supply of oxygen can increase biodegradation rates but fertilization alone (e.g. where physical ripping of the soil is unacceptable or impracticable due to lack of access by equipment and personnel) is unlikely to decrease the time to degrade oil. Given that the time to restore biological productivity (as distinct from oil removal) can be increased by intensive treatments (Gudimov 2002), fertilization treatment may not be warranted and could be detrimental in many situations.

It has been argued that chemical dispersion of oil can aid biodegradation, by increasing the available surface area to bacterial action. Limitation of nitrogen and phosphorus concentrations has been shown to limit this process in practice, because the dispersed oil represents an oversupply of carbon only (Harris et al. 2002). Controlled application of different nitrogen and phosphorous ratios to dispersed oil in seawater has been shown to stimulate the biodegradation rates for saturate components, but not PAHs (Harris et al. 2002).
Phytoremediation (degradation aided by living plants) and zooremediation (degradation aided by macro-scale animals) are emerging tools that have shown some promise for use in areas where mechanical and physical clean-up are difficult. Plant-based remediation techniques have been established for a range of contaminants in soils and waters. Plants have been shown to introduce oxygen into the sediments, stimulate bacterial populations in the sediment, exude enzymes that catalyze chemical degradation of toxic compounds and to take up pollutants within the plant where they are metabolically degraded (LaRiviere et al. 2002). Studies have shown the uptake of oil by wetland plants can effectively remove oil from anaerobic sediments (Carlson & Forrest, 1982) and that oxygen and carbon released by plant roots can stimulate oil-degrading bacteria (Mendelssohn 2000). However, evidence has also been presented for limitations on the technique in practice. For example, Phytoremediation was tested for effectiveness in treating contaminated soil contaminated by weathered refinery waste-oil in a three-year study in northern California, following a test protocol and analytical procedures developed by the US EPA (Camp et al. 2002). Results suggested only subtle benefits of phytoremediation for this highly weathered source oil. In another study using weathered light crude oil, growth of an oil tolerant saltmarsh plant species appeared to have little or no impact on the biodegradation rates of oil stranded in the plant root/sediment matrix of a Canadian estuary (Lee et al. 2002). In contrast, the limited available evidence suggests that zooremediation can be beneficial. For example, Gudimov (2002) reported field experiments on a cool temperate bay shore (Barents Sea) to evaluate the biodegradation of oil in the sandy littoral zone by local populations of bivalve molluscs. Oil degradation was accelerated 10-20 times in the presence of the bivalves, which proved to be tolerant of the oil pollution.

4.9 Wildlife Impact Management and Minimisation

Oiled Wildlife Care Facilities

The greatest commitment to oiled wildlife care, in terms of the establishment of permanent treatment facilities, training of personnel and fostering of research and development has been in the United States. Within this region, there is also a geographically disproportional distribution of facilities, with 24 operating in the state of California, co-ordinated by the Oiled Wildlife Care Network [57], and one each in Alaska, Oregon and Delaware. The proliferation of care facilities in California has been fostered by state legislation that has been in place since 1990 which requires the California Department of Fish and Game Office of Spill Prevention and Response (OSPR) to establish rescue and rehabilitation stations for aquatic birds, sea otters, and other marine mammals. OWCN receives government funding under an oil-levy system and co-ordinates the sharing of experience and resources by member organisations. There are a number of the larger care facilities available within the OWCN.

1. The California Department of Fish and Game (CDFG) Office of Spill Prevention and Response (OSPR) Marine Wildlife Veterinary Care and Research Center (MWVCRC), which is designed to care for oiled wildlife in the event of an oil spill. The MWVCRC was specifically built within the range of the southern sea otter and is capable of caring for 125 sea otters, but flexible enough to care for other species of marine animals as well. The MWVCRC’s oiled animal care wing is equipped with an avian and marine mammal clinic, nursery, and triage; a surgical suite; washing, drying, and recovery rooms as well. The centre’s laboratory services wing houses an animal food preparation kitchen. The out door pool yard is equipped with five pools and 40 two-otter pool pens serviced by a sea water
pumping, disinfection and filtration system. The centre is also equipped with a full pathology suite and evidence storage freezer.

2. Tri-State Bird Rescue & Research Inc. is a private, non-profit wildlife rehabilitation organization located in Newark, Delaware. Tri-State provides professional care for injured, oiled & orphaned wild birds. Tri-State Bird Rescue and Research has been responding to wildlife involved in oil spills since 1976 and has staff on call 24-hours-a-day to respond to wildlife contaminated by oil spills anywhere in the world. The organization will respond to an oil spill at the request of the responsible party, clean-up contractor, federal or provincial agency. Staff will travel to any site worldwide to prioritise the response, establish care facilities and methodology, train field personnel, and assist management of oiled bird treatment. The organisation also operates the Frink Centre for Wildlife, which has veterinarian and treatment facilities for oiled or injured birds [58].

3. The International Bird Rescue and Research Center (IBRRC) is a non-profit organization that operates three treatment facilities in the US; two in California and the third in Alaska, where care can be provided for a large number of oiled birds. IBRRC provides training and consultation to the petroleum industry, local, state, and federal Fish and Wildlife agencies, wildlife rehabilitators and researchers and develops treatments and protocols for aquatic birds and waterfowl. IBRRC also provide response teams that will travel to spill sites world-wide and has responded to over 150 oil spills over the past 30 years. IBRRC staff are experienced at establishing oiled wildlife care centres in remote location, training and managing local volunteers and mounting search and collection programs [59].

4. The International Wildlife Research Center is a non-profit organisation that was founded in 1992 to assist in the critical care needs of sensitive, threatened and endangered wildlife species impacted by oil spills. IWRC currently operate facilities in Oregon that include wildlife inspection stations, warehouse and cold storage facilities, and oiled wildlife medical care facilities suitable for large numbers of oiled wildlife [60].

A number of care facilities and networks of care professionals and volunteers have also been established in other countries. Earthkind is a United Kingdom-based charity that was established to protect seabirds and marine wildlife from the effects of pollution, through a combination of emergency wildlife rescue, education and conservation [61]. Earthkind has a permanent team of mobile veterinary paramedics that are available to offer assistance to local organisations internationally, assist with rehabilitation protocols and train local volunteers. EarthKind has also been active in development of improved handling and treatment and improving international co-ordination of spill response. The Westkuestenpark Oiled Seabird Rehabilitation Centre is a new facility that was established in 2002 at St Peter-Ording in Schleswig-Holstein in the northwest of Germany [62]. The International Fund for Animal Welfare (IFAW) provided funding to build and establish the Westkustenpark Centre, which was set up under guidance provided by IBRRC. The centre offers facilities and personnel to care for oiled birds and will carry out research to increase survivorship of local bird species. Massey University is responsible for developing and maintaining capabilities to respond to wildlife affected by marine oil spills in New Zealand, under contract to the Maritime Safety Authority of New Zealand [63]. Massey’s Oiled Wildlife Response programme includes maintaining facilities for oiled wildlife care at the Palmerston North campus of Massey University, development and delivery of training courses and fostering regional capabilities for emergency oiled wildlife care.

Care facilities in Australia are currently limited. No dedicated oiled-wildlife care facilities have been established, and most efforts to respond to oiled wildlife in the past have been carried out using mobile facilities or at veterinarian facilities established by wildlife parks.
and other institutions, and thus are only available as a secondary and voluntary function to their normal responsibilities. In contrast to the funding support enjoyed by members of the OWCN, no external funding is currently available to these facilities to support their care work. Taronga Zoo, in Sydney, runs some training courses on the rescue and rehabilitation of oiled fauna and has a veterinary clinic that has limited capacity to handle oiled fauna. SeaWorld in Queensland have a marine rescue team and limited veterinarian and wildlife care facilities. Veterinarian facilities for oiled penguins and training courses on oil penguin response are run by Phillip Island Nature Park.

General protocols for the care of oiled birds and marine mammals have been prepared by the OWCN [64]. These protocols are made available to non-OWCN participants via the World-Wide-Web as a guideline to assist other professionals with handling and medical management of animals affected during spill events. Factors such as petroleum type, species impacted, numbers of individuals affected, and seasonal factors are known to be critical variants on the optimum procedures and OWCN offer advice in individual spill situations to non-OWCN participants. “Protocols for Oiled Mammals” are presently only available from OWCN in hardcopy. They are currently undergoing major revisions and will be available around July 2003.

Protocols for the care of oiled birds have been published in Australia by Erna Walraven and published by Taronga Zoological Park in Sydney. The field manual includes a technical section for veterinarians and a booklet for photocopying and handing out to field staff and volunteers. Some of the information in this manual has become superseded and a revision of the existing manual has been identified as a priority for support from the Australian Maritime Safety Authority (pers. comm. Trevor Gilbert, AMSA).

Michael Short, from the Queensland Parks and Wildlife Service, received funding under the Churchill Fellowship in 2000 to visit and document the practices and experiences of international facilities for the care of oiled wildlife. These included 13 facilities in the USA and one in South Africa. His report, submitted in January 2001 contained recommendations for planning, funding, training, response structures, equipment and enforcement [65]. The recommendations were focussed on the organisation of response arrangements in Queensland and have been used to guide improved preparation and training for oiled wildlife response in that state (pers. comm. Michael Short, QNPWS).

The Australian Maritime Safety Authority has more recently (September 2002) developed national guidelines for the development of oiled wildlife contingency plans following a period of development and consultation co-ordinated by the National Wildlife Response Plan Working group, with members from each of the Australian States and Territories. The guidelines have been issued as a contents guide, with recommendations that the States and Territories prepare plans appropriate to their jurisdictions (pers. comm. Trevor Gilbert, AMSA). Oiled wildlife cleaning & rehabilitation kits have also been assembled and distributed by AMSA to major response centres in all states and territories, satisfying a recommendation of the National Plan to Combat Pollution of the Sea by Oil and other Noxious and Hazardous Substances [66].

The International Fund for Animal Welfare (IFAW) co-ordinates rapid responses to animals affected by disasters worldwide [67]. Funding is provided through the Worldwide Emergency Relief Fund, which relies on donations. IFAW responds to oil spills and other man-made or natural disasters through provision of emergency relief teams. Working in partnership with personnel from IBRRC, the IFAWs stated approach is to “co-ordinate and support local groups and community-based wildlife rehabilitators and veterinarians in order to most effectively rescue and rehabilitate oiled wildlife”. Some of the recent large responses
that have been co-ordinated by IFAW emergency relief teams included responses to spills from the *M. V. Treasure* off Cape Town, South Africa; *the Erika*, off Brittany, *the Jessica* off the Galapagos Islands and the *Prestige*, off Spain. Three experienced Australian wildlife carers (Erna Walraven and Elizabeth Hall and Mike Short) attended the most recent response to the Prestige spill as part of the IFAW team. Experiences gained during the response have been documented in a report to the National Plan (pers. comm Trevor Gilbert, AMSA).

The protocols that have been developed from Australian experience differ in some critical areas to those followed by the IFAW response team and dialogue is currently underway to establish the scientific evidence or other bases for the protocols to help standardise protocols in preparation for responses in Australia requiring international support (pers. comm Erna Walraven, TZP).

One of the most significant developments in moves to share and collectively develop response technology for oiled wildlife internationally has been progress to develop The International Alliance of Oiled Wildlife Responders. The Alliance is a professional association of individual organisations who will come together with the collective aim of establishing the standards and setting the guidelines for oiled wildlife response globally. The stated purpose of the Alliance is to strive for higher levels of professionalism among organisations and individuals in the care of oiled wildlife. The Alliance itself does not respond, train or prepare contingency plans. Individual member organisations carry out these tasks - either singly or as a team.

The stated roles of the Alliance are to:

- Facilitate updates of the standards and guidelines for oiled wildlife care;
- Facilitate dissemination of the standards and guidelines;
- Conduct accreditation reviews;
- The Alliance may act as a unified voice on issues regarding oiled wildlife response;
- Serve as a clearing house for information;
- Facilitate training, contingency planning and response;
- Foster development of in-country expertise in many areas throughout the world;
- Support or otherwise foster research into new technology for oiled wildlife response;

The Alliance is still under development and is to be incorporated in the United Kingdom, with the formal release to take place at the “International Effects of Oil on Wildlife” conference in October 2003, which will be conducted in Germany. The Alliance will be composed of a board of directors who will be elected by the membership. Membership for the Alliance is to be inclusive and not exclusive to encourage any individuals and organisations globally to become a part of the organisation.

The founding organisations include:

- International Bird Rescue and Rehabilitation Centre – USA
- Tri-State Bird Rescue – USA
- International Fund for Animal Welfare-Global
- Royal Society for the Prevention of Cruelty to Animals – UK
Innovations in Oiled Wildlife Protection

Many of the established international care facilities conduct in-house research to improve knowledge of handling and cleaning technology for oiled wildlife. For example, IBRRC supports a research program that focuses on improving oiled wildlife care and response and the general rehabilitation of aquatic birds through application of new techniques, clinical trials and post release studies [68]. Current research projects include:

- revising and developing new sea bird diets;
- developing protocol for the control of airborne fungal disease in oiled birds;
- long term alcid (otter) rehabilitation techniques;
- improved caging for difficult species;
- post-release radiotelemetry studies to quantify post-release mortality and behaviour of rehabilitated oiled birds; and
- establishing normal blood analyses for each species as a benchmark for quantifying levels of health of oil-affected birds.

External recurrent funding for oiled wildlife research in the USA is also provided by the Research and Technology Development program managed by the Oiled Wildlife Care Network. OWCN offers funds annually, via a competitive grants scheme, for research in two areas:

- Oiled wildlife care and the effects of oil on wildlife;
- Post-release survival studies on rehabilitated oiled wildlife.

Abstracts of past and current rounds of research are posted on the world-wide-web [69]. Abstracts of research presented to the most recent Oiled Wildlife Care Network Research Symposium (May 2001) are also available online [70]. With few exceptions, the past and current projects that have received funding via this program concentrate on the care or
response to treatment of individual bird and mammalian species that are endemic to the United States, or specific regions of this continent. This reflects the species-specific focus that has evolved within this funding environment, presumably driven by the experience that such information is necessary for effective response. Thus, much of this research may have limited relevance to species that occur in Australia or New Zealand.

Another international forum for oiled wildlife response is the International Effects of Oil on Wildlife conference, last held in South Carolina in 2000 and next planned to be held in Germany in 2003. Abstracts of the 2000 conference have not been published. Thus were unavailable for this review.

Recent research efforts in Australia and New Zealand have been limited, with the major focus on improved cleanup techniques for oiled birds to reduce the time and stress involved in the procedure. A detergent-effectiveness test has been devised and applied in laboratory trials and during a recent spill off Gisborn, New Zealand (Monfils et al. 2000, Monfils unpublished). The test compares the cleansing time required for samples of detached feathers that are contaminated with fresh and dried oil. The procedure is recommended as a standard protocol to select the best available cleanser for individual oil-types and conditions. Another research effort involves the development of a dry-cleansing method and apparatus for oiled bird feathers. The method involves the application of iron-powder, which adsorbs effectively to the oil, followed by cleansing of both the iron-powder and adsorbed oil using a magnetic comb. Initial tests on individual feathers indicated that up to 100% oil removal could be achieved rapidly and that feather microstructure was less disturbed than by wet-washing with detergent (Orbell et al. 1999). The research is continuing with investigation of whole-bird models, optimization of the pick up rates and development of pre-conditioners for dealing with weathered oil contamination. Other studies include development of an assay for feather damage based on digital imaging and mathematical analysis of the feather vane (pers. comm. John Orbell.). This work is in collaboration with the Phillip Island Nature Reserve and SeaWorld Research and Rescue Foundation of Australia.

Other International research that is relevant to Australia has examined the benefits of treating oiled birds, in terms of the effect on populations. The South African Foundation for the Conservation of Coastal Birds (SANCCOB) applied a simple, deterministic population model to estimate the potential benefits of rehabilitation of oiled penguins (Ryan 2002). Using actual numbers of oiled penguins released from SANCCOOb since 1968, a Population Variability Assessment (PVA) model was used to compare population estimates with and without cleaning of oiled penguins. The results suggested that, due to SANCCOOb’s efforts, the current (2002) African Penguin population is 19% larger (163,000 adults) than it would have been in the absence of rehabilitation efforts (137,000) during two major oiling events, and numerous smaller spills. The average population size in the next 20 years was predicted to be 22-61% per year greater if oiled birds are rehabilitated, allowing for an increased probability of spills ranging from 5 – 20% per year. The results suggest that rehabilitation efforts have significant positive outcomes for population sizes, especially in the longer-term and thus will be especially beneficial for endangered species.

4.10 Developments in Chemical Spill Response

In contrast to oil spill response technology, the development of equipment, techniques and systems to handle non-oil chemical spills into marine environments have received less attention from the marine spill response community, despite the unique characteristics of chemical spills, compared to oil spills, and the potential for greater environmental and human health damage associated with many of the pure and mixed chemicals that are
routinely transported by vessels, or handled in situations where they can be spilled into waterways. The only notable advances that could be identified were in the areas of modelling to predict the trajectory and fate of spilled chemicals; improved instrumentation to identify and quantify concentrations of spilled chemicals; and the development of databases for material safety data on chemical behavior, handling and environmental and safety hazards.

Environment Canada has run a chemical spill response program for over 20 years, during which time a number of initiatives have been trialed and developed (Goldthorp et al. 2002). One outcome of this program has been the development of chemical spill response manuals. The Hazardous Materials Manual, first published in 1984, includes information to guides on-site decisions for 220 commonly-spilled compounds. The Handbook of Hazardous Materials Spills Technology (Fingas 2002e) has also been published with the aim of providing a central source of information for chemical spill response internationally. The current edition includes information on risk assessment, modelling, analytical tools community consultation and current government regulatory arrangements in various countries. A Survey of Chemical Spill Countermeasures has also been completed under this program to collate information on equipment suitable for containment, clean-up and disposal of spilled compounds. Another initiative of this program has been the development of portable instrumentation and analytical procedures for carrying out field-based analysis to determine the extent of contamination at the site of a spill.

Innovations have been made to improve the prediction of chemical fates using modelling systems. The requirements for modelling of chemical spills differ from those for oil spills because of the far wider range of states (powders, crystals, blocks, colloids, solutions, pure liquids, gases etc.) and behaviours (dissolving, reacting, precipitating, evaporating etc) presented by chemicals. A number of three-dimensional chemical spill models have recently been developed. These have used the architecture of operational three-dimensional oil spill models but have been developed with mathematical algorithms specific to the behaviour of pure, and in some cases mixed chemicals, given the initial nature of the product and the chemical/physical nature of the water (water temperature, salinity and other factors such as the suspended solids concentration depending on the model). Available models vary in the range of chemicals and general chemical behaviours (e.g. dissolvers, floaters, sinkers, evaporators) that can be modelled. Chemsis is a three-dimensional chemical fates model that predicts the time-varying concentration of soluble chemicals within the water column. The model was applied to calculate expected concentrations of the various pollutants (styrene, methyl ethyl ketone, isopropyl alcohol, fuel oil and diesel) spilled from the *Ievoli Sun*. Concentrations could then be judged against threshold concentrations of concern. Another model, the Chemical spill mapping and analysis package (CHEMMAP) includes an inventory of materials safety data for over 7000 chemical compounds as well as algorithms to model the fate of dissolving, precipitating and reactive chemicals. An atmospheric plume model is provided to assess risks to responders or local populations. In addition, a biological effects model can be run to quantify potential or actual damage (French-Mccay 2001).

The CAMEO (Computer-Aided Management of Emergency Operations) program is a publicly available set of software modules jointly developed by NOAA and the US EPA to help first responders and emergency planners plan for and quickly respond to chemical accidents. CAMEO includes a chemical database of response recommendations for about 6,000 chemicals, and a synonym searcher to identify substances during an incident. Firefighting and spill response recommendations, physical properties, health hazards, and first aid guidance are provided for each chemical. CAMEO will also predict potential reactivity between two or more chemicals, if mixed. Another module, ALOHA, is a simple
air dispersion model that predicts the downwind dispersion of a chemical cloud. Graphical outputs include estimates of the cloud footprint (representing the area where hazardous gas concentrations may reach a level of concern), the rate and duration of release of the chemical to the atmosphere, and chemical concentration over time at locations of particular concern [71].

The availability and type of personal protective equipment that is worn by responders is usually more critical for chemical spills. Fingas (2000c) provides an overview of these requirements as well as a checklist of the health exposure limits and recommended level of protection for over 200 chemicals.
5.0 FUNDED RESEARCH EFFORTS BY INTERNATIONAL AGENCIES

This chapter reviews relevant research and development work currently underway that is sponsored by large international government and industry agencies.

5.1 Minerals Management Service (Department of the Interior, USA Government)

The Minerals Management Service (MMS), a bureau in the U. S. Department of the Interior, is the U. S. A. federal agency that manages the nation's natural gas, oil and other mineral resources on the outer continental shelf. The agency also collects, accounts for and disburses more than $5 billion per year in revenues from federal offshore mineral leases and from onshore mineral leases on federal and Indian lands. The program is national in scope and headquartered in Washington, D. C.

The Offshore Minerals Management Program conducts research specific to issues associated with OCS mineral leasing and development, via two major programs:

- The Environmental Studies Program assesses the potential environmental risks of offshore development and provides information necessary to minimise any adverse risks. Since 1974, the Environmental Studies Program (ESP) has spent over US $650 million and completed over 900 research projects. These studies encompass biological, physical oceanographic, ecological, and socioeconomic issues associated with offshore mineral leasing and development.

- The Oil Spill Response Research Program provides information on oil spill response capabilities and conducts studies on spilled oil and its effect on the marine environment. On average, the agency spends more than US $6 million per year on research into oil spill prediction, prevention, and response technologies. MMS also spends about US $1 million per year to manage the National Oil Spill Response Test Facility (known as “OHMSETT”), a facility that evaluates oil spill cleanup equipment technologies under controlled conditions.

All MMS environmental studies information can be accessed on-line through the ESP Information System (ESPIS). ESPIS makes available the results of more than 20 years of scientific research, including oil spill research [72].

Environmental Studies Program

A number of oil-spill response related projects are commissioned under this program [73]:

**The Modelling Review Board** is a panel of recognized national experts on physical oceanography and oceanographic modelling [74]. The Board provides advisory services in ocean modelling to the MMS regarding ongoing and planned research in physical oceanography. Much of this review work has focussed on defining the necessary spatial and temporal scales of models in order to represent critical influences of circulation dynamics within the models. Several site specific projects to improve field observations and model resolutions are managed.

**Predictability of Ocean Models for Strategic and Long Term Modelling.** The MMS is conducting two physical oceanography field programs with concurrent modelling effort in the OCS regions [75]. One of them is the NE Gulf of Mexico Physical Oceanographic Study and the other is the Santa Barbara - Santa Maria Basin Circulation Study. The primary purpose of this initiative is to perform basic research on ocean and atmospheric modelling to
determine what the limitations are of present modelling methods, and develop new techniques that can extend the time period over which useful predictions can be made. Study areas include study of quasi-stable structures in the ocean models, such as fronts, eddies, squirts and jets, analysis of Lagrangian drifter trajectories, and assimilation of satellite data.

Deepwater Subsea Oil Spills. Deepwater development in the Gulf of Mexico is raising concerns about the transport and fate of oil released by accidents near the seafloor in locations where the water depth is great. The Deepwater Subsea Oil Spills project has the objective of developing a modelling tool to estimate the transport and fate of oil spilled below the sea surface near the sea floor in deepwater. Fate investigations include whether the oil surfaces in a recoverable state or changes behaviour at deeper levels in the water column [76].

Persistence of Crude Oil Spills. The objective of this study is to collate and analyse historical data on the persistence of crude oil on open water primarily in relation to spill size. Additional factors that relate the persistence of crude oil on open water will be identified and analysed. This study aims to provide historical validation for determining the persistence of crude oil spills on open water for setting end points for future trajectory modelling of various sizes of crude oil spills [77].

Deepwater Currents in the Gulf of Mexico. The objectives of this study are: (1) to conduct an exploratory study of currents over the entire water column with limited but essential spatial coverage in deepwater of the Gulf of Mexico; (2) to analyse the data collected to identify temporal and spatial scales of motion; (3) to evaluate the physical processes detected in terms of energy content and frequency; and (4) to design and evaluate a mooring array and hydrographic survey for a comprehensive study of currents in deepwater of the Gulf of Mexico [78].

New Remote Sensing Methodologies for Surveillance of Ocean Features and Circulation in the Gulf of Mexico. The first objective of this new project to run from 2002-2005 is to develop, apply and assess new techniques for detecting ocean features and predicting regions of strong currents using a combination of remote sensing and in-situ measurements. The second objective is to quantify the spatial scales, temporal behaviour, and vertical structure and velocities of frontal eddies [79].

Coastal Marine Environmental Modelling. This study, which is currently concluding, was continuing a program to model physical, geological, chemical, and biological interactions between estuaries and the shelf specific to Louisiana, with spin-offs for understanding of other coastal systems with large inputs of freshwater. Numerical models are being developed in estuaries along the Louisiana coastline to study their circulation and interactions with the adjacent shelf. Biological and sediment transport models are being developed and coupled with the circulation models to study changes in the estuaries. The model will include overbank flooding capability to study the effects of floods on adjacent marshes [80].

Environmental Sensitivity Index (ESI) Shoreline Classification using New Remote Sensing Data and Techniques. The Environmental Sensitivity Index (ESI) is a shoreline classification, and sensitivity ranking system. The project is to develop repeatable ESI classification procedures for use with newer, higher resolution remote sensing products such as IKONOS and QuickBird satellite imagery. Using archived IKONOS 4-meter multispectral imagery, digital, vector shorelines and shoreline classifications are being derived using novel image processing techniques. Quantitative and qualitative accuracy assessments are then being used to judge the success of the automated interpretations. Final data products will include a digital shoreline, ESI coverage in Arc/Info format, and associated metadata. The project commenced in 2002 [81].
Recruitment to Rocky Shores. Intertidal communities are considered among the most vulnerable to impacts resulting from oil spills because most species are sessile and because oil is deposited on intertidal surfaces. This study (1) assesses spatial and temporal variability in recovery of intertidal communities across a biogeographic break to examine recovery dynamics across an oceanographic feature associated with pronounced changes in temperature, upwelling, community structure and recruitment dynamics; (2) determines if there is a relationship between recruitment intensity and/or variability and community recovery following a disturbance; and (3) develops and assesses a predictive model of recovery potential incorporating information obtained from this study and from ongoing monitoring of intertidal communities along the coast of California. The project commenced in 2001 and is due for completion in 2004.

Oil Spill Response Research Program

The Oil Spill Response Research (OSRR) Program provides research to improve the capabilities for detecting and responding to an oil spill in the marine environment.

Ongoing MMS studies commissioned under this project which are relevant to Australia include:

Physical Behaviour of Oil in the Ocean. This is a Joint Industry Project (JIP) between MMS and Environment Canada to study oil behaviour and oil properties, particularly those of heavy oils and other oils transported through this region. The study includes: buoyancy behavior, solubility, evaporation, dispersion, photo-oxidation, and emulsification. Several information gaps were identified on the behaviour of oils where more experimental work is needed: 1) the kinetics of oil emulsification; 2) the rate of solubilization; and 3) the rate of dispersion. Experiments will be conducted to study these processes in context with the typical environmental variables of temperature, wind speed, sea state, and oil type. The physical and chemical properties of oils from a number of crude oils from deepwater Gulf of Mexico have been analysed to produce an updated catalogue of Crude Oils and Oil Products, containing information on more than 450 different types of oils. The Oil Catalog can be found at Environment Canada’s Internet website. Work continues on the BOSS (Behavior of Spilled Oils) project.

A Method to Determine Worst Case Discharges from Facilities that Produce or Transport Oil in the US Outer Continental Shelf. To date, this project has produced a beta-version of a model to calculate a discharge from a pipeline and a pocket guide for quick assessment of a worst case discharge from a pipeline for field use. The model is known as the Minerals Management Service Pipeline Oil Spill Volume Estimation Model (POVIVEM). POVIVEM includes a Release Module and a Near Field Module, linked together with necessary databases through a Graphical User Interface (GUI). The GUI allows the user to sketch a platform - pipeline layout, enter characteristic parameters, and run the model to estimate the volumes of potential or actual leaks. Inputs to the model are parameters describing the configuration and characteristics of a pipeline system, the fluid it contains, and the perforation or break from which the discharge occurs. Key outputs are the evolution of the release rate over time, the total mass of oil released, and the mean thickness of any eventual surface slick being formed. An evaluation version, user’s manual and pocket guide was posted to the web for public comment in March 2003.

General review of the research, development and technology activities of the MMS indicates that significant resources from the agency are allocated towards environmental studies to improve model predictions of the environmental fate, transport and effects of oil discharges, including discharges from more unusual situations, such as deep water; development of
technologies around new and emerging remote sensing data, to improve description of resources and as input to models, as well as basic research to better understand the properties of oils and response equipment. Further, the agency continues to support the National Oil Spill Response Test Facility (known as OHMSETT), a unique facility that supports evaluation at full scale of oil spill cleanup equipment technologies. Recent trends in research at the facility highlight the increasing interest in in-situ burning as a response option.

Another obvious trend in the recent allocation of research monies from the MMS is the discontinuation of most of the remote sensing projects for on-water oil detection and measurement. In the recent past, the MMS had commissioned a number of studies to detect oils spills and measure oil thicknesses using shipborne, satellite and aircraft sensors. Almost all of these projects were unsuccessful and were put on hold due to inconsistent results or unreliable equipment.

5.2 Environment Canada (Canadian Government)

The Environmental Technology Centre (ETC) of Environment Canada is directly involved in the response to pollution emergencies such as oil and chemical spills, the cleanup of hazardous waste and the provision of technical research and development to support these and other activities. In general, ETC undertakes research on the properties, behaviour, and effects of spilled hazardous materials and the effectiveness and environmental benefits of in-situ countermeasures including the development of treatment guidelines, treating agent performance and effects, development of testing protocols and performance standards, effectiveness and toxicity testing, and burning techniques. Current Research and development programs include:

Chemical Spill-treating Agents. The chemistry (especially stability over periods approaching days) and physics (especially dispersant particle size) of dispersants are being studied in an on-going program. In addition, work is continuing on the development of new dispersants. Some of the prototype formulations offer potential to disperse heavy oils, including Bunker-C. Environment Canada and the U. S. Minerals Management Service jointly fund this work.

Sorbent Evaluation. A project to develop an improved performance standard for the testing of oil spill sorbents. A Canadian General Standards Board testing protocol was developed earlier, which targets performance parameters for sorbents used to combat oil spills. Additional work was performed to ensure that compatible testing protocols were developed in the U. S. Results to date have been tabulated in a database that is to be made available as a public resource on the Internet. Development has also continued on a similar protocol and test program targeting sorbents used for chemical spills. Sorbent performance and chemical compatibility were the initial parameters investigated.

ETC also maintains a Spills Technology Database. This database contains an Oils Properties Database, which contains information about companies, oil properties, chemicals and instruments related to oil spills [86].

Delivery of spill and contaminated site remediation research and development and related scientific activities is also now conducted by SAIC Canada, which is partially made up of a now-privatized group of former Environment Canada research scientists, engineers and technicians, continuing their work under a new working relationship with Environment Canada.
5.3 European Commission

The Joint Research Centre carries out research for the European Commission and has previously (up to January 2003) supported oil spill response technology development projects. However, the current (2003 year) scientific work programme does not list any projects related directly to oil spill response.
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Data were collated from various sources, including peer-reviewed scientific journals, proceedings of recent (post 1998) international conferences, technical notes, trade publications, information supplied by manufacturers and private research and development organisations as well as information published on the world-wide-web. Contact was also made to primary research organisations within Australia (e.g. CSIRO, AIMS, Parks and Wildlife Services, Universities etc.) and other countries to source information on research activities. Links to web addresses that are referenced in this document are provided as numbered hyperlinks, with the following format [23]. These can be followed directly from the document where this document is viewed electronically in Word© format. A list of these web addresses is also provided. While these links were active at the time of writing of this review, the authors acknowledge that web-addresses may become inactive.
REFERENCES


LINKS TO INFORMATION AVAILABLE ON THE WORLD WIDE WEB

3. http://www.epa.gov/seahome
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