APPENDIX VI

OIL DISPERSION MODELS

APPENDIX VI - OIL DISPERSION MODELS

Contents

VI.1 INTRODUCTION

VI.1.1 Objective

This appendix describes the models of oil dispersion at sea that are used in the project. Their aim is to quantify the probabilities that oil spills in different locations offshore will result in significant pollution ashore, in order to help convert estimates of oil spill frequencies at sea into measures of environmental risk.

VI.1.2 Limitations

The study addresses the whole of the Australia's Exclusive Economic Zone (EEZ) and Offshore Territories, including the Australian Antarctic Territory. The risks are presented as average values for approximately 120 sub-regions of the EEZ. These consist of 40 coastal segments, divided into 3 distances offshore:

- Near-shore (0-12nm)
- Intermediate (12-50nm)
- Deep-sea (50-200nm)

Therefore, the probabilities must be obtained at the same level of granularity, i.e. a single average value for each of the 120 sub-regions.

In reality the transport and fate of marine oil spills is extremely complex, depending on many factors, including the size and precise location of the spill, the type of oil, the local wind, current and sea conditions, and the oil spill mitigation response. It is impractical in a wide-scale study such as this to model all these factors in full probabilistic detail. Estimating 120 probabilities to represent the variation across the entire Australian EEZ therefore implies extreme simplification compared to the real world. It is therefore appropriate that the probabilities are estimated on a conservative basis, i.e. tending to over-predict risks where variability and uncertainty are greatest. It is also important that the necessary degree of simplification is understood, and that the resulting probabilities are not used inappropriately outside their intended application.

VI.1.3 General Approach

The present study adopts a very simplified methodology that considers the following groups of influences on the probability of oil pollution ashore:

- Oil type (Section VI.2)
- Oil weathering in the marine environment (Section VI.3)
- Oil transport to the shore (Section VI.4)
- Oil spill mitigation response (Section VI.5)

This appendix also presents information on the impacts of different oil types and spill quantities, which are used elsewhere in the present study.

VI.2 OIL TYPES

VI.2.1 Oil Density Units

Oil is commonly characterised by its relative lightness (since light crude oils are most valuable), measured on a scale of American Petroleum Institute (API) gravity. This is related to the relative density (or specific gravity) at 15^{o}C as follows:

$$SG = \frac{141.5}{API + 131.5}$$

Oil quantities are commonly measured in barrels (bbl), which are related to the mass in tonnes (t) as follows:

$$Barrels = \frac{Tonnes}{0.159 \cdot SG}$$

VI.2.2 Representative Oil Types

The scope of the study covers crude oil and condensate produced from offshore installations and exploration rigs, crude oil and liquid petroleum products shipped as cargo, and fuel or diesel oil used as bunkers. Other hazardous and noxious substances are excluded.

The following representative groups of oil types are used in the present study:

- Crude oil. Most crude oil produced in the Australian EEZ is light crude with API in the range 40-55, once condensates have been separated. A typical oil is taken as an API gravity of 42, equal to a relative density of 0.82. This is based on stabilised Gippsland crude, but is also equal to average refinery intake, including imported crude oil (Reece 2004).

- Condensate. The large Bayu/Undan condensate field has an API of 56, and the important condensate fraction of the North-West Shelf has an API of 62. These indicate a typical condensate relative density of 0.74.

- Volatile products. This category includes refined products such as gasoline, kerosene, aviation fuel and naphtha. Gasoline is the main product, so is used as the representative material. The average density of gasoline produced in Australia is 0.74 (Reece 2004).

- Diesel oil. This is a distillate fuel, used mainly for road vehicles and generators. It also includes marine gas oil (a pure distillate fuel) and marine diesel (a blend of diesel oil and heavy fuel oil). The average density of gas/diesel oil produced in Australia is 0.84 (Reece 2004).

- Heavy fuel oil (HFO). This includes intermediate and residual fuel oils, and marine bunker fuel that is based on residual fuel oil. For simplicity, this category also includes other refined products that are produced in much smaller quantities, including lubricating oil and bitumen. The average density of fuel oil including bunker fuel produced in Australia is 0.97 (Reece 2004).

VI.3 OIL WEATHERING

VI.3.1 Weathering Processes

Given time, a spill of oil into the sea will reduce naturally due to weathering processes of evaporation, natural dispersion, dissolution, biodegradation and photo-oxidation. The weathering may be impeded by emulsification and sedimentation. These processes are described below.

Evaporation begins as soon as the oil is released. The rate of evaporation is highest for light oils. Virtually all components of C_{12} and below evaporate within 12 hours. For most crude oils this is over 50%. For condensate it is over 98%. Since the most toxic components (e.g. benzene, toluene and xylene) are among these more volatile fractions, spilled crude quickly loses its toxicity - often with a few hours. Evaporation is also accelerated by high wind speed, turbulence, and air, sea and oil temperature.

Natural dispersion is the dispersion of oil, under the influence of waves, into finely divided droplets below the slick. This increases the total surface area of the oil, and so speeds biodegradation. In a large spill, this dispersion reaches its maximum rate after 4-10 hours, and continues for several days. The dispersion rate depends mainly on sea state, and may produce loses in crude oil between 20% per day in a low sea state (<1m wave height) and 50% per day in a high sea state (>6m wave height) (Blaikley et al 1977).

Dissolution of oil into the sea water takes place early in the spill, but most hydrocarbons are not highly soluble in water, so this is a relatively minor component of weathering.

Biodegradation is bio-chemical breakdown of oil by bacteria, yeast and fungi able to metabolise it. The rate and extent of biodegradation depends on the abundance and variety of such organisms, the availability of oxygen and nutrients, the water temperature and the hydrocarbon composition. Dissolved or dispersed hydrocarbons degrade best.

Photo-oxidation is a slow process of weathering due to certain wavelengths in sunlight. It is a relatively minor component of weathering.

Emulsification is the formation of a water-in-oil emulsion, known as “mousse”, containing 20-80% water. It may be caused by dispersed oil droplets resurfacing under wave action. Water turbulence and highly asphaltic or waxy oils seem to promote emulsification. However, even light oils and possibly condensates may form emulsions. Tests showed marine diesel oil formed an emulsion containing over 80% water after 4 hours at sea (CONCAWE 1981). Emulsions may be very stable, inhibiting biodegradation because the water trapped in the oil keeps out essential nutrients and oxygen. Early treatment of the spill with dispersants can be sufficient to prevent emulsification and permit natural weathering to continue.

Sedimentation is the process whereby particles of floating oil sink to the seabed. Sinking can occur as a result of adhesion of particles of sediment or organic matter. Shallow coastal waters are often laden with suspended solids, and therefore provide favourable conditions for sedimentation. Overall this is a relatively minor component of weathering.

VI.3.2 Weathering Rates

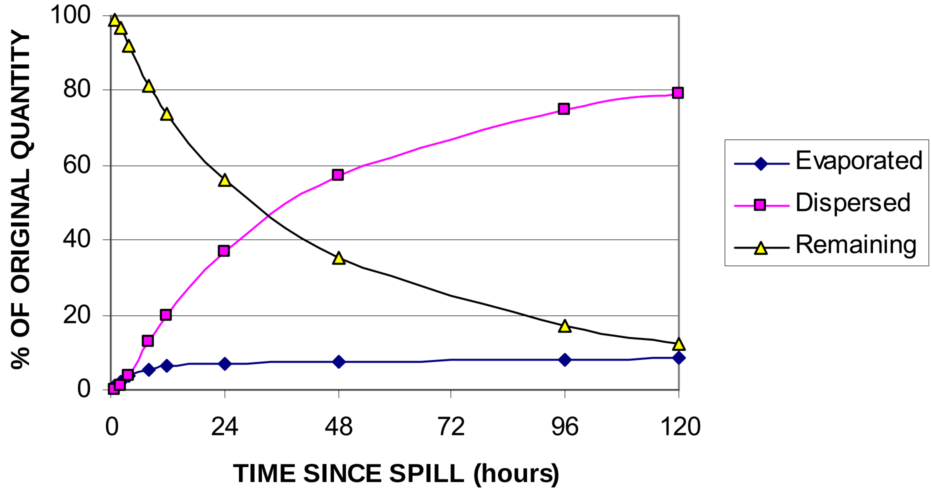
The overall weathering may be defined as the variation of the quantity of oil remaining in the slick versus time since the spill. For the present study, this has been modelled using the program ADIOS2 (NOAA 2011). In this program, the 5 oil types (Section VI.2.2) have been represented using:

- Crude oil - Gippsland crude (API 46.4, SG 0.80)
- Condensate - North-West Shelf condensate (API 53.1, SG 0.76)
- Volatile products - unleaded gasoline (SG 0.75)
- Diesel oil - diesel/heating oil No2 (API 33.5, SG 0.86)
- Heavy fuel oil (HFO) – Fuel oil No6 (bunker C) (API 33.5, SG 0.86)

The water temperature is taken as 23°C. This is the average for seas around Australia; the range is 3 to 32°C (Sea Temperature 2011).

Figure VI.3.1 gives an example weathering curve (for HFO in 23°C and 20 knot wind with associated waves.

Figure VI.3.1 Weathering Curves for Heavy Fuel Oil



The variation is sensitive to many different conditions, and so for the present study it is sufficient to represent this as an exponential decay defined by a half life (H). The fraction of the original spill quantity remaining at time T after the spill is:

$$FQ = 2^{-T/H}$$ for T and H in consistent units, e.g. hours

In order to fit this to the data from ADIOS2, the fraction remaining (F_m) after the longest available time (T_m) is used, which in ADIOS2 is at most 120 hours. Then the half life is estimated as:

$$H = \frac{-0.3T_m}{\log(F_m)}$$

Figure VI.3.2 shows the fit to the ADIO2 weathering curve in the example above.

Figure VI.3.2 Fit to Weathering Curve for Heavy Fuel Oil

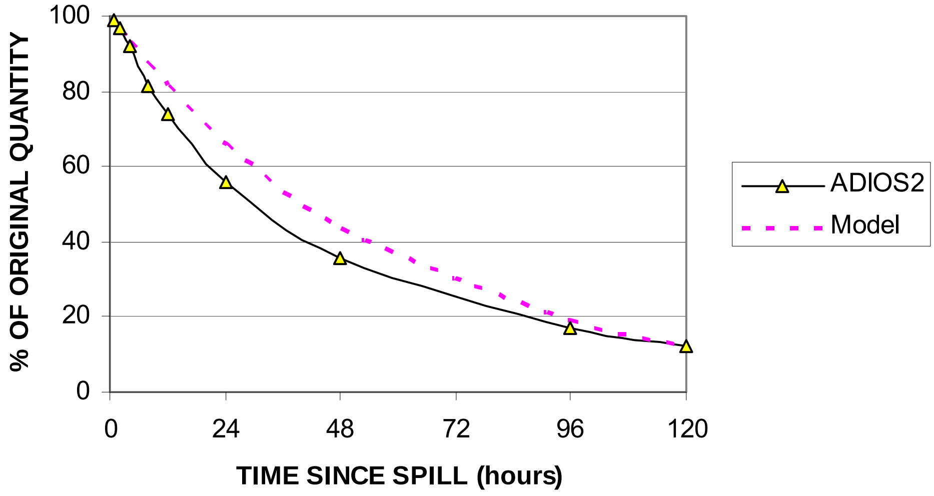


Table VI.3.1 shows the sensitivity of the half-life for HFO to the wind speed, spill quantity and sea temperature. The greatest sensitivity is to wind speed.

Table VI.3.1 Half-Lives for Heavy Fuel Oil

QUANTITY (tonnes)	WIND SPEED (knots)	SEA TEMP (°C)	T_m (hours)	F_m (%)	HALF LIFE (hours)
100	5	23	120	91	882.0
100	20	23	120	12	39.2
100	40	23	6	25	3.0
100	60	23	2	25	1.0
1	20	5	120	13	40.8
10	20	5	120	12	39.2
100	20	5	120	12	39.2
1000	20	5	54	50	54.0
10000	20	5	90	50	90.0
100	20	5	120	70	233.2
100	20	10	120	54	135.0
100	20	20	120	35	79.2
100	20	23	120	19	50.1
100	20	25	120	12	39.2
100	20	30	40	25	20.0
100	20	32	34	25	17.0

Table VI.3.2 shows the half-lives for the different oils and wind speeds, based on spills of 100 tonnes in sea temperature of 23°C.

Table VI.3.2 Half-Lives for Oil Types (Hours)

OIL TYPE	CALM (5 knots)	FRESH (20 knots)	GALE (40 knots)	STORM (60 knots)
Crude oil	86.0	39.2	1.3	0.4
Condensate	63.5	9.8	0.6	0.3
Volatile products	0.7	0.3	0.2	0.1
Diesel oil	75.0	2.5	1.0	0.2
Heavy fuel oil	882.0	39.2	3.0	1.0

This is sufficient to demonstrate that in such temperatures volatile products such as gasoline have negligible potential to survive long enough to cause pollution ashore, unless they are spilled directly onto the shore. Diesel and condensate are somewhat more affected by weathering than the light crude that is produced in Australia. Heavy fuel oil is significantly less affected by weathering than the other oils.

VI.4 OIL TRANSPORT

VI.4.1 Spreading

When oil enters the sea, it spreads out as a slick on the sea surface under the combined action of gravity and surface tension. Eventually, when the thickness has reduced to 0.1 to 0.01mm, the slick ceases to spread. This may be due to an increase in the surface tension at the water-hydrocarbon interface due to hydrocarbon fractions dissolving in the water layer beneath the slick. For a large oil spills, spreading typically ends within 7-10 days, depending on the hydrocarbon characteristics and environmental conditions. For condensate, evaporation halts the growth of the slick, typically within 1 day.

VI.4.2 Drifting

In addition to spreading under gravity, the slick also drifts under the action of wind, current, waves and tide. The slick speed corresponds to approximately 3% of wind speed and 60% of current speed (Blaikley et al 1977).

Sea currents are typically parallel to the coast, and therefore have minimal influence on the probability of the oil reaching the shore.

The thick part of a slick drifts faster than the thinner parts, so the leading edge of a drifting slick contains heavy hydrocarbon accumulations. Wind and wave action tend to elongate the slick, and eventually break it into patches.

VI.4.3 Beaching

The time between the occurrence of the spill and the leading edge of the slick reaching the shore (T_{shore}) depends mainly on the distance offshore (D_{zone}), the component of wind velocity in the direction of the shore (V_{wind}) if positive, and the slick's drifting velocity as a fraction of the wind velocity (RV_{drift}):

$$T_{shore} = \frac{D_{zone}}{V_{wind} RV_{drift}}$$

The average distances to shore for spills in each zone are taken as:

Near-shore (up to 12 nm offshore)	D_{zone} = 6 nm
Intermediate waters (12-50 nm offshore)	D_{zone} = 30 nm
Deep sea (50-200nm offshore)	D_{zone} = 120 nm

Four weather categories are considered, with the following representative wind speeds:

Calm	V_{wind} = 5 knots
Fresh	V_{wind} = 20 knots
Gale	V_{wind} = 40 knots
Storm	V_{wind} = 60 knots

The slick drift speed is taken as 3% of wind speed, as above. The times to reach the shore are then as shown in Table VI.4.1.

Table VI.4.1 Time to Beaching (hours) for Onshore Winds

ZONE	CALM (5 knots)	FRESH (20 knots)	GALE (40 knots)	STORM (60 knots)
Near-shore zone	40	10	5	3
Intermediate zone	200	50	25	17
Deep sea zone	800	200	100	67

The quantity of oil remaining in the slick at this point, and hence the quantity of oil that may be deposited on the shore, is estimated from the original spill quantity (Q) and the weathering half-life (H) as:

$$Q_s = Q \cdot 2^{-T_{shore}/H}$$

The probability of significant quantities of oil reaching the shore is then estimated from the probabilities of spills (P_Q) in which Q_s exceeds a significant amount (say, 10 tonnes). The summation takes account of the probability of the weather state ($P_{weather}$), and the conditional probability of the wind direction being towards the shore ($P_{onshore}$) in a particular weather state:

$$P_s = \sum_{werather} P_{weather} P_{onshore} \sum_{Q_s > 10} P_Q$$

VI.4.4 Weather Probabilities

The weather probabilities have been calculated for each sub-region from wind rose data supplied by the Bureau of Meteorology (BM 2011). No comprehensive offshore wind roses were available, so the data was selected from the nearest in a set of 36 coastal locations locations. The analysis used the full datasets from currently reporting wind stations, in order to obtain reliable weather probabilities that also reflect recent climate change.

The wind speeds were split into the categories shown in Table VI.4.2. The data gave only occurrence probabilities above 0.1% of measurements, so in most cases there were no measurements in the storm category. Therefore, the probability of wind ≥50 km/hr was split into 90% gale and 10% storm categories.

Table VI.4.2 Wind Speed Categories

	CALM	FRESH	GALE	STORM
Beaufort range	0-4	5-6	7-9	10-12
Speed range (knots)	0-15	16-38	39-47	≥48
Typical speed (knots)	5	20	40	60
Speed range in met data (km/hr)	0-30	30-50	50-90	>90

The wind directions were split into 8 groups (i.e. N, NE, E, SE, S, SW, W and NW), plus calm (i.e. no direction). There were sufficient measurements to determine the distribution of directions for the calm and fresh categories. The distributions for gale and storm were assumed to be the same as the fresh category.

Onshore wind directions were determined for the centroid of each sub-region. Directions that led towards shores more than 200nm from these points were neglected. The calm category was also neglected. The conditional probability of the wind direction being towards the shore ($P_{onshore}$) in a particular wind speed category was then determined from the sum of the corresponding probabilities in the wind rose.

VI.4.5 Shoreline Length Affected

The average length of shoreline affected by the oil, given that a significant quantity of oil reaches the shore, is difficult to estimate with any degree of realism, as it depends on the spreading of the slick.

In order to give an approximate indication of the length of shoreline affected, it is assumed that when the oil reaches the shore it has spread to an average thickness (t) of 0.1mm. From this the average diameter of the slick is calculated from the quantity remaining when it reaches the shore (Q_s) and its relative density (SG):

$$D_s = \sqrt{\frac{4Q_s}{\pi \cdot t \cdot SG}}$$ for Q_s in tonnes; D_s and t in metres

The length of shoreline oiled (L_s) is assumed to depend on this and the relative indentation of the shore (RI), expressed as the total shoreline length divided by the length of the territorial sea baseline in each calculation sub-region. Except in the case of island sub-regions, this is approximated as a straight line length between the ends of the shoreline. Then the length of shoreline oiled is:

$$L_s = D_s \cdot RI$$

This is important in estimating the relative impact as follows.

VI.5 SPILL RESPONSE

VI.5.1 The National Plan

Australia's National Plan to Combat Pollution of the Sea by Oil and Other Noxious and Hazardous Substances (the National Plan) is a national integrated government and industry organisational framework for response to marine pollution incidents.

The National Plan designates competent national and local authorities, and maintains:

- National Marine Oil and Chemical Spill Contingency Plans
- Detailed state, local and industry contingency plans
- Strategically positioned response equipment
- A national training program, including conducting regular exercises.

The National Plan is supported by the National Maritime Emergency Response Arrangements (NMERA). NMERA provides a minimum level of maritime emergency towage capability around the Australian coastline and appoints a single national decision maker to coordinate a response to a maritime casualty.

Spill response approaches may include:

- Booms and skimmers to contain or recover the oil, if wind, current and sea conditions are favourable.
- Sorbent materials to complement booms and skimmers if the spill is small.
- Chemical dispersants, if environmental conditions are favourable. The National Plan includes a Fixed Wing Aerial Dispersant Capability (FWADC), using large agricultural aircraft with a dispersant capacity of 2200-3600 litres. Their locations are:
    - Ballarat, Victoria
    - Adelaide, SA
    - Ballidu, WA
    - Batchelor, NT
    - Emerald, Queensland
    - Moree, NSW

  Each aircraft is available to fly with a maximum of 4 hours notice. Helicopters may also be used for dispersant spraying inshore.
- Natural biodegradation, which is often the most appropriate approach.

The National Plan holds a wide range of response equipment at all major ports. Equipment provided by AMSA is generally targeted at larger spills (Tier 2 and 3, i.e. over 10 tonnes). This is complemented by equipment held by port authorities for Tier 1 spills (i.e. below 10 tonnes), individual oil and chemical companies and by the Australian Marine Oil Spill Centre stockpile in Geelong. Types of equipment include oil spill control booms of varying types and sizes, self-propelled oil recovery vessels, static oil recovery devices and sorbents. A range of storage devices including free standing tanks and towable storage bladders and bags complement recovery devices.

A computer-based Oil Spill Trajectory Model (OSTM) is used to simulate and predict the movement of oil spills. The information assists decision-making on response measures.

The National Plan Oil Spill Response Atlas (OSRA) is a computer-based digital mapping system that allows operators to overlay various types of data to identify biological, cultural, geomorphological and socio-economic resources and how a marine pollution incident may impact these resources.

VI.5.2 Modelling of Spill Response

Since the model of oil spill risk is to be used to inform the planning of response measures, it is necessary for any modelling of oil spill response to be optional, rather than embedded. Then the model can be used to show the benefits of additional measures in terms of reductions in environmental risk.

However, the oil spill risk model has been optimised to show the national distribution of risk, and uses models that are too crude to give reliable estimates of the impact of most response measures.

AMSA advised that the most important response measure to be modelled is FWADC, since this has a realistic potential to prevent large oil spills reaching the shore.

The necessary time for FWADC to arrive (T_{air}) depends on the distance from the FWADC airfield to the slick (D_{air}), the aircraft speed (V_{air}), and the time taken to mobilise the aircraft (T_{mob}):

$$T_{air} = \frac{D_{air}}{V_{air}} + T_{mob}$$

A typical aircraft speed is taken as 120 knots. The average time to mobilise the FWADC is taken as 2 hours. The maximum distance of deployment from the FWADC airfield is taken as 250nm.

The criteria for use of FWADC are complex, and not suitable to represent in detail in the present model. As a simple representation, it is assumed that FWADC is used if all the following criteria are met:

- Coast near to oil spill is within FWADC deployment range (i.e. $D_{air} < 250$nm).
- Oil spill does not reach coast before FWADC arrives (i.e. $T_{shore} > T_{air}$)
- Oil type is suitable for dispersant application (assumed to be crude oil or diesel only).

The effect of dispersant application is modelled as an 85% reduction in the quantity remaining in the slick, based on an 80-90% reported effectiveness of dispersant applications in oil spills (Etkin 2000).

VI.6 OIL IMPACT COSTS

VI.6.1 Cost Components

In principle the following components are included in the cost estimates (although in practice they are not all comprehensively included):

- Clean-up costs - expenditure on recovering or dispersing oil at sea and clean-up of affected shoreline, including disposal of recovered product.

- Commercial losses - actual compensated losses plus estimated value of damage to social resources.

- Environmental damage - estimated value of damage to natural resources.

The costs do not include:

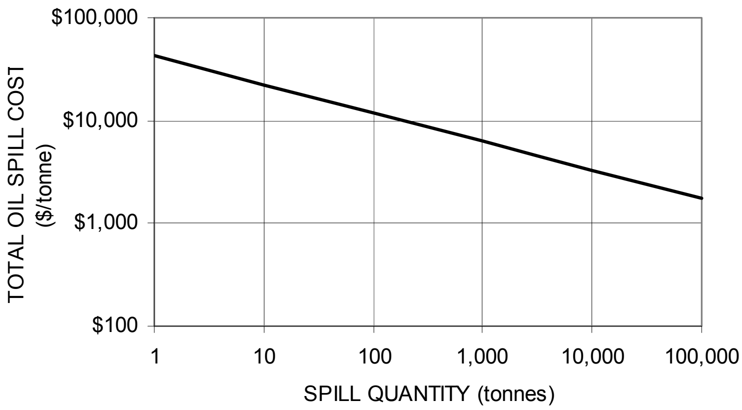
- Cost of repair or replacement of the ship
- Lost revenue to the shipowner
- Punitive fines
- Capital value of lost oil

VI.6.2 Effect of Spill Size

In general, larger spills have larger costs. However, the clean-up cost of an oil spill is not linearly related to the spill quantity. In fact, the clean-up cost per tonne is negatively correlated with spill size. This is because of economies of scale in spill response (Etkin 2000).

Figure VI.6.1 shows the estimated cost per tonne for oil spills (costed in 2009 US$) adopted by the 62nd session of the Marine Environment Protection Committee (MEPC 2011). Although this is based mainly on clean-up costs, it has been adopted by MEPC as a cost to avert a tonne of oil spilled (CATS) when evaluating risk control options, and is therefore a suitable estimate of total costs for this study. The possibility that MEPC incompletely estimated natural resource damage therefore becomes one of the uncertainties of this study.

Figure VI.6.1 Oil Spill Costs per Tonne



The variation of cost (C) with spill quantity (Q) is defined by the following cost function:

$$C = 42301Q^{-0.7223} \quad \text{for C in \$ and Q in tonnes}$$

VI.6.3 Cost Adjustments

The costs above are in US dollars, whereas the results of this study are required in Australian dollars. The conversion has varied but is currently approximately A$1 = US$1, so the two currencies are treated as equivalent.

Clean-up costs are sensitive to the labour costs, clean-up standards and liability standards in the country where the spill takes place. They are also affected by the environmental sensitivity and logistic costs of the specific spill location. Vanem et al (2008) estimated that on average clean-up costs in the Oceania region which was dominated by spills in Australia) were 0.43x global average. This is based on costs reported by Etkin (2000), and is sensitive to the costs of a few incidents in this region prior to this date. No such modification is recognised by MEPC (2011), so this is neglected in the present study.

Clean-up costs are also very sensitive to the response strategy. However, it is not appropriate to model these in the present study, which aim to quantify the average risk, which is assumed to involve different response strategies as appropriate for the individual spills.

VI.6.4 Effect of Shoreline Length

The length of shoreline affected by the oil spill has a significant positive effect on the clean-up cost per tonne. The cost of spills affecting shore length L_s relative to the cost C_o of cases with virtually no shoreline affected is estimated as (Etkin 2000):

$$C_s = C_o\left(1 + 8\frac{L_s}{1000}\right) \quad \text{for } L_s \text{ in metres}$$

These are clean-up costs per tonne, including the whole clean-up (not just the shoreline response). The spill quantities may refer to the total quantities spilled, not just the quantity reaching the shore, but this is not clear in the original source.

In the model of shoreline length affected (Section VI.4.4), L_s is proportional to $Q_s^{0.5}$. Hence C_s is almost proportional to $Q_s^{0.5}$. It is counter-intuitive that C_s should be less sensitive to Q than the overall cost, so it is preferable to assume all cost effects are proportional to $Q^{0.72}$.

VI.6.5 Effect of Oil Type

The oil spill cost is significantly influenced by the type of oil. Table VI.6.1 gives average clean-up costs for different oil types (Etkin 2000). The overall average is not given, but is assumed to be similar for average crude oil, which is the most common type. Gasoline is not listed because it often requires little or no clean-up.

Table VI.6.1 Oil Spill Clean-up Costs per Tonne

OIL TYPE	CLEAN-UP COST($/te)	RELATIVE COST
Heavy crude	$8,541	1.18
Average crude	$7,250	1.00
Light crude	$4,266	0.59
Diesel	$2,308	0.32
Heavy fuel oil	$16,952	2.34

The differences are partly due to the more rapid weathering of lighter oils, which have already been modelled above. However, oil type does affect the cost once oil reaches the shore, and therefore the relative cost C_T is included in the cost model below. These differences are important in the future spill risk predictions when considering a possible phase-out of heavy oil and a bunker fuel. Further consideration is therefore given as follows.

The difference between heavy fuel oil and diesel is that diesel has average clean-up costs 7 times less than heavy fuel oil. Another analysis (DNV 2001), which takes account of the different spill sizes, shows an even greater difference, with diesel having average clean-up costs 20 times less than heavy fuel oil spills of the same size.

This is consistent with ITOPF (2010), which states:

> "Oil type is one of the most important factors governing cleanup costs. In general, the more viscous, sticky and persistent the oil, the more difficult and costly the cleanup is likely to be, all other factors being equal. Spills of light refined products (e.g. gasoline and diesel) do not normally require a cleanup response. They may be toxic in the short term and require careful monitoring, but because of their high volatility, they do not persist on the sea surface for any significant time. Instead, due to rapid evaporation of the "light end" components and the speed with which they disperse and dissipate naturally, especially in rough seas, spills of light hydrocarbons do not result in long, expensive cleanup operations. At the other end of the spectrum are the highly persistent heavy crude oils and heavy fuel oils which are normally very viscous and have only a small proportion of volatile components. Because they do not break-up easily and often emulsify into persistent mats of oil, these oils have the potential to travel great distances from the original spill location and can cause widespread contamination of coastlines. They are difficult to clean up at sea, in coastal waters and on shorelines. As a consequence, cleanup is invariably long, resource- and manpower- intensive, and therefore, costly."

The relative impacts of fuel types on sensitive environments (e.g. coral reefs) may differ from the world average data above, because toxicity may be more important there. Furthermore, the clean-up costs above reflect the fact that persistent oils give more opportunities for prolonged clean-up than volatile oils, and may not reflect the natural resource damage from the different oil types.

GBRMPA (2011) advised:

> "GBRMPA considers that in many circumstances a spill of marine diesel is of greater environmental consequence than a spill of heavy fuel oil... Bunker fuels (HFOs) are more persistent with higher quantities of residues on the water surface and on shorelines and have greater potential to smother wildlife and habitats but MDOs

> (marine diesel oil) are considerably more toxic, with a high potential to bioaccumulate, have high water solubility and a higher potential to naturally entrain into the water column than HFOs."

AMSA (2011) advised:

> "The impacts of diesel and HFO on a coral reef environment seem to me to be an apples and oranges issue. It all depends on so many factors that any comparison may be meaningless. For example, if the spill occurred over an emergent coral reef: (much of the following is based on supposition and conversation):
>
> - Diesel has a shorter half-life but is more acutely toxic in the early phases of the spill and disperses into the water column more quickly and thoroughly, with the potential to act more like a coral "herbicide" over a relatively tight and constrained area. But the effects will be far less persistent and there should be no latency or long-term effects, and so coral re-colonisation should occur in the same manner as after storm damage.
>
> - HFO will weather more slowly, mix less in the water and potential spread over a wider area before weathering – more of it will be available longer for its type of impacts to arise. However, anything it sticks to will suffer less toxic effects, but more smothering, with potentially a blanket effect. There is no response to this other than mechanical cleaning, which for coral seems to make the cure worse that the cause. Re-colonisation should be retarded under these conditions as the asphaltenes will create a "road surface" layer, which may retard growth from below, but provide a possibly suitable substratum for new settlement"

Detailed comparison of the costs of spills of fuels of different types is beyond the scope of the study. Nevertheless, the above discussion is sufficient to conclude that the world average costs may be misleading, and that it is possible that in some environments there may be little difference in spill costs between the oil types.

VI.6.6 Overall Environmental Risk Index

The overall environmental risk index (ERI) is defined as:

$$ERI = \sum_{spills} FC_U \left[Q^{0.72} ESI + P_s Q_s^{\ 0.72} ESI_s \right]$$

The exponent 0.72 and the unit cost C_U = \$42,300 are rounded values from MEPC (2011).

In practice, to make the spill rate explicit and take account of the oil type, this is calculated as:

$$ERI = \sum_{spills} FQ\left(C_U C_T C_Q\right) ESI\left(1 + C_S\right)$$

Here, C_T is the relative cost for the specific oil spill type from Table VI.6.1.

The relative cost for the spill quantity (C_Q) (i.e. the cost per tonne for the spill divided by cost of a 1 tonne spill) is calculated as:

$$C_Q = \frac{\sum_{spills} FQ^{0.72}}{\sum_{spills} FQ} \qquad C_{Qs} = \frac{\sum_{spills} P_s Q_s^{\ 0.72}}{\sum_{spills} P_s Q_s}$$

The relative cost of oil spills that drift onto the shore (i.e. the extra cost of the oil on shore as a fraction of the total cost if none reached the shore), is defined as:

$$C_S = \frac{R_s}{R} C_{Qs} \frac{ESI_s}{ESI}$$

The fraction of oil that reaches the shore is defined as:

$$\frac{R_s}{R} = \frac{\sum_{spills} FP_s Q_s}{\sum_{spills} FQ}$$

ERI is intended to be proportional to the total oil spill cost, if measured in units of A$million. However, because it is not at present possible to estimate such costs accurately, it is appropriate to use the name ERI rather than oil spill cost.

The strengths and weaknesses of this metric are discussed in Sections 2.7 and 2.8 of the main report. The method of using it in practice, taking account of its limitations, is proposed in Section 2.9 of the main report.

VI.7 REFERENCES

1. AMSA (2011), Confidential e-mail from Paul Irving, Australian Maritime Safety Authority, 20 June 2011.

2. Blaikley, D.R. et al (1977), “SLIKTRAK - A Computer Simulation of Offshore Oil Spills, Cleanup, Effects and Associated Costs”, EPA/API Oil Spill Conference, New Orleans.

3. BM (2011), Climate data file, supplied to DNV 18 August 2011.

4. CONCAWE (1981), “A Field Guide to Coastal Oil Spill Control and Clean-up techniques”, Report 9/81.

5. DNV (1999), “Risk Assessment of Pollution from Oil and Chemical Spills in Australian Ports and Waters”, Det Norske Veritas Project 9330-3972, December 1999.

6. DNV (2001), “Formal Safety Assessment of Tankers for Oil”, Confidential Internal Report, Det Norske Veritas Project 383184/4, June 2001.

7. Etkin, D.S. (2000), “Worldwide Analysis of Marine Oil Spill Cleanup Cost Factors”, Arctic and Marine Oilspill Program Technical Seminar, June 2000.

8. Etkin, D.S. (2004), “Modelling Oil Spill Response and Damage Costs”, Freshwater Spills Symposium, April 2004.

9. GBRMPA (2011), Confidential e-mail from Rean Gilbert, Great Barrier Reef Marine Park Authority, 8 June 2011.

10. ITOPF (2010), “Cost of Spills”, International Tanker Owners Pollution Federation, http://www.itopf.com/spill-compensation/cost-of-spills/ (Accessed July 2011).

11. MEPC (2011), “Report of the Working Group on Environmental Risk Evaluation Criteria within the context of Formal Safety Assessment”, MEPC 62/WP13, Marine Environment Protection Committee, 13 July 2011.

12. NOAA (2011), “ADIOS2 (Automated Data Inquiry for Oil Spills)”, National Oceanic and Atmospheric Administration.

13. Reece, M. (2004), “Densities of Oil Products”, Energy Statistics Working Group Meeting, Special Issue Paper 9, IEA, Paris, November 2004.

14. Sea Temperature (2011), “World Sea Temperatures / Australia and Oceania / Australia”, http://www.sea-temperature.com/country_water/australia/81 (Accessed March 2011)

15. Vanem, E., Endresen, Ø. & Skjong, R. (2008), ”Cost-Effectiveness Criteria for Marine Oil Spill Prevention Measures”, Reliability Engineering and System Safety, 93 (2008), 1354-1368.