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ABSTRACT

Even with the recent developments in renewable energy, oil & gas are still our most important energy source today. This will also be the case in the foreseeable future, but new demands are constantly being forced on the industry. The need for hydrocarbons is recognized, but they are expected to be produced with minimal risk to operating personnel, company economy and the environment. The latter is the subject in this thesis, which aims to propose a new procedure to assess environmental consequence of failure within the discipline of risk-based inspection.

Risk-Based Inspection (RBI) is a formal approach developed to aid in the assessment of risk connected to the static equipment on a process plant, and to assign inspection intervals which give a good balance between safety, practicality and economy. The risk for each module is calculated using the probability of failure (PoF) and the consequence of failure (CoF). These two factors are combined to give a risk rating, which is then used to set an appropriate inspection interval for the module or component in question.

The consequence part of RBI is typically divided into three main categories: safety, cost and environment. Safety consequence is concerned with the possible injuries or fatalities in the case of an accident, while cost consequence covers the material damages, loss of production and reputation damage. The last category describes the consequence if the surrounding environment is exposed to spills or emissions.

The study presented in this thesis is partly based on existing literature, but the previous work in this area has proved to be limited. The environmental consequence has mostly been based on cost for clean-up, fines and penalties. The reason for this limited approach is probably the huge number of factors which could affect the environmental consequence from a spill. Detailed models exist, but they are too comprehensive to be applied in a practical RBI context.

In this thesis, factors influencing the environmental consequence of failure (E-CoF) are first identified and discussed. A procedure is then presented to assess the various factors and combine them into an E-CoF rating. The procedure is presented in the form of flowcharts, and a guide is provided to show the calculation of each contributing factor. As quantitative calculations are not always possible for RBI purposes, several methods for evaluation are presented for some of the factors.

The cost term has been left out of the E-CoF analysis, as it is difficult to compare cost to environmental harm. However, as costs are important, a separate procedure has been prepared for estimating the costs involved with a liquid hydrocarbon release. A matrix is also provided to allow combination of E-CoF and cost into a common consequence rating.

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CHAPTER 1

Introduction

1.1 Background

In previous years, several master theses focusing on consequence of failure have been written at DNV. However, these were mostly concerned with safety consequences, such as release of toxic substances, fire and explosions. With the help of these theses, DNV has now prepared new practices for the assessment of safety consequence. The purpose of this thesis is to follow up and recommend a practice for the environmental part of consequence.

The previous work in the field of environmental consequence assessment has been sparse. Both the DNV recommended practice G-101 (2009) and the API 580 (2002a) are mostly limited to assessing the clean-up cost from spills, together with the fines imposed by local government. API recommended practice 580 also states that "Environmental consequence measures are the least developed among those currently used for RBI" (API, 2002a).

The limited number of assessment models available, together with an increasing awareness for the environment, calls for an improvement in the assessment of environmental consequence following a failure. Detailed models exist, but these are used to illustrate worst-case scenarios in fields. A simpler procedure with less demand for detailed input data is required for risk-based inspection (RBI), which this thesis aims to support.

This thesis presents the result from a study aimed to identify the most important factors which would influence future practice, as well as an attempt to put these together in a procedure.

1.2 Aim of the thesis

The aim of this thesis is to review existing models for assessing environmental consequence, and to identify and describe the most influential factors. Ultimately, a new procedure is to be proposed, including the best from existing practices and available literature. The new procedure should be simple to implement and use in an RBI analysis, yet it should provide enough attention to details to give a correct picture of the situation.

1.3 Scope of work

This thesis focuses on the following:

- Brief presentation of the RBI methodology
- Study and presentation of existing models for assessing environmental consequence of failure
- Mapping and discussion of factors which should be included in an environmental consequence of failure (E-CoF) analysis

- Proposal for a new procedure for assessing environmental consequence in an RBI analysis for offshore topside static process equipment
- Proposal for a new procedure for calculating costs involved with oil spills, and, if applicable, combining this with the E-CoF assessment results.

1.4 Limitations

This thesis is written on the basis of existing practices, standards and literature. Even though most aspects have been considered, some simplifications have been made due to the vast number of factors influencing the calculations. The proposed procedure should only be considered as general guidance, as more detailed assessments and local conditions may influence the consequence assessment.

To be able to complete the project in due time and with the resources available, limitations have been applied. These are the most important ones:

- The thesis only focuses on environmental consequence assessment. For usage in risk-based inspection, probabilities will also have to be addressed.

- The procedure has been developed for liquid hydrocarbon releases only. Chemical pollution and air emissions have not been considered.

- Calculations regarding hole size and leak rate have previously been presented in a master thesis written for DNV by Chen (2010). Hence, these topics are not covered in this project.

- Norwegian standards and examples have been utilized where needed. Different rules and regulations may apply in other areas.

1.5 Structure of thesis

The thesis has been divided into chapters based on topic.

Chapter 1 contains the introduction, with background, aim of thesis, limitations, etc.

In Chapter 2, a brief introduction is given on risk-based inspection (RBI) and how it is used in the industry.

Chapter 3 contains a mapping of the existing practices for estimating environmental consequence. The practices are presented one by one, and their strengths and weaknesses discussed.

Chapter 4 identifies the factors which should be included in an environmental consequence assessment. Background theory is given for each of them, before they are discussed at the end of the chapter.

Chapter 5 contains the proposed procedure for environmental consequence assessment. The procedure is presented in the form of flowcharts, which contain references to a guide for calculating the values. The guide has a section for each step in the procedure, to show how to obtain the necessary information. At the end of the chapter, an explanation for the given consequence rating is provided.

Chapter 6 presents the proposed procedure for cost estimation. The chapter contains both a brief presentation of the factors as well as the procedure. A matrix for combining E-CoF and cost is also provided.

Chapters 7 and 8 contain the conclusions and suggestions for further work, respectively.

1.6 Abbreviations

API	American Petroleum Institute
RBI	Risk-Based Inspection
BTEX	Benzene, Toluene, Ethylbenzene and Xylene
CBM	Condition Based Maintenance
CoF	Consequence of Failure
DNV	Det Norske Veritas
E-CoF	Environmental Consequence of Failure
ESA	Environmentally Sensitive Area
ESD	Emergency ShutDown
FAR	Fatal Accident Rate
HOCNF	Harmonized Offshore Chemical Notification Format
HSE	Health and Safety Executive
MIRA	Metode for Miljørettet Risikoanalyse
NOFO	Norsk Oljevernforening For Operatørselskap
OLF	Oljeindustriens Landsforening
OSPAR	Oslo-Paris Commission
PAH	Polycyclic Aromatic Hydrocarbons
PLL	Potential Loss of Life
PoF	Probability of Failure
RP	Recommended Practice
SG	Specific Gravity
VEC	Valuable Ecological Components

CHAPTER 2

Introduction to the Concept of Risk-Based Inspection

2.1 Introduction

Maintenance philosophy can be said to have two extreme limits: preventive and corrective maintenance. In preventive maintenance, items are repaired or replaced based on fixed intervals. This is an effective, but also very expensive solution. By utilizing such an approach, components may be replaced long before they are worn out. However, preventive maintenance is sometimes used in high-risk systems due to the severe consequences of a failure.

At the other end of the scale is corrective maintenance, which is also known as the "run-until-failure" approach. As the name implies, the philosophy is based on the idea that components should be allowed to run until they fail. Corrective maintenance gives the maximum lifetime for a component, but it is still not recommended in most systems. In cases where breakdowns will lead to hazards for humans or environment, a corrective approach to maintenance will not be accepted. Also, it could prove to be expensive if the whole system needs to be shut down while the faulty part is being replaced.

Even though preventive or corrective maintenance may be utilized in some situations, a compromise between the two is often desirable. The solution is then to apply condition based maintenance (CBM). In CBM, parts are replaced or repaired based on their actual condition. This will allow adjustment of the maintenance interval based on the reliability and criticality of the part in question. Provided that the condition of components is assessed accurately enough, the optimal balance between maintenance frequency and cost may be reached, as seen in Figure 2-1.

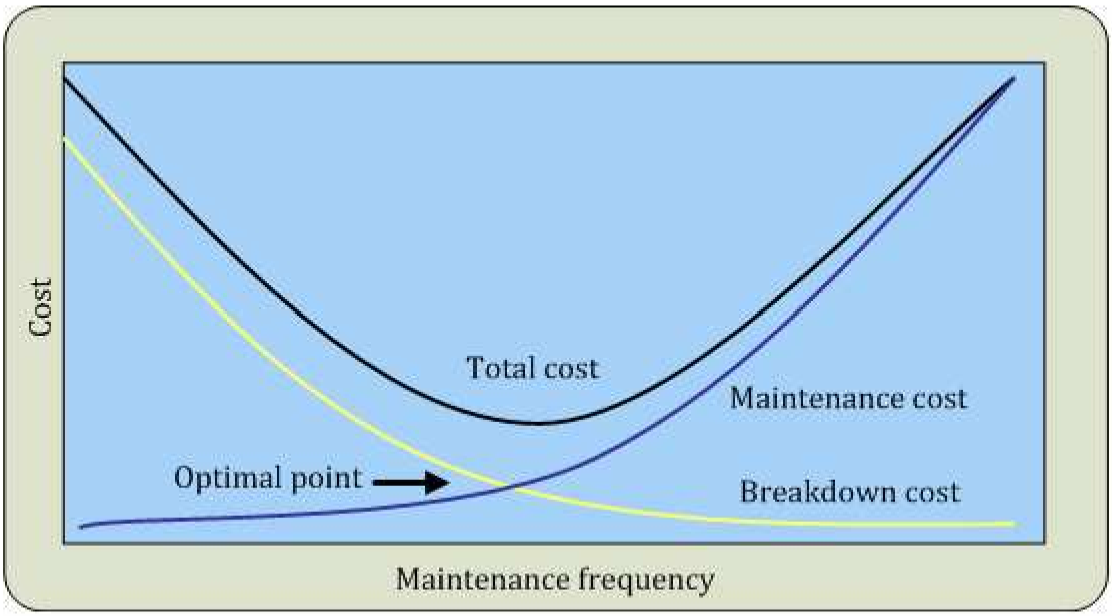


Figure 2-1: The relationship between maintenance frequency and cost

2.2 Risk-based inspection as a tool for inspection planning

To successfully implement CBM, components will need to be inspected to assess their current condition. The inspection intervals should not be too long, which could be a challenge in a process plants with thousands of components to check. A priority list is then needed to figure out which components to inspect often, and RBI offers a method for making these priorities.

RBI is a decision-making technique for inspection planning based on the risk connected with each component or module. The technique combines the probability of failure (PoF) with the consequence of failure (CoF) to obtain a risk picture for the part in question. It is a formal approach designed to aid the development of optimized inspection, and recommendations for monitoring and testing plans for production systems. RBI is suitable for application to all pressure systems in the plant, whether they are hydrocarbon-containing or utility (DNV, 2009). RBI can be carried out in three different ways: qualitative, quantitative or semi-quantitative.

2.2.a Quantitative RBI methods

In a quantitative approach, numerical values and probability distributions are used to express PoF and CoF. This yields precise results, even if the method may be initially data-intensive, and requires precise knowledge of many variables. Updating the inspection programme is, however, often easier in a quantitative analysis (DNV, 2009). Another advantage with a quantitative analysis is that the results are easy to interpret for everyone. Values are expressed numerically, such as potential loss of life (PLL) or fatal accident rate (FAR).

2.2.b Qualitative RBI methods

Rather than depending on numerical values, the qualitative RBI methods are based on expert judgements. Descriptive rankings are given, such as “low”, “medium” and “high”. The advantage of a qualitative RBI approach is that the initial analysis is simpler and much less demanding than the quantitative. Little or no data is needed, as the rankings are based on the judgements from competent personnel. However, such results will always be subjective. The risks will also be harder to update if they vary with time, as no limits are set for where the risk should move up or down in the rankings (DNV, 2009).

2.2.c Semi-quantitative approach

In practice, an RBI analysis will usually consist of a combination of quantitative and qualitative methods. Typically, the initial screening process is done in a qualitative way, and the high-risk components are then analyzed quantitatively. The approach taken in each case will also depend on the available data. In cases where little reliable data is available, most of the analysis may be conducted using expert judgement.

2.2.d Probability of Failure (PoF)

The probability of failure is the probability of an event occurring per time unit, such as annual probability. It is calculated on the basis of component degradation in given conditions. PoF may be calculated quantitatively, e.g. probability of failure per year, or in qualitative rankings. The ranking could then span from "negligible" to "failure expected".

2.2.e Consequence of Failure (CoF)

The consequence of a failure is defined as the outcome of a failure given that a failure will occur (DNV, 2009). Usually, CoF is divided into categories, depending on what will be affected by the failure. Typical categories are:

- Safety consequence (personnel injury)
- Economic consequence (asset damage, downtime, lost production)
- Environmental consequence (air emissions, hydrocarbon and chemical spill)

2.2.f Establishment of risk picture

The risk associated with a failure is estimated by combining the probability of failure and the consequence of failure. A matrix is often used to illustrate the risk picture. This will visualize the relative contributions of PoF and CoF, and as such it is easier to spot which can be reduced in case the risk is unacceptable. A matrix of 5x5 squares is usually recommended to achieve a satisfactory level of detail (DNV, 2009).

The matrix shown in Figure 2-2 shows the risk illustrated by colour, as well as inspection interval with numbers.

PoF Ranking	PoF Description	Time to Inspect (years)				
5	(1) In a small population, one or more failures can be expected annually. (2) Failure has occurred several times a year in the location.	Corrective Maintenance	4	2	1	1
4	(1) In a large population, one or more failures can be expected annually. (2) Failure has occurred several times a year in operating company.	Corrective Maintenance	4	2	1	1
3	(1) Several failures may occur during the life of the installation for a system comprising a small number of components. (2) Failure has occurred in the operating company.	Corrective Maintenance	Corrective Maintenance	4	2	2
2	(1) Several failures may occur during the life of the installation for a system comprising a large number of components. (2) Failure has occurred in industry.	Corrective Maintenance	Corrective Maintenance	8	4	4
1	(1) Several failures may occur during the life of the installation for a system comprising a large number of components. (2) Failure has occurred in industry.	Corrective Maintenance	Corrective Maintenance	8	8	8
CoF Types	Safety	No Injury	Minor Injury Absence < 2 days	Major Injury Absence > 2 days	Single Fatality	Multiple Fatalities
	Envirnoment	No pollution	Minor local effect. Can be cleaned up easily.	Significant local effect. Will take more than 1 man week to remove.	Pollution has significant effect upon the surrounding ecosystem (e.g. population of birds or fish).	Pollution that can cause massive and irreparable damage to ecosystem.
	Business	No downtime or asset damage	< € 10.000 damage or downtime < one shift	< € 100.000 damage or downtime < 4 shifts	< € 1.000.000 damage or downtime < one month	< € 10.000.000 damage or downtime one year
CoF Ranking		A	B	C	D	E

Figure 2-2: Example of risk matrix (DNV, 2009)

CHAPTER 3

Mapping and Evaluation of Existing Practices

3.1 Introduction

Not many assessment methods for environmental consequence of failure (E-CoF) exist which are suitable for RBI analysis. Part of the reason for this is that there are huge numbers of factors which could potentially influence the effects from a spill. The most complete methods include advanced simulations used on a case-to-case basis, which are too complicated to be used in a practical RBI setting. At the other end of the scale, some consequence assessment methods mostly ignore E-CoF in consequence assessments due to its complex nature. In this chapter, some practices will be introduced. These are all practices that try to deal with E-CoF in different ways, and which have influenced the work in this thesis. The presentations in this Chapter will mostly pay attention to the parts of the documents which consider E-CoF assessment.

Due to its importance and comprehensive content, the MIRA procedure (Section 3.5) will receive more attention than the others in this chapter.

The procedures described are:

- DNV recommended practice DNV-RP-G101 (2009)
- API recommended practice 580 (2002a)
- HSE Report 363/2001 (2001)
- DNV/OLF MIRA (2007)

3.2 DNV recommended practice DNV-RP-G101

The objective of the DNV-RP-G101 is to describe a method for establishing risk-based inspection plans for pressurized systems offshore. The document is divided into two parts, of which the first gives a basic introduction to RBI and the second focuses on the working process. Further, it includes appendixes which give more details about the material presented (DNV, 2009).

In the recommended practice, the consequence is divided into three categories. These are safety, economic and environmental. The environmental part is only briefly covered, and mostly converted into economic consequence.

A basic equation is presented for liquid hydrocarbon releases, which could be used for a quantitative analysis. This is shown in Equation 1 (DNV, 2009):

$$C_{ENVIRONMENT} = V_{RELEASE} \times (C_{CLEAN-UP} + C_{LOST\ PRODUCT}) \qquad (1)$$

In Equation 1, environmental consequence is expressed as cost (C). A cost is assigned for loss and clean-up effort of each volume unit and this is multiplied with the release volume (V) to yield a total cost for the spill.

Even though the DNV-RP-G101 recognizes the potential for damage to biotopes, no advice is given as to how to assess this. The document does, however, give a suggestion for a qualitative categorization of environmental consequence. The five proposed categories are:

- No pollution
- Minor local effect, can be cleaned up easily
- Significant local effect, will take more than one week to remove
- Pollution that has significant effect upon the surrounding ecosystem
- Pollution that can cause massive and irreparable damage to the ecosystem

The impression from the DNV-RP-G101 is that it gives a fair general overview regarding which factors to consider, but not much regarding the actual calculation of environmental consequence.

3.3 API recommended practice 580/581

The API recommended practice, issued by the American Petroleum Institute, consists of two documents. The first one is the actual recommended practice (API, 2002a), while the other is the base resource document which gives more details on each topic (API, 2000). Like DNV, the API recommended practice also opens with a basic introduction to the concept of RBI and the methodology. The consequence categories are somewhat different, but E-CoF is still in a separate category.

The API RP emphasises some important factors to consider when assessing E-CoF (API, 2002a):

- Volume of fluid released
- Ability to flash to vapour
- Leak containment safeguards
- Environmental resources affected
- Regulatory consequences (citations for violation, fines, potential shutdown)

The calculations in API RP are also based on cost. A formula is provided, as seen in Equation 2 (API, 2002a).

$$Environmental\ Cost = Cleanup\ Cost + Fines + Other\ Costs \qquad (2)$$

Further, consideration is given to factors affecting the cost. The fines and penalties depend on the local government, while the clean-up costs depend on the substance, the volume released and the accessibility.

The API RP base resource document (2000) states that the type of scenarios considered in RBI often have limited environmental consequences, since only process systems, with their modest volumes, are addressed. The safety or economic consequence will then be the governing category, and E-CoF may more or less be ignored. Further, it states that it is extremely difficult to assess E-CoF due to the many factors involved in estimating clean-up cost and civil penalties. The suggestion is to base the assessment on a dollar-per-barrel basis for the substance and location in question.

3.4 HSE Report 363/2001

This report, issued by the British Health and Safety Executive, discusses best practice of RBI as a part of plant integrity management. It contains a general introduction to the subject, along with guidelines on how to set up an inspection strategy (HSE, 2001).

The HSE report provides very little specific information on the assessment of E-CoF. However, it does mention that there is an increasing environmental awareness among the public, and that E-CoF should be included as a part of the consequence assessment.

The impression from the report is that it is more a general guideline to the RBI methodology than a tool for estimating probabilities and consequences.

3.5 DNV/OLF MIRA rev. 2007

This report is issued by Oljeindustriens Landsforening (OLF), and carries the name "Metode for Miljørettet Risikoanalyse" (DNV, 2007). This roughly translates to "Method for environmental risk analysis", indicating that the environmental aspect is the key factor.

The "MIRA-method" consists of seven steps:

1. Define acceptance criteria
2. Establish an activity description
3. Establish probability estimate for unwanted event
4. Rate/duration estimation
5. Estimate spread of leak
6. Damage assessment
7. Estimation of environmental risk

Unlike the other reports described in this chapter, MIRA does not mention RBI at all. Instead, it is written as a framework for conducting risk assessments with respect to the environmental hazards. The purpose of the report is to standardize important parameters and input data, so that analyses from different locations may be compared.

MIRA is frequently used in environmental risk reports which are prepared as part of the application for field development permission in Norway. This underlines its significance in the offshore industry, and indicates that it is a relevant and accepted method for assessing E-CoF.

There are three ways of performing an analysis in MIRA, based on the level of detail required:

1. Reference-based analysis
2. Exposure-based analysis
3. Damage-based analysis

The *reference-based analysis* is the simplest one, but relies on previous drift models and assessments from a more thorough analysis conducted in a representative area. The *exposure-based analysis* is based on mapping of vulnerable areas, and the potential for oil contamination of these. Lastly, the *damage-based analysis* is the most comprehensive model of the three. This is based on analysis of specific wildlife populations and their reaction to a potential oil spill contamination.

MIRA utilizes oil drift simulations to check for areas which could be influenced by a spill. The area is divided into a grid with 10km x 10km cells, and the probability for a certain concentration of oil in each cell is considered. This is then cross-checked with a vulnerability map, which shows the vulnerability of important resources and species in a corresponding grid. In the most detailed analyses, the vulnerability is also assessed on an individual basis for selected species.

Some important parameters are introduced in MIRA:

ESA (Environmentally Sensitive Area) – An ESA is a limited geographical area which contains one or more valuable natural resources which are sensitive to oil pollution. A criterion set is established to find the areas which qualify as ESA.
Note: ESA is translated from the Norwegian SMO - "Spesielt Miljøfølsomme Områder"

VEC (Valuable Ecological Component) – VEC is a term for environmental resources which are especially important. A VEC could be a species, a habitat, a coral reef or similar. The selection of VECs is done to find the resources which should undergo a consequence assessment to find the potential effect of oil spills. The results from these assessments will then be considered as representative for the area as a whole.
Note: VEC is translated from the Norwegian VØK – "Verdsatt Økosystem Komponent"

Consequence is expressed as the expected restitution time for the resource considered. The following categories are given:

- Minor (1 month – 1 year)
- Moderate (1 – 3 years)
- Significant (3 -10 years)
- Serious (>10 years)

Even though MIRA does not focus on RBI, environmental consequence is well covered in the report. Also, environmental parameters are categorized in a way which makes them well suited for an E-CoF assessment. This makes MIRA a good source of inspiration and reference for a new procedure for E-CoF in RBI.

3.6 Discussion of existing models

To summarize this chapter, it is obvious that the existing RBI practices do not put much effort into the assessment of E-CoF. Some views towards the most important considerations are provided, but little or no information is given on how to calculate these. That leaves much in the hands of the RBI team, and the environmental consequence will either be estimated in a rough qualitative analysis, or even just considered as less important than the other consequence categories.

A good example of this comes from the API base resource document (2000), which states: "Assessing environmental damage is extremely difficult because of the many factors involved in clean-up efforts and in estimating the cost for possible civil penalties or fines". This shows that even though API limits environmental consequence assessment to estimating costs, no attempts are made at a procedure for calculating the consequence. While safety consequences are described with formulas and schematics covering hundreds of pages, the E-CoF is limited to small paragraphs and statements similar to the ones stated in this Chapter.

The MIRA model stands out here, as it focuses solely on the environmental aspects of risk. It is, however, quite comprehensive, and too detailed to be used in a practical RBI setting. Also, it focuses on worst-case scenarios, such as blowouts. The volumes released in such events are far beyond what can be expected from process leaks, and the model is therefore not directly adaptable to the RBI context.

Despite these shortcomings, all the reports represent a source of inspiration for a new and better practice. The challenge is to create a procedure which is simple and user friendly, yet sensitive enough to yield a reliable E-CoF value. Together with other literature, logic reasoning and input from qualified personnel, the reports in this chapter form the basis of the procedure for assessing E-CoF proposed in this thesis.

CHAPTER 4

Identification of Important Factors Influencing the Environmental Consequence of Failure

4.1 Introduction

This chapter will present and discuss the most influential factors for an environmental consequence assessment following an oil spill. Ideally, there are large numbers of factors that should be included, but generally some stand out as more important than others. There is also a need to limit the input factors to make the procedure as simple and user-friendly as possible.

The factors selected for closer examination in this chapter are selected on the basis of literature: most importantly DNV recommended practice (2009), API recommended practice (2002a) and the plan for total management of marine environment in the Norwegian Sea (Miljøverndepartementet, 2009).

In Chapter 5, the factors will be put together to form a procedure for E-CoF assessment. However, since the procedure is fairly simple and relies on a minimum of input data, the background theory is important in order to recognize the strengths and weaknesses of the proposed procedure. It also serves as a justification as to why it is difficult to make E-CoF assessments in an easy way and with few input factors.

It should be noted that in this thesis, it is assumed that the substance and amount are already known when the E-CoF is assessed. The probabilities, hole sizes and leak rates are not addressed.

The following factors are identified as most important, and will be presented and discussed in this chapter:

- Type of hydrocarbons released (Section 4.2)
- Volume of hydrocarbons released (Section 4.3)
- Release barriers (Section 4.4)
- Fate of oil – Weathering (Section 4.5)
- Fate of oil – Spreading and shore impact probability (Section 4.6)
- Oil spill response options (Section 4.7)
- Acute effect of oil spills (Section 4.8)
- Long-term effect of oil spills (Section 4.9)

4.2 Type of hydrocarbons released

The adverse environmental impact of a spill depends heavily on the type of substance which is released. As the composition of the crude oil or refinement varies, each type of product has its unique properties and characteristics. These properties influence many of the factors which are decisive for E-CoF assessment, of which the most important ones are listed here (Fingas, 2001):

- Adverse effects on living organisms
- Spreading
- Weathering (evaporation, dissolution, etc.)
- Effect of clean-up efforts

4.2.a The composition of oil

The main contents of hydrocarbons are, as the name implies, hydrogen and carbon. However, these two main components may form a variety of molecules, ranging from small single-carbon molecules to long chains and circles. While the smaller compounds flow easily and are very volatile, the longer chains are heavy and viscous (Fingas, 2001).

Besides the two main components, the oil may also contain smaller amounts of sulphur, nitrogen, oxygen and mineral salts. Trace metals such as nickel, vanadium and chromium are also likely to be found. Table 4-1 shows the typical composition of some common oil types.

Group	Compound class	Gasoline	Diesel	Light crude	Heavy crude	IFO (Intermediate Fuel Oil)	Bunker C
Saturates		50-60	65-95	55-90	25-80	25-35	20-30
	Alkanes	45-55	35-45				
	Cycloalkanes	5	30-50				
	Waxes		0-1	0-20	0-10	2-10	5-15
Olefins		5-10	0-10				
Aromatics		25-40	5-25	10-35	15-40	40-60	30-50
	BTEX	15-25	0.5-2	0.1-2.5	0.01-2	0.05-1	0-1
	PAH		0-5	10-35	15-40	40-60	30-50
Polar compounds							
	Resins		0-2	0-10	2-25	10-15	10-20
	Asphaltenes			0-10	0-20	5-10	5-20
Metals (ppm)				30-250	100-500	100-1000	100-2000
Sulphur		0.02	0.1-0.5	0-2	0-5	0.5-2.0	2-4

Table 4-1: Typical composition of selected oil and petroleum products. All values are given in percentages, except for metals which are listed in ppm (Fingas, 2001)

In the environmental context, the toxicity of the oil is an important parameter. In general, light oils will contain high amounts of the BTEX aromatics, which are a common term for Benzene, Toluene, Ethylbenzene and Xylenes. These aromatics are highly toxic to living organisms, but have a high volatility and will evaporate quickly (Beyer, 2011).

Heavier oils will usually have a higher content of PAH (PolyAromatic Hydrocarbons) and alkylphenols. These compounds are heavier than the BTEX, and tend to stick with the heavier oil components. They are also more persistent, and will stay in the environment longer than the more volatile BTEX components (Beyer, 2011). PAH and alkylphenols are listed as "priority chemicals" by The Oslo-Paris Commision (OSPAR) due to their potential long-term effect on biota (OSPAR, 2009).

Table 4-2 provides an overview of some of the most important compounds in hydrocarbons.

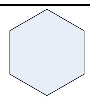
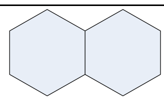
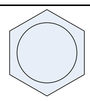
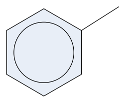
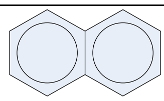
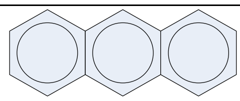
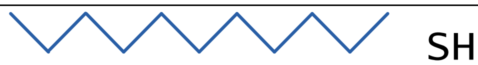
Group	Sub-group	Example compound	Illustration
Saturates	Alkanes	Butane	
		Hexane	
	Cyclo-alkanes	Cyclo hexane	
		Tetrahydronapthalene	
	Waxes	Large alkane	
Aromatics	BTEX (Benzene, Toluene, Ethylbenzene, Xylenes)	Benzene	
		Toluene	
	PAH (Polyaromatic hydrocarbons)	Napthalene	
		Phenanthrene	
Polar compounds	Resins	Thiols (General group of sulphur-bearing compounds)	–SH
		Decanomercaptan	
	Asphaltenes	Structure unknown – very large polar compounds	

Table 4-2: Chemical componds in oils (Adapted from Fingas, 2001)

4.2.b Properties of oil

While the composition of oil is important to note due to the varying toxicity potential of its components, the properties are crucial to determine the behaviour of a spill. Light oils flow easily and are weathered quickly by effects such as dispersion and evaporation, while the heavier ones will be more viscous and persistent. The viscosity of the oil will be decisive for its spreading, and also for the effectiveness of clean-up efforts.

From Table 4-3, it can be seen that the properties of oil somewhat correlate with each other. However, the correlations should be used with care, as oil may vary in composition. As an example, oils with a high wax content tend to have much higher viscosity than their density would indicate (Fingas, 2001).

Also, it should be noted that the properties will vary depending on ambient conditions. Values for viscosity and density in Table 4-3 are given at 15°C, but they will be different at other temperatures. As an example, the listed oils would be more viscous in Arctic waters, where the sea is unlikely to have a temperature above 4°C.

Property	Units	Gasoline	Diesel	Light crude	Heavy crude	IFO	Bunker C	Crude emulsion
Viscosity	mPa.s. @15°C	0.5	2	5-50	50-50,000	1000-15,000	10,000-50,000	20,000-100,000
Density	g/mL @15°C	0.72	0.84	0.78-0.88	0.88-1	0.94-0.99	0.96-1.04	0.95-1
Flash point	°C	-35	45	-30 to 30	-30 to 60	80-100	>100	>80
Solubility in water	ppm	200	40	10-50	5-30	10-30	5-20	-
Pour point	°C	-	-35 to -1	-40 to 30	-40 to 30	-10 to 10	5-20	>50
API gravity		65	35	30-50	10-30	10-20	5-15	10-15

Table 4-3: Typical oil properties (Adapted from Fingas, 2001)

4.3 Volume of hydrocarbons released

The volume of hydrocarbons which is released in the case of a spill will have a significant impact on the E-CoF. A larger volume will have the potential to cover and contaminate larger areas, and it will also have a higher probability of reaching shore.

4.3.a Events and volume range considered

When considering the size of a spill and its potential value, the context must be kept in mind. The RBI analysis, which this thesis aims to support, is limited to addressing topside static process equipment. The boundary for RBI application is usually set at the emergency shutdown valve (ESD), which rules out some of the worst spill sources such as pipeline leak, storage tank rupture and blowouts. Separators will generally be the units containing the largest volumes at platform topsides, along with the adjacent piping system. Table 4-4 gives a suggestion for spill volume ranges for different sources.

Unwanted event	Lower part of volume range		Upper part of volume range	
	Vol (m^3)	Duration	Vol (m^3)	Duration
Blowout	3,000 m^3	1 day	650,000 m^3	<2 days
Well leakage	40 m^3	<15 min	900 m^3	1 hour
Pipeline leak	50 m^3	hours	7,300 m^3	2 weeks
Riser leak	5 m^3	hours/days	1,000 m^3	Weeks
Process leak	0 m^3	minutes	50 m^3	1 hour
Storage tank leak	<1,000 m^3	hours	150,000 m^3	weeks/months
Storage transfer leak	6 m^3	minutes	150,000 m^3	hours

Table 4-4: Overview of upper/lower part of volume range and representative spill volume/duration (Translated from Petroleumstilsynet, 2010)

From Table 4-4, it is evident that the potential for hydrocarbon leak is significantly lower from process equipment than it would have been if blowouts and storage tanks were to be included. The volume of 50 m^3, which is given as the upper limit for process leaks in the table, is based on the argument that a segment in the process train is unlikely to contain more than a volume of 50 m^3. However, some assumptions have been made to provide this estimate (Petroleumstilsynet, 2010):

- The drain system at the process plant has the capacity to contain large spills
- The leak is detected within a short time (< 1 hour)
- The segment can be isolated quickly after detection

These assumptions will be valid for most fields in operation, but a larger spill should still be considered as a possibility in a worst-case scenario. As an example, ageing platforms with old designs may not have the drain capacity of a modern platform. Based on the data and assumptions from Table 4-4 and discussion with senior engineers at DNV, the worst-case spill from process equipment is thought to be in the area of 200 m^3. Barriers such as drains could reduce the amount being released into the sea, and this will be discussed in Section 4.4.

Even though riser leaks are usually not part of an RBI analysis for topsides, it is included in the proposed assessment method in this thesis. The reason for this is that RBI is often used for risers as well, even though it is usually done in a separate analysis. Including it in the proposed model enables it to be used for both kinds of analyses. Hence, the upper part of the volume range considered will be 1000m^3.

4.3.b. Historical view on release volumes

Fortunately, large spills are very rare in the offshore industry. As can be seen from the graph in Figure 4-1, even the total volumes for a year in Norwegian waters rarely exceed 200m^3. If the volumes are divided by number of events, it becomes clear that most spills are very small. As an example, the average spill volume for 2006 events were around 1 m^3.

The large fluctuations in some years, such as 2007, are often caused by single larger events. For 2007, a ruptured loading hose accounted for approximately 4400 m^3 of the 4488 m^3 spill in that year (Miljøverndepartementet, 2009). Such an event, termed "storage transfer leak" in Table 4-4, is not part of the scope for RBI. In sum, it becomes clear that the spill volumes considered within the RBI analyses will usually be well below the upper range limit set at 1000 m^3.

For the last 40 years, there have only been three occasions where oil spills larger than 1000 m^3 have been recorded from Norwegian installations (Miljøverndepartementet, 2009). These are:

- Blowout at Ekofisk Bravo, 1977
- Oil leak at Statfjord C, 1989
- Oil leak during transfer at Statfjord A, 2007

It should be noted that none of these events caused any noticeable effects on the environment. However, several of the recorded releases from ship traffic have caused contamination to seabirds and shore, even with moderate volumes (Miljøverndepartementet, 2009).

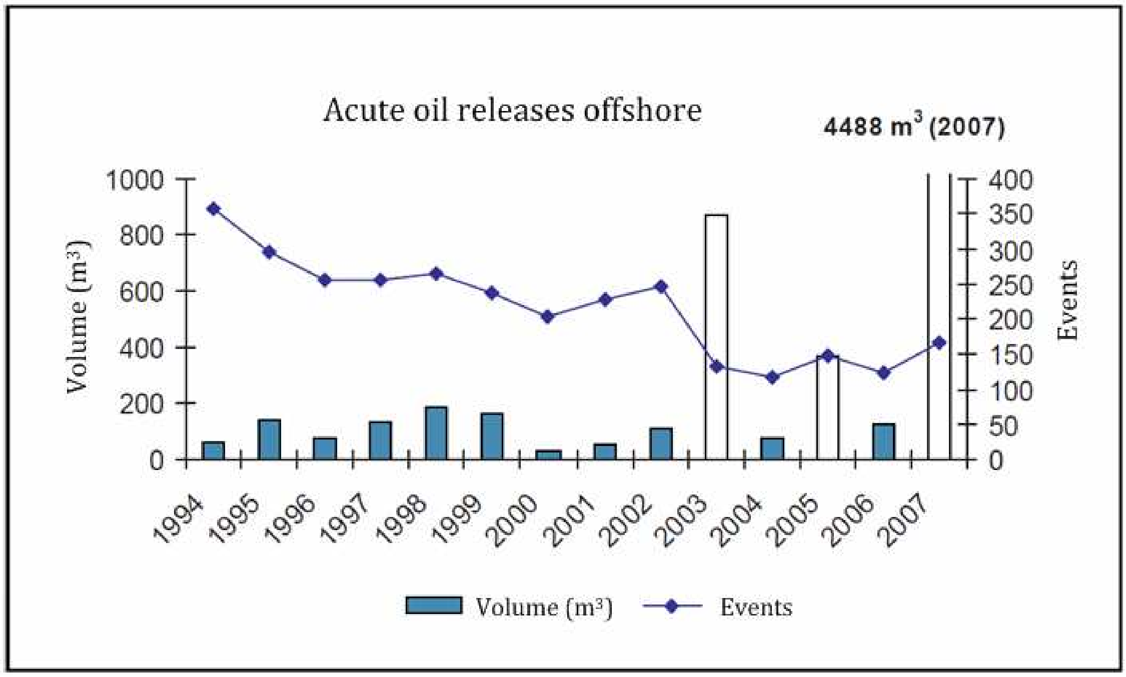


Figure 4-1: Graph showing spilled volume on number of acute events in Norwegian waters for the years 1994-2007 (Translated from Miljøverndepartementet, 2009)

4.4 Release barriers

The term "release barriers" in this context means all physical barriers on the installation which are designed to contain the spill on the platform. Typically, the barriers will be in the form of trays or open drains, which route the spill into a slop tank on the platform. An example sketch of a barrier system is shown in Figure 4-2. The ability of the drain to collect a spill will depend on two main factors:

- The capacity of the drain piping
- The capacity of the slop tank

Exact volumes and rates of drain capacity are hard to come by, as they depend on the platform layout and demands. The standard NORSOK P-100 (2010) states that "The overflow lines shall be designed for full deluge capacity in each area", which means that the drains shall be able to route the whole firewater capacity into the open drain system. No values are given, but the fire water system at full effect will give a considerable amount of water. Hence, for process leaks, the drains should normally catch most liquid spills.

Other barriers could be small elevations at the deck edge, or any deck shape which will be able to contain the spill before it reaches the sea. It should be noted that toxic or combustible liquids in trays on deck could potentially be a safety concern. However, if the liquid reaches the drains, it will be trapped in an inert slop tank and, as such, be neutralized with respect to ignition potential.

Barriers will keep the spill contained and make it easier to collect and dispose of and thereby reduce the E-CoF.

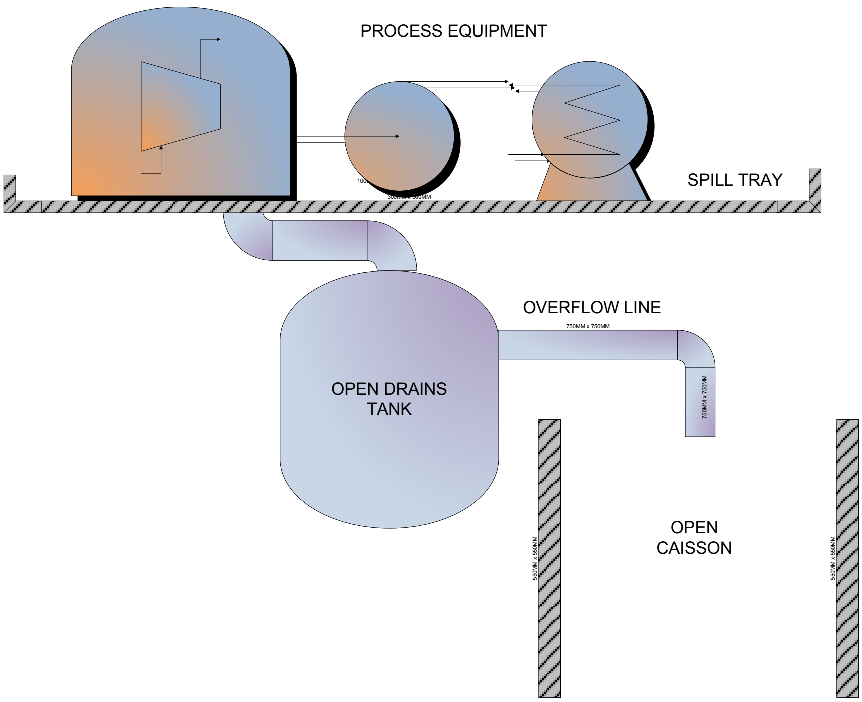


Figure 4-2: Example sketch of an open drain system

4.5 Fate of oil – Weathering

When an oil spill hits the sea, a number of transformation processes begins. This is often referred to as the "fate" of a spill, and determines the natural transportation and degradation of the oil from natural processes (Fingas, 2001).

The term "weathering" refers to the series of processes which changes the physical and chemical properties of a spill, such as evaporation and dissolution. The spreading of the oil determines the area it will cover, and hence whether it will have the potential to reach shore or other fragile areas. The processes of spreading and weathering are not independent. They overlap each other, so that the weathering may strongly influence spreading and vice versa. Spreading is often considered to be part of the weathering process, but it has been given a separate section in this thesis because of its significance in E-CoF assessment (Section 4.6).

The weathering of oil starts as soon as it hits the surface, as illustrated in Figure 4-3. The speed and effect of the weathering process depends on many factors, of which oil type and weather on the spill site are among the most influential (Fingas, 2001). In the right conditions, weathering processes may significantly reduce the volume of the oil within a short time span, especially for light oils.

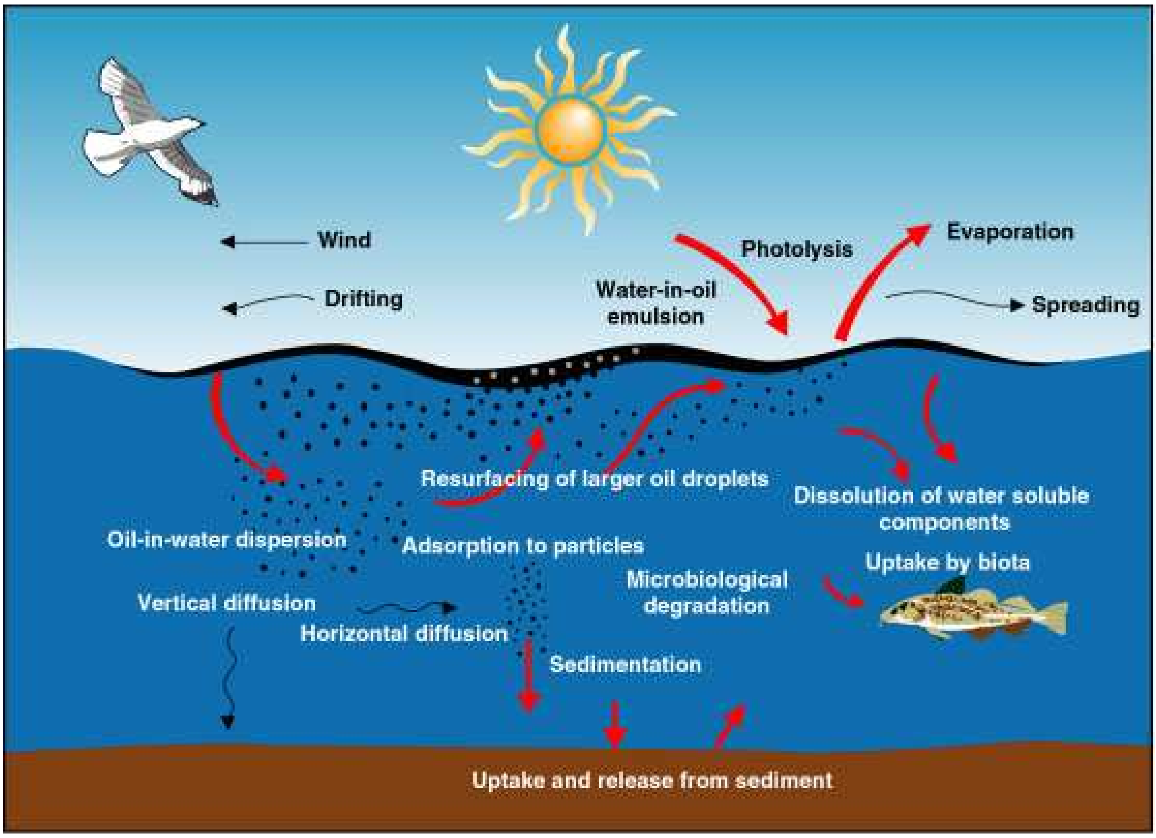


Figure 4-3: Oil weathering processes (SINTEF, n.d.)

Along with spreading, evaporation is the predominant process during the first days after a spill, while biodegradation and sedimentation take over in the later stages of the weathering process (ITOPF, 2002). An approximate timeline of the processes is shown in Figure 4-4.

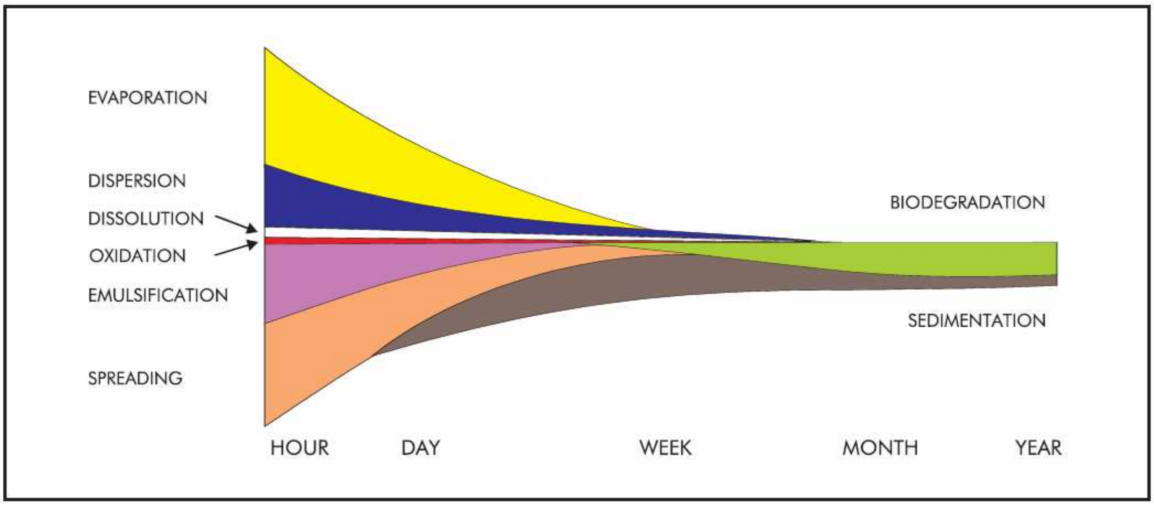


Figure 4-4: A schematic representation of the fate of an oil spill (ITOPF, 2002)

Evaporation is often the most important weathering process. At temperatures above freezing, a gasoline spill will be completely removed after a few days at sea. At the other end of the scale, the heavy grade Bunker C is unlikely to be reduced by more than a few percent. The rate at which the oil evaporates is primarily based on its composition, as lighter oils with a high content of volatile components will evaporate quickly (Fingas, 2001).

Dispersion is another important process in the early days after a spill. The phenomenon occurs in areas with high sea energy, e.g. where there are a lot of waves and movement on the surface. The smaller droplets in the oil will be transferred into the water column with help from waves and currents, removing significant amounts from the surface (Fingas, 2001). Dispersion is most effective on lighter oils, such as diesel and light crudes, as these oils have a high amount of light saturates and low amount of heavier components such as resins and asphaltenes.

It should be noted that, besides oil composition, temperature is an important factor in oil weathering. As the temperature approaches zero degrees, most processes will be slowed to very small rates (Fingas, 2001). This means that in cold Arctic areas, all oil types will be more persistent in the environment due to the lack of weathering from natural processes.

An overview of the weathering of a selection of oil types can be found in Figure 4-5. This figure also shows the increase in volume which may arise from the water-oil emulsions taking place during the first days after a spill. Besides the increase in volume, emulsification may drastically change the viscosity of the oil (Fingas, 2001).

Group	Specific density	Example
Group 1	< 0.8	Gasoline, Kerosene
Group 2	0.8 – 0.85	Diesel, Abu Dhabi crude
Group 3	0.85 – 0.95	Arabian light crude, North Sea crude
Group 4	> 0.95	Heavy fuel oil, Venezuela crude

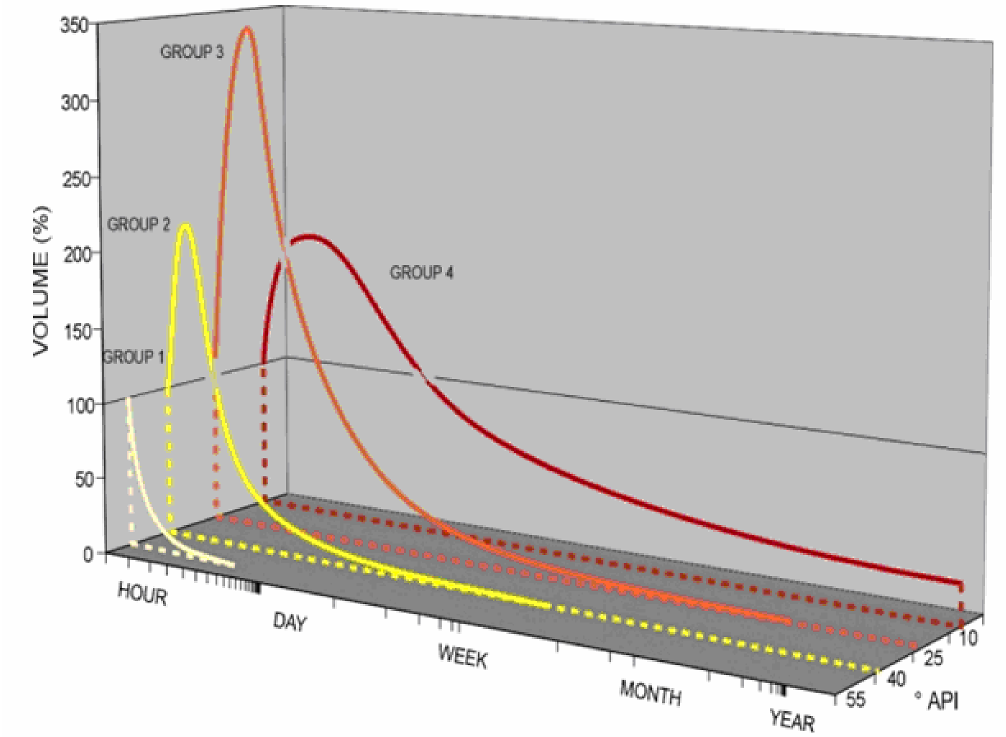


Figure 4-5: Evaporation rates of different oil types at 15°C (Adapted from Fingas, 2001)

4.6 Fate of oil – Spreading and shore impact probability

Predicting the influence area of a spill is crucial for an environmental consequence assessment, as it decides which areas are likely to be impacted. Still, it is possibly one of the most difficult tasks in the E-CoF assessment. Besides the fact that the composition of the oil and its viscosity play major roles, there are many external factors which also influence where the spill is likely to make its impact. Wind, current, sea state, temperature and weathering are probably among the most important ones of these.

4.6.a Prediction of oil spill spreading

To make a general model for the spreading of oil is, to say the least, very challenging. As each area will have its own characteristics, no assumptions will be valid for all areas. Also, conditions are subject to seasonal changes, such as winter storms and temperature variations.

In comprehensive environmental risk assessments, the spreading of oil is predicted by the use of advanced computer simulations. A widely used tool in Norwegian waters is the OILTRAJ model by DNV, which is used in many of the environmental consequence assessment studies on fields in development. One example of such is the Ververis analysis, conducted by DNV (StatoilHydro/DNV, 2008).

In a simulation, the range of parameters such as temperature, current, wind, etc. are collected from relevant databases and used as input to the program. The program then picks random values from the given ranges and runs a simulation. This process is repeated many times over to cover the majority of scenarios. In the case of Ververis, 3600 simulations were conducted (StatoilHydro/DNV, 2008). The outputs from the simulations are represented by a graphical image which shows the probability of oil impact in each area. It should be noted that the image does not actually show the spreading of an oil slick, but the total probability of hit in each 10x10km square in the grid based on all the simulations. An example of such a graphical illustration is shown in Figure 4-6.

From images illustrating oil spill spreading, such as Figure 4-6, it is easy to get the impression that a spill will spread out almost in an even circle from its origin. This is, however, far from the truth. While Figure 4-6 shows an average from 3600 simulations, single scenarios are more likely to look like a thin line of oil in a distinct direction. Figure 4-7, which shows a single scenario from the Goliat field, gives a good illustration of this.

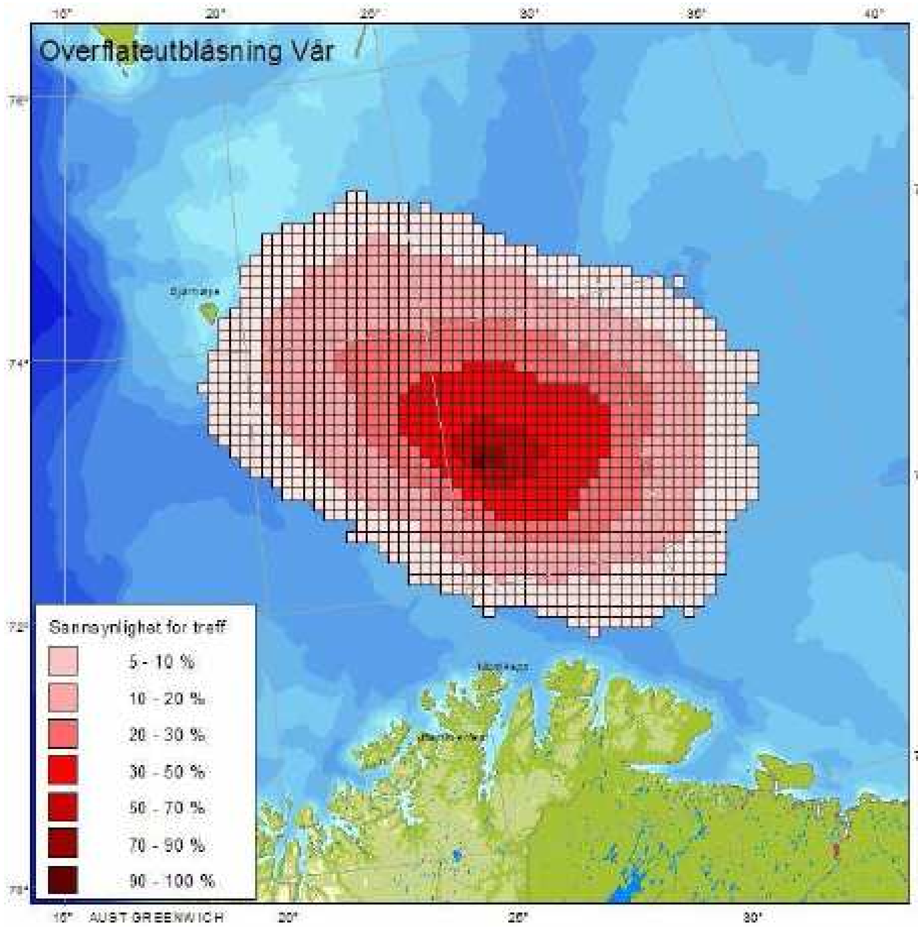


Figure 4-6: Graphical representation of spill impact probability based on 3600 simulations on the Ververis-field. The colours represent probability of impact (StatoilHydro/DNV, 2008).

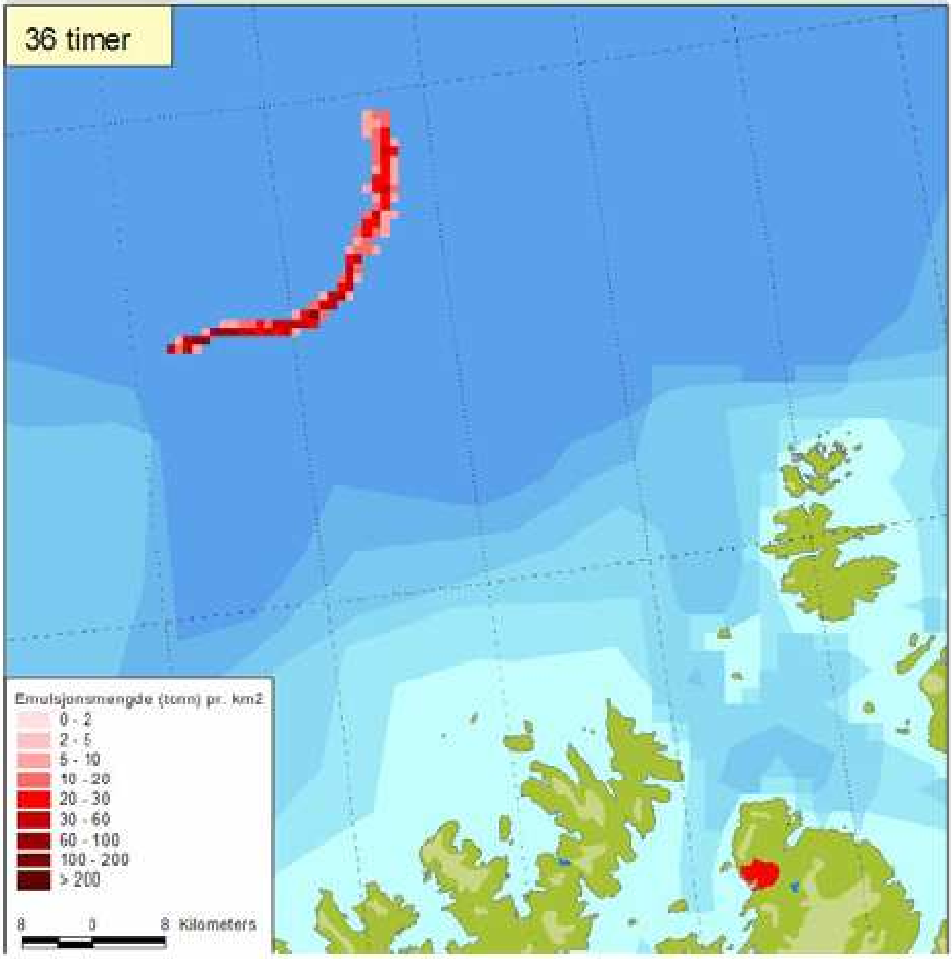


Figure 4-7: Graphical representation of a single spill scenario on the Goliat field, in this case after 36 hours. The colours represent different concentrations of oil in each square (ENI Norge/DNV, 2006)

The oil volumes on the surface are important for assessing the consequences for surface-dwelling species, as well as the probability of a shore impact. However, the biota living in the water column will not necessarily be very influenced by this. For fish stocks and other underwater species, the concentration of toxins in the water column is more important. For this reason, assessment of the concentration of oil in the water column is also part of oil drift simulations.

As seen from Figure 4-8, the diluted hydrocarbon in the water column has a limited spread area compared to surface oil. The figure is based on the same simulations as those in Figure 4-6, which shows that the oil in the water column has a limited spreading compared to surface oil.

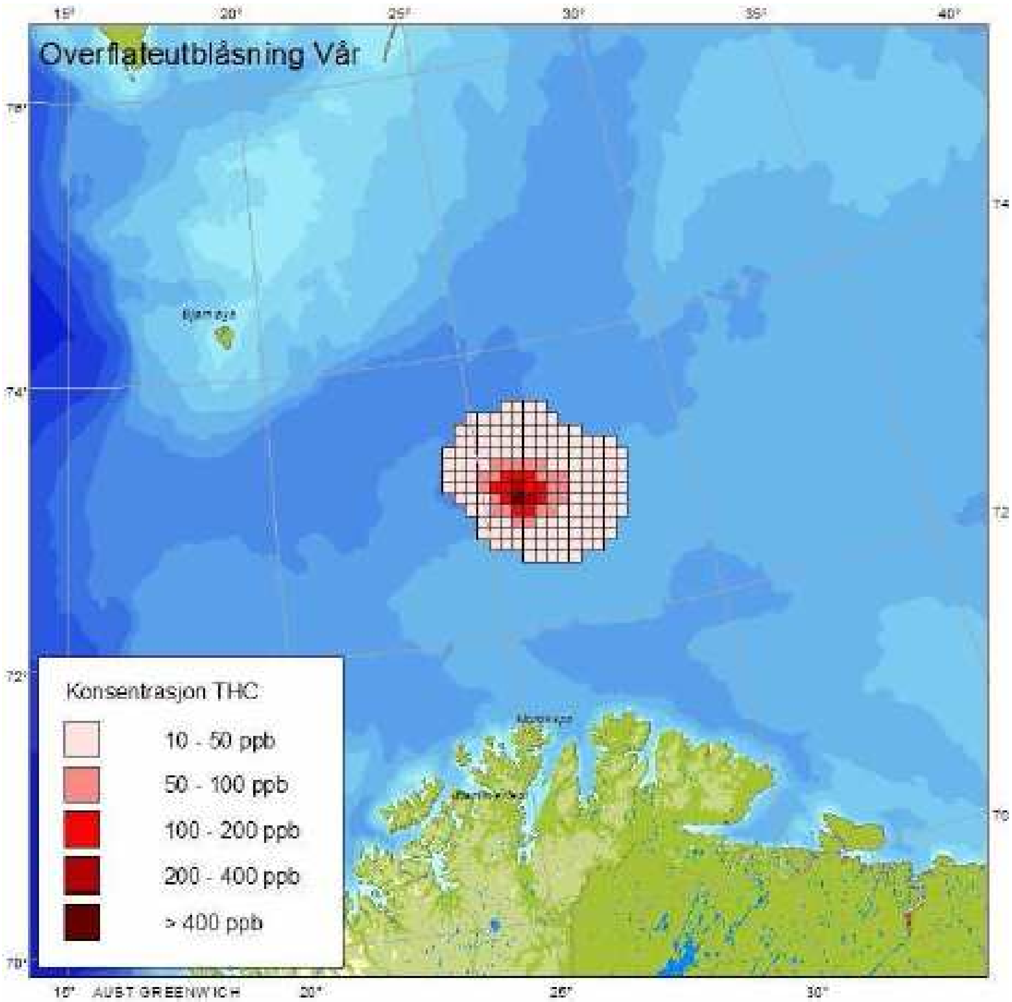


Figure 4-8: Illustration of the total hydrocarbon (THC) spreading in the water column upon a spill from the Ververis field (StatoilHydro/DNV, 2008)

4.6.b. Shore impact probability

In general, a shore impact of oil seems highly unlikely, at least from the volumes considered in this thesis. Of all the fields along the Norwegian coast, only one has more than 5% probability of a shore impact in the case of a release (Miljøverndepartementet, 2009). It should also be noted that these calculations are based on worst-case scenarios, usually several thousand tons/24h and with duration of weeks. The only field with a higher probability of impact is Draugen, located approximately 65km from the coast, with a 13% probability of shore impact in case of a blowout (Miljøverndepartementet, 2009).

4.7 Oil spill response options

When spilled at sea, hydrocarbons tend to form thin slicks on the water's surface. This is due to the relatively low density of most hydrocarbons compared to seawater. Many regions with offshore activity are well prepared for spills, and have equipment ready on short notice. If the spill is successfully removed or significantly reduced, this would give a lower E-CoF.

There are several ways of dealing with floating slicks of oil. The most common ones include (WWF, 2007):

- Mechanical recovery
- Dispersants
- In situ burning

Unfortunately, these methods all require relatively calm weather to be efficient. Quick response time and right equipment are also essential, which makes infrastructure a critical factor in the oil spill response operations.

4.7.a. Oil spill response in Norway

In Norway, oil spills from offshore activity are dealt with by Norsk Oljevernforening For Operatørselskap (NOFO). The organisation is a joint venture by offshore operators as well as government, and administers oil spill response equipment along the coastline (NOFO, 2010). As this thesis is primarily focused on Norwegian fields, NOFO requirements and guidelines are considered to be valid.

The oil spill response in Norway is built on a principle of barriers. These are defined as follows (NOFO, 2010):

Barrier 0: Physical barriers on installation which prevent oil from reaching the sea
Barrier 1: First oil barrier, to be deployed as close to source as possible
Barrier 2: Oil spill response in open sea
Barrier 3: Oil spill response in coastal areas
Barrier 4: Clean-up efforts on coast and beaches

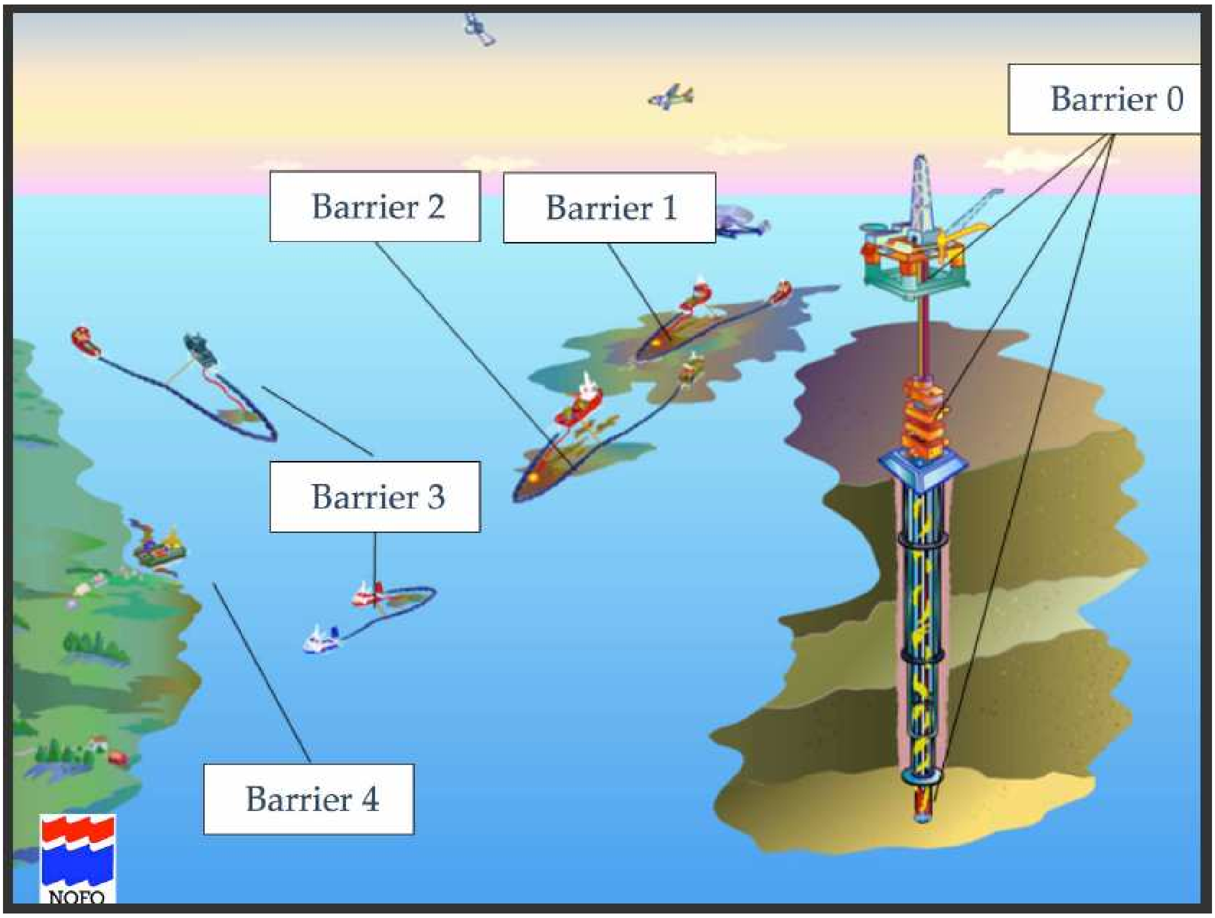


Figure 4-9: Principle sketch of the barrier system in NOFO (NOFO, 2010)

In such a system, the physical barriers described in Section 4.4 equal “Barrier 0” in Figure 4-9, which are the barriers designed to prevent oil from reaching the sea in the first place.

If the oil gets into the sea, barrier 1 is the most important one. Since the oil slick will be limited to a fairly small area, the oil spill response team may be able to get the majority of it trapped and collected (NOFO, 2008a). For barrier 1 to be effective, time is of the essence. The response team must be on site as quickly as possible, before the oil slick spreads to larger areas. Hence, the distance between the installation and the base or response vessel must be limited to allow a short response time. If a successful barrier close to the installation is established, considerable amounts of oil may be salvaged from the surface. Figure 4-10 shows an average percentage of collected oil in different wave heights, provided that a barrier is established quickly.

For barriers 2 and 3, no estimates for recovery are given by NOFO (2008a). Barrier 2 may be able to catch a considerable amount, but the oil will be spread to larger areas and hence it will demand more resources to cover all of it. Barrier 3 primarily focuses on protecting fragile areas, rather than collecting as much oil as possible. Barrier 4 is the final clean-up of shore and beach from the oil which has escaped the previous barriers. This is less time-critical than the others, but may take a long time and demand lots of resources (OLF/NOFO, 2007).

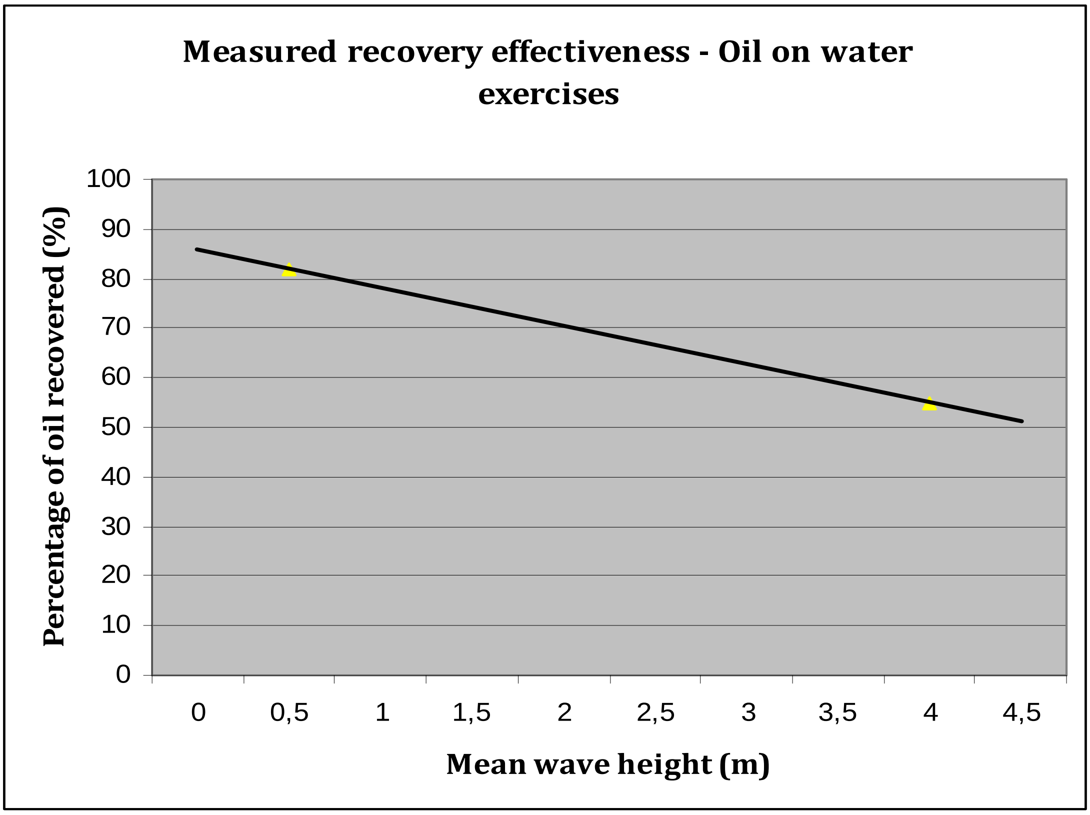


Figure 4-10: Measured recovery effectiveness as a function of wave height (adapted from NOFO, 2008a)

With regard to capacity for oil spill response equipment, NOFO has defined "packages" which shall be able to handle a certain volume. From the capacities shown in Table 4-5, it seems fair to assume that one standard system should be able to handle the maximum volume of 1000 m^3 which was set in Section 4.3, even if the oil may form emulsions and hence expand somewhat in volume after it has reached the sea.

System	**Capacity**
Barriers 1 & 2	
NOFO system w/Transrec 350 oil skimmer	2400 m^3/24h
NOFO system w/Hi-Wax oil skimmer	1900 m^3/24h
NOFO system w/Foxtail 8-14 oil skimmer	800 m^3/24h
Barrier 2	
Coastguard systems	1200 m^3/24h
Barrier 3	
Coastal system	120 m^3/24h
Fjord system	17 m^3/24h

Table 4-5: Uptake capacity for NOFO-systems (Translated from OLF/NOFO, 2007)

4.7.b Oil spill response in Arctic areas

In recent years, the Arctic areas have received increased attention from the oil and gas industry. However, there is a great concern for the environment, which is considered to be fragile in the harsh northern areas. The Arctic conditions also make oil spill response a challenge. Among the factors affecting the response opportunities are sea ice, rough seas, wind, extreme cold and limited visibility. This, combined with great distances and poor infrastructure, could potentially make for a long response time.

High density sea ice makes mechanical recovery of oil and the use of dispersants difficult. In some cases, in situ burning is the only viable option for oil spill response in the Arctic (Brandvik et al., 2006). Table 4-6 gives an overview of the suitability of response methods in different levels of ice coverage.

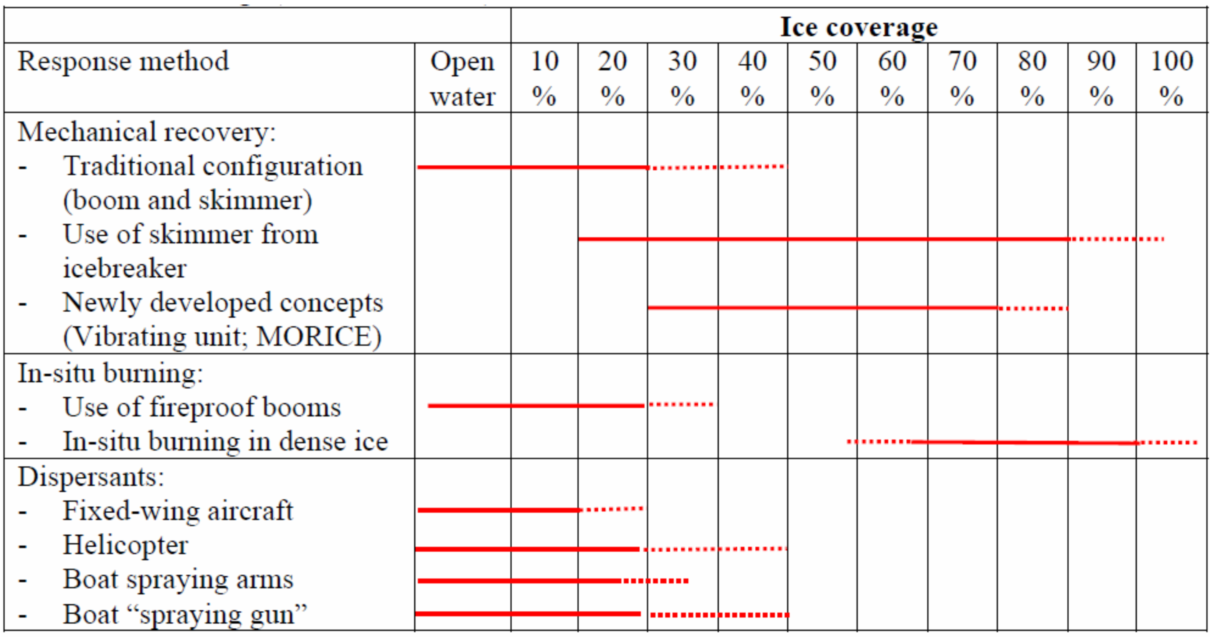


Table 4-6: Indication of expected effectiveness of different response methods as a function of ice coverage (Brandvik et al., 2006)

Another great challenge for oil spill response in the Arctic is the so-called "window of opportunity" for in situ oil burning. As the light components in oil evaporate, the flash point of the oil increases, and it will become harder to ignite. Also, the water becomes emulsified into small droplets in the oil. Both these processes make burning of oil less effective. A percentage of evaporative loss of 20-30% and water uptake rates of 25-50% are listed as "rules of thumb" in literature (Brandvik et al., 2006). When the window of opportunity is combined with the long response time in Arctic areas, it becomes clear that oil spill recovery in the Arctic areas is a big challenge compared to temperate waters.

4.8 Acute effect of oil spills

The acute effects on marine life refer to the short-term effects within the first weeks after a spill, and are also called the lethal effects. Acute effects are typically physical and visual, like the oil sticking to feathers of seabirds.

The severity of the effects on the species and surroundings will depend on factors such as (AMSA, n.d.):

- The type of oil spilled
- Wildlife populations in the area
- Shoreline and seabed type
- Time of season with regards to breeding cycles, etc.
- Wind and weather at the time of the spill
- The species' sensitivity to oil pollution

In general, the very light oils such as jet fuel and gasoline will be the most acute toxic substances. However, these will evaporate fairly quickly and not stay in the sea for long. The heavier components are more persistent, and represent more of a long-term concern (Beyer, 2011).

When oil is first released into the sea, it tends to form an oil slick on the surface. Fish are sometimes attracted to the area, seemingly because they sense the floating oil as possible food. Seabirds and sea mammals follow in their hunt for fish, and dive through the layer of oil in pursuit of prey (AMSA, n.d.). The following sections describe some of the most important acute concerns for the wildlife and environment in coastal areas.

4.8.a Seabirds, seals and sea otters

Initially, the oil has most impact on the animals which utilize the water surface, such as seabirds, seals and sea otters. The oil sticks to feathers and fur, which disrupts the insulation ability. This could cause hypothermia, which means that the animal will freeze to death. This is of particular concern in Arctic areas, where birds and mammals are totally dependent on their insulation to protect them from the cold. If birds are heavily affected by oil, it could also make them unable to fly or cause drowning due to loss of buoyancy (U.S. Fish & Wildlife Service, 2004).

Among the sea mammals, seal pups are more exposed than adults, since they have a woolly fur. Besides the risk of hypothermia, the oil could stick their flippers to their bodies, leaving them unable to swim. Layers of oil also disguise the scent which seals use to identify their pups, so that the pups may be rejected and face starvation. When the animals attempt to clean themselves, it could cause ingestion or inhalation of oil, which in turn may cause damage to vital organs and subsequent death (AMSA, n.d.). Figure 4-11 shows how birds and mammals were affected after the Exxon Valdez incident in Prince William Sound.

Figure 4-11: Oiled Loon and Sea otter, after the Exxon Valdez grounding in Prince William Sound (U.S. Fish and Wildlife Service, 2004)

4.8.b Whales and dolphins

Unlike birds and land-based mammals, whales and dolphins do not have fur. This means that the oil is unlikely to stick to their bodies. Still, they may come in contact with the oil through feeding, or when they break the surface to breathe. The oil may also affect the senses of the animals, such as eyesight or smell, making it harder for them to hunt for food (AMSA, n.d.).

4.8.c Plants, algae and invertebrates

Plants respond very differently to oil. Some will die off almost immediately, while others seem practically unaffected. As for algae, some populations will decline. Others, however, will increase in numbers as they are able to use the oil as nutrition (U.S. Fish & Wildlife Service, 2004).

Invertebrates are found in many forms, both in sediments and on rocky shorelines where they attach their shell to the surface. As these small organisms are mostly immobile, they are sensitive to local variations in pollution (U.S. Fish & Wildlife Service, 2004). Many invertebrates are used as pollutant indicators for specific areas.

4.8.d Fish

In general, eggs and young individuals in fish populations are more sensitive to oil toxins than adults. This means that the younger generation is likely to be reduced, while the adult fish have a higher survival rate. Oil pollution is mostly a concern for fish if it is released close to their breeding grounds (U.S. Fish & Wildlife Service, 2004).

4.8.e Habitat

An oil spill will pollute the habitat of a number of species, especially if it hits shore. Although habitat disturbance is an acute effect, the spill may persist for decades. This could cause shifts in population structure and diversion. Offshore populations tend to be more resilient, while near-shore species are strongly affected by habitat changes. Even though a species may not be directly influenced, it will need to move if its prey no longer resides in the area (U.S. Fish & Wildlife Service, 2004).

In some areas, maps have been made to show sensitive habitats. Where available, these may be used to show where an oil spill could have the most severe impact on the various species. An example of such a vulnerability map is shown in Figure 4-12. This sample is a map which combines the vulnerability for fish, birds and commercial interests.

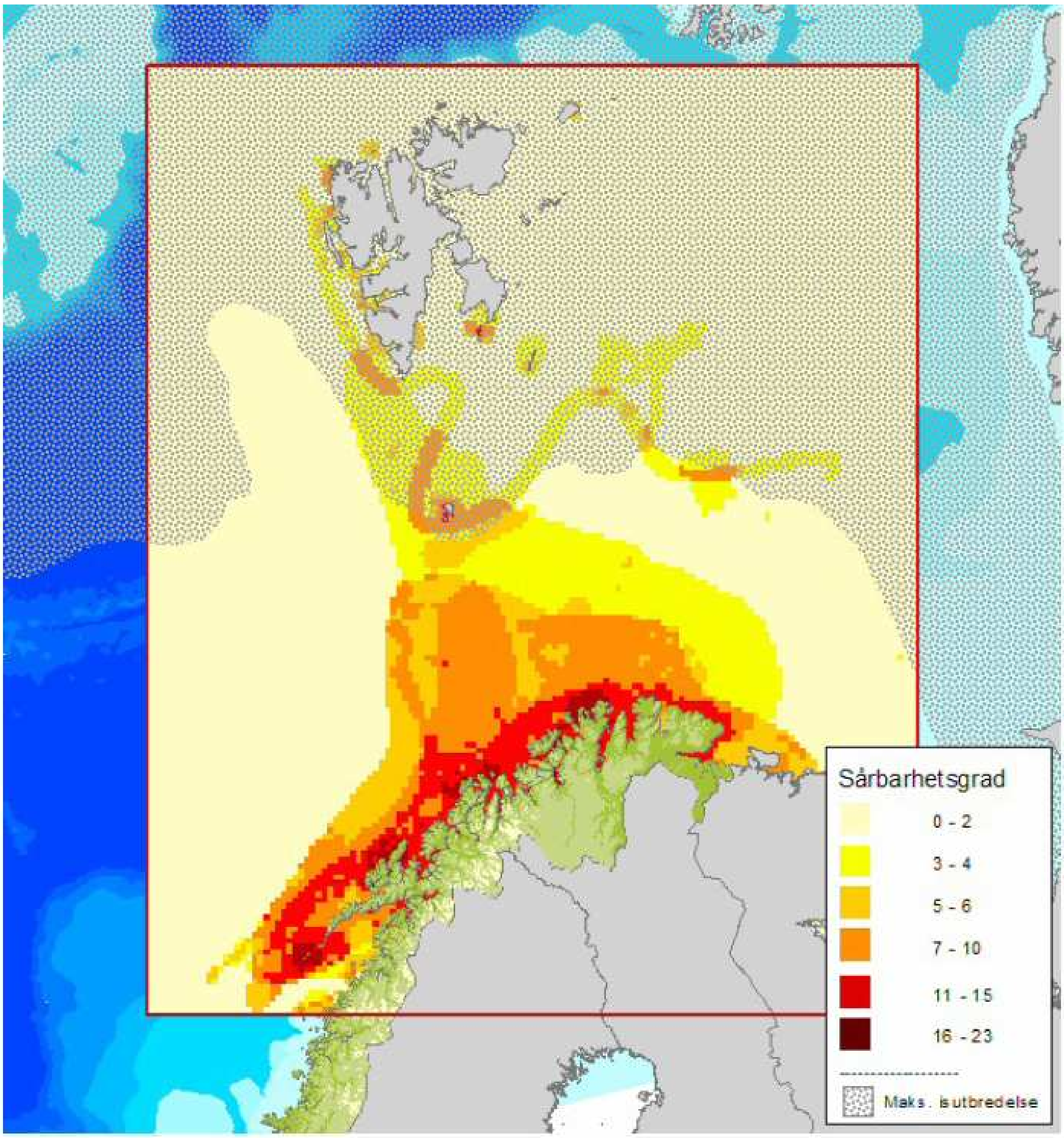


Figure 4-12: Vulnerability map for the Lofoten/Barents area (DNV, 2005)

4.9 Long-term effects on marine life

Knowledge about the long-term effects of oil and chemical spills is less developed than for acute effects, since it requires great efforts to measure them. While acute effects may be measured in a controlled environment with dose-response tests for lethality, long-term effects are often sub-lethal. The species affected will have to be monitored for years in their natural environment to assess the long-term effect from exposure to toxins (Beyer, 2011).

4.9.a Unweathered oil

The long-term effects of a spill may be viewed in different ways. One concern is the cases where a spill continues to display "acute" effects for years. This happens in cases where the spill is not weathered, and remains in its initial form for a long time. In such cases, the spill maintains its potential to stick to seabird feathers, disturb habitats and pollute shorelines (Short et al., 2001). An example of such long-term effects is seen from the Exxon Valdez incident in Prince William Sound, Alaska, in 1989. The oil tanker ran aground close to shore in the sound, releasing an approximate 40,000 tonnes of crude oil. Findings have shown that while the remaining surface oil is mostly weathered and almost asphalt-like, liquid oil still exists right below the surface. Disturbances such as storms or burrowing animals may re-deploy this oil into the sea, causing acute effects once again (Short et al., 2001).

Figure 4-13: Liquid oil spill in an excavated pit on an impacted beach. The picture was taken in 2001, 12 years after the Exxon Valdez incident (Short et al., 2001)

4.9.b Non-lethal effects

Knowledge about the chronic, non-lethal effects is less developed than for acute effects. This is also acknowledged in several reports, such as OSPAR's status and trends on marine pollution (OSPAR, 2009). However, OSPAR has defined some chemicals which are of particular concern with regard to chronic effects. These are primarily chemicals which possess one or more of the following abilities:

- *Bioaccumulation*
  - The chemical has the ability to accumulate in biota.

- *Persistence*
  - The chemical displays a low biodegradability, meaning that it is not easily degraded by natural processes in the environment.

- *Biomagnification*
  - The chemical has the ability to be brought upwards in the food chain, causing high concentration in predators and scavengers.

- *Carcinogenic effects*
  - The chemical has the ability to cause cancer in biota.

- *Endocrine disruption*
  - The chemical has the ability to disrupt the hormone system in biota. Xenoestrogens are the most common of these, and are able to replace the naturally occurring oestrogen in the organisms. Endocrine disruption may cause changes in development, behaviour and ability to reproduce.

The concerns about these properties in chemicals are appreciated in the Harmonized Offshore Chemical Notification Format (HOCNF), which is used to rank the toxicity of chemicals used offshore (OSPAR, 2003). The long-term goal is to phase out these chemicals altogether, but some of them are essential to industries, and satisfactory substitutes are yet to be found. Some of the chemicals are also naturally occurring, such as in crude oil. To monitor the development of chemical pollutants and increase the attention paid to them, OSPAR has also made a list of "priority chemicals" (OSPAR, 2009). For the oil and gas industry, two of these are of particular concern:

<u>PAHs (Polycyclic Aromatic Hydrocarbons)</u>

PAHs are natural components of coal and oil, and may be formed as by-products from incomplete combustion of carbon-containing fuels. PAHs are toxic, persistent and have the potential to bioaccumulate. Some PAHs are also known to be carcinogenic, meaning that they could cause mutations and cancer in biota (OSPAR, 2009).

<u>Alkylphenols</u>

Like PAHs, alkylphenols are natural constituents of petroleum and may also be present in produced water from offshore installations. They are also used for industrial purposes, such as emulsifiers, dispersing agents and tackifiers. Alkylphenols are toxic, and fill the OSPAR criteria for persistency and bioaccumulation. Some types are also suspected to be endocrine disruptors which induce sex change in male fish (OSPAR, 2009).

For crude oil and refinements, the PAHs and alkylphenols are the main concerns. Assessing the content of these compounds in oil is difficult, but toxins tend to stick with the heavier components in the oil (Beyer, 2011). This means that light oils will be more of a short-term concern, while heavy crude oil and bunker are more likely to cause chronic effects in the wildlife population. An illustration on how PAHs and alkylphenols affect fish is shown in Figure 4-14.

Besides the fact that chronic effects are somewhat related to the properties of the released oil, it will not be further evaluated in the E-CoF procedure in this thesis. Though it is an important subject, little is known about the effects and their consequences. This also makes it hard to quantify and use in an assessment. This view is shared by other environmental assessment models with much more detailed scope than this thesis, such as the method for environmental risk to fish, developed by DNV (2008).

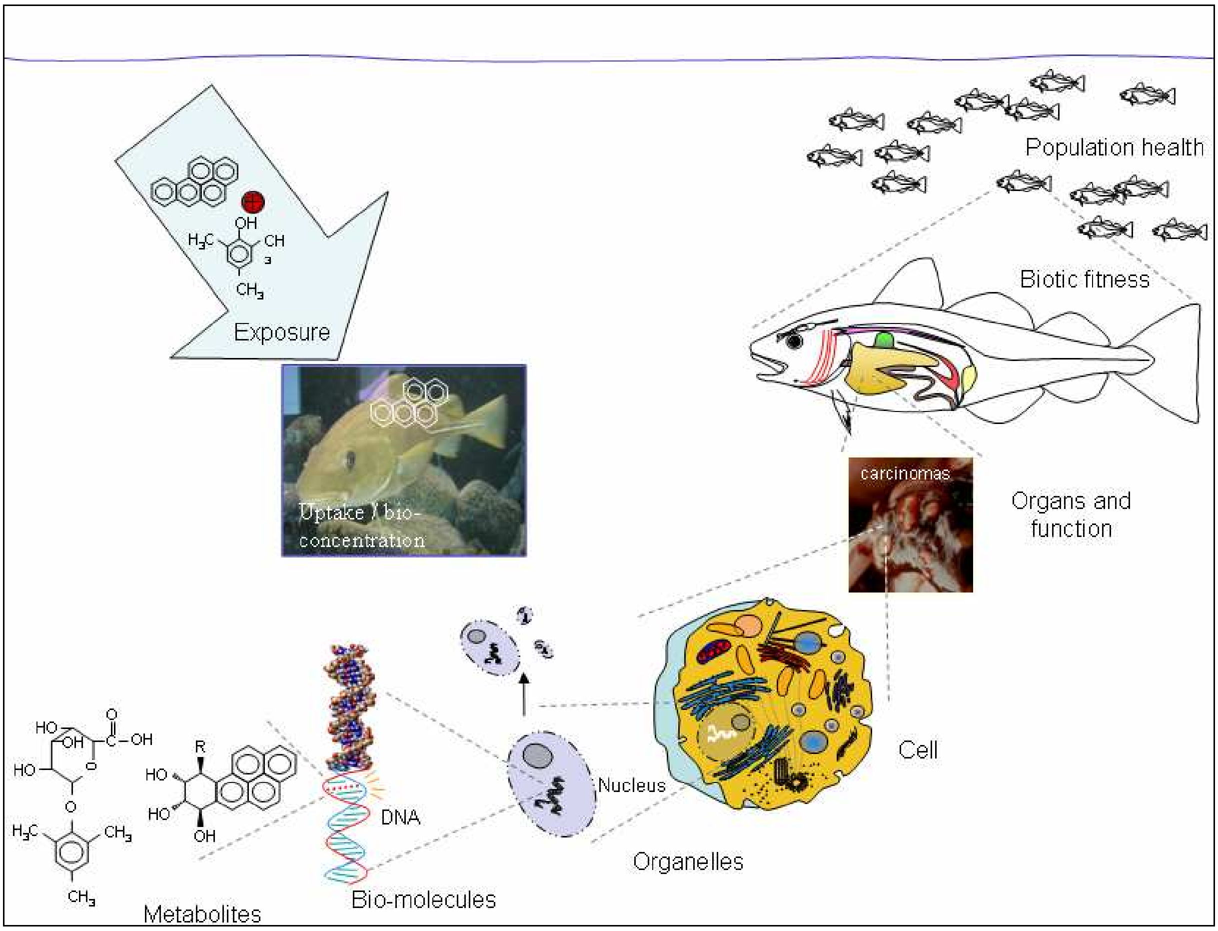


Figure 4-14: Illustration of how released chemicals may affect fish population. Toxins stick to the DNA in the form of DNA adducts, which could cause carcinogenic effects in the organism (Beyer, 2010)

4.10 Discussion of included factors

In this chapter, efforts have been made to identify the most important factors influencing the environmental consequence of a spill, along with a presentation. Since not all of the factors can be equally weighted in a simple procedure, background information is important in order to recognize the contribution and significance of the different factors.

It should be noted that the presentation given on each factor is very brief compared to the wealth of information and research available. Efforts have been made to point out the most important features on each of the factors, but some relevant information is bound to be left out when each factor is described as briefly as in this thesis.

Also, for area-specific factors, such as local environmental features and spill response, the presentation has focused on Norwegian conditions. Other parts of the world may have different topography and weather conditions, different rules, and other ways to approach oil spill response operations.

Despite the relatively brief presentation which has been made in this chapter, it is thought to be a good introduction to Chapter 5, which presents the procedure for putting the factors together to yield a consequence rating for E-CoF.

CHAPTER 5

Proposed Procedure for Assessing Environmental Consequence of Failure

5.1 Introduction

Assessment of the environmental consequence of a hydrocarbon release ideally requires a lot of specific data. However, this is usually not readily available, and also requires a lot of detailed knowledge to utilize in a proper way. This chapter presents a proposal for a simple procedure, using only a minimum of input data. Such an approach will naturally involve some assumptions and generalization. The challenge is then to balance the simplicity of the procedure with sufficient accuracy.

The idea is that the procedure should be flexible. This means that if the input data needed in a certain step is available from ready-made sources, it may be used directly. In cases where the required information is missing, it shall be possible to make a qualitative estimation. This is to be done by using known data which is combined with expert judgement and guidance from the procedure. Also, some of the steps which require great effort to collect data are only required to be done once for the whole platform. Hence, it is not necessary to complete the whole procedure over again for each loop in the RBI analysis.

This chapter will go through the factors and show the procedure step by step, and give explanations to the calculations as well as justification to the assumptions made.

It may be noted that some parts from the background theory are missing from the procedure; namely the weathering of oil and the long-term effects. The main reason for this is that these factors are very hard to predict even in detailed analyses. In a simple model, it would be almost futile to try and incorporate them. Despite these obstacles, the weathering and the long-term effects are important aspects in an environmental consequence assessment, and this should be acknowledged. The way this has been approached in the proposed procedure is to incorporate the factors into other steps.

The weathering of oil is actually included in most of the steps. In the initial release, the type of oil is considered. This also determines its fate in the environment, as various kinds of oil will display different behaviour when they reach the sea. The difference between light and heavy oil is considered in the first crossroad in the model. Further, the fate of the oil is important when assessing the probability for a shore impact, which is also a step in the procedure.

The long-term effects are even more difficult to assess than the fate of oil, and are left out even in detailed models such as DNV's method for environmental damage assessment on fish (DNV, 2008). Still, they are somewhat incorporated in the last step of the procedure, where the damage potential is weighted together with the volume of the spill. As light oils will have less long-term effects than the heavier ones, these are also given lower consequence ratings.

The E-CoF model for liquid hydrocarbons is divided into three parts:

- Initial considerations (Section 5.2.a)
- Light oils assessment (Section 5.2.b)
- Heavy oils assessment (Section 5.2.c)

The light and heavy oils assessments will share some common factors, which means that references will be made to the appropriate factor in the description.

The costs involved with an oil spill are treated in a separate procedure. This can be found in Chapter 6.

5.2 Overview of procedure

This section will show an overview of the procedure, in the shape of flowcharts. All calculations start with the initial considerations, shown in Section 5.2.a. After some basic calculations, the procedure is split into separate parts for light oils (Section 5.2.b) and heavy oils (Section 5.2.c).

In the flowchart, references are made to the explanation and guidance for each step. These can be found in Section 5.3. An explanation of the assigned consequences is given in Section 5.4.

5.2.a Initial considerations

All E-CoF assessments in the proposed procedure start with some common initial considerations. Knowledge about the spill is collected, as well as an estimation of the volume which will reach the sea. According to the oil type, reference is made to the procedures for light or heavy oil, respectively.

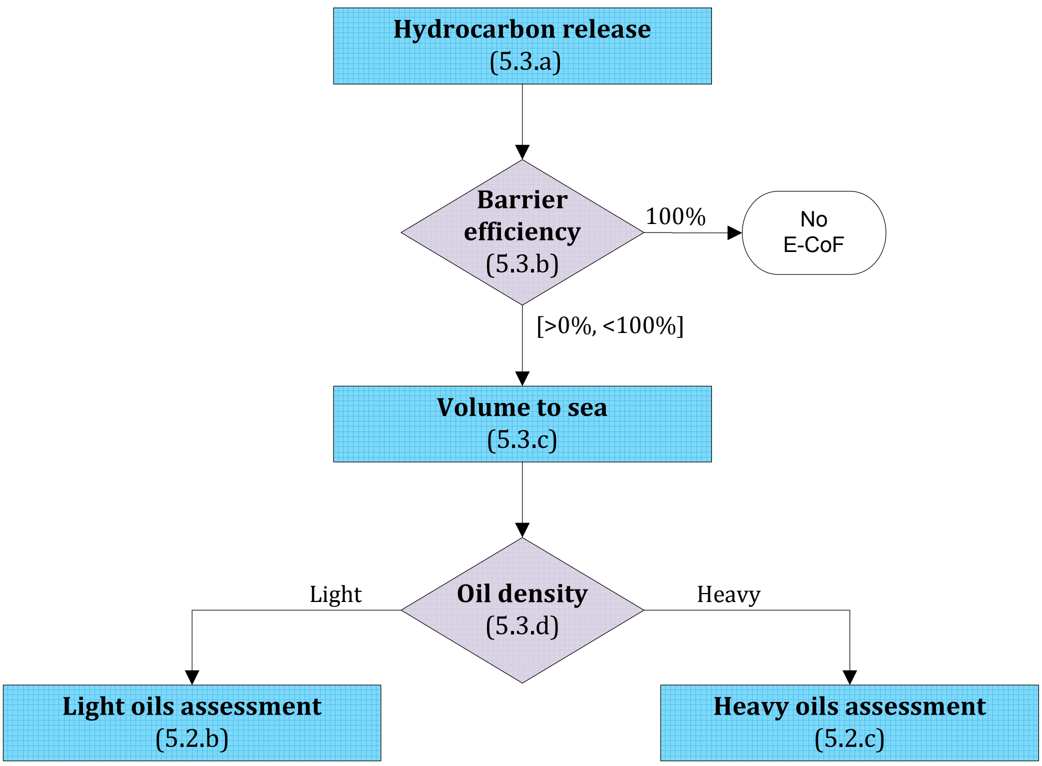


Figure 5-1: Initial considerations for a liquid hydrocarbon release

5.2.b Light oils assessment

If the released hydrocarbons are considered light, this procedure is used. As light oils are considered less harmful than heavier ones, the procedure is somewhat simpler than for heavy oils. Also, probability of oil spill response or shore hit is neglected. More about this can be found in Section 5.3.d.

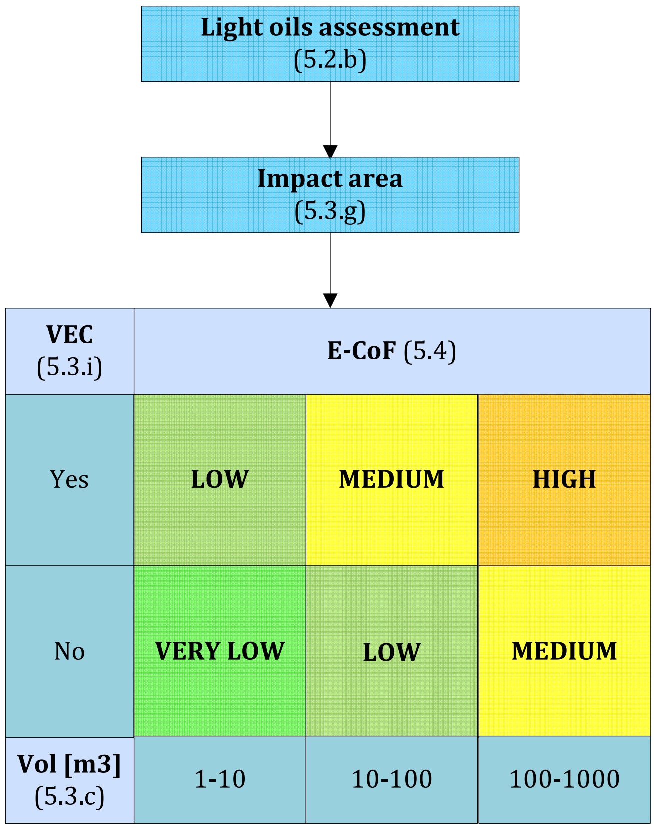
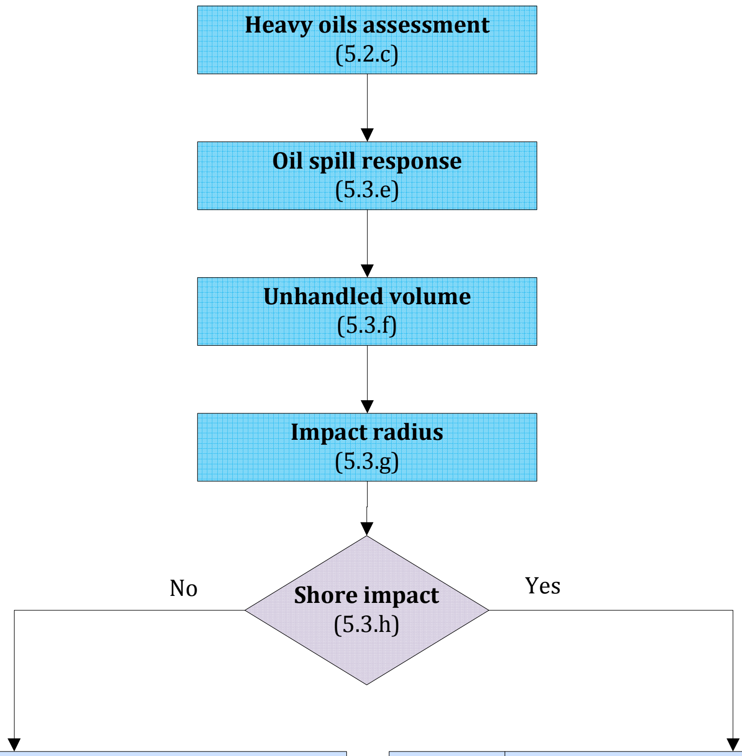


Figure 5-2: Procedure for E-CoF assessment on light oils

5.2.c Heavy oils assessment

As described the theory in Chapter 4, heavy oils represent more of a threat to the environment than lighter oils. In addition, there is a greater chance of shore impact due to the reduced weathering and increased persistency of heavy oil. Oil spill response possibilities are also included in the heavy oils assessment.



VEC (5.3.i)	**E-CoF** (5.4)		
Yes	**LOW**	**MEDIUM**	**HIGH**
No	**VERY LOW**	**LOW**	**MEDIUM**
Vol [m3] (5.3.f)	1-10	10-100	100-1000

VEC (5.3.i)	**E-CoF** (5.4)		
Yes	**MEDIUM**	**HIGH**	**VERY HIGH**
No	**LOW**	**MEDIUM**	**HIGH**
Vol [m3] (5.3.f)	1-10	10-100	100-1000

Figure 5-3: Procedure for E-CoF assessment on heavy oils

5.3 Guidance and explanations for steps in the procedure

This section will explain how each step in the procedure should be handled. The number of each part corresponds with the numbers stated in each box in the flowcharts in Section 5.2, to provide an easy reference.

Each step in the procedure is given its own description in Section 5.3, and some have several methods to estimate or calculate a parameter. At the end of each step, the requirement for output from the step is stated. This indicates the information which must be obtained before moving on to the next step in the procedure.

5.3.a Hydrocarbon release

The procedure starts with assessment of the liquid hydrocarbon spill. It is assumed that the released volume and its properties are already known at this stage; hence, this procedure does not deal with considerations regarding hole size and leak rates. For details on how to calculate the release volume, reference is made to the works by Chen (2010).

In addition, it is assumed that the location of the spill is known; i.e. where on the platform the hydrocarbons are released. This is important information for evaluating the effectiveness of barriers, and the volume which will ultimately reach the sea.

Output from step 5.3.a:

- Volume (m^3)
- Location on the platform/installation
- Properties of the oil, most importantly its density

5.3.b Barrier efficiency

Barriers in this context refer to the physical installations on the platform which is designed to prevent a spill from reaching the sea, such as drains and spill trays. As long as a spill is contained on deck or in drain systems, it will not pose a threat to the environment.

In the E-CoF assessment procedure, barriers are weighted by how much of the released volume they are able to contain. Platforms have different kinds of drains, with varying capacity. In addition, the drains may have such a layout that some parts of the process area are better covered than others. Hence, it is not possible to give a general solution as to how barriers should be treated in the procedure.

If details on the drain system are easily available, these may be utilized to check the capacity for the area in question. As the emergency shutdown (ESD) segments for CoF evaluation are often limited in size, it is likely that the specific barrier capacity in the area can be found. However, if there is any doubt that the barriers are able to catch the release, conservative values should be used.

It is worth noting that this E-CoF assessment procedure is limited to acute spills, with an assumption that the whole volume will be released almost at once. In reality, the spills will be released over a certain time span, depending on the leak rate from the hole. Hence, both the total capacity of the barriers and their rate of uptake should be considered.

As an example, consider a spill of 100m^3. The barriers have the capacity to contain it all, but the uptake rate to the overflow tank from the trays is maximum 5m^3/min. This means that if the 100m^3 was released quickly, the drain would have been unable to stop the majority of the leak from hitting the sea. It could also be the other way round; the drain could have handled the rate, but not the volume. This would also have caused a certain amount to reach the sea.

These considerations should be kept in mind when assessing the effectiveness of the barrier system. If there are no barriers in the area, or if no information is available, the effectiveness should be set to zero. If, however, the barriers are highly likely to contain the whole spill, no hydrocarbons will reach the sea. The spill will then not be considered an environmental threat, and the E-CoF may be neglected.

Output from step 5.3.b:

- Reduction of the initial release (m^3)

5.3.c Volume to sea

The next step in the model is calculating the volume into the sea. This is calculated by deducting the volume caught by the barriers from the volume released, as shown in Eq. 3:

$$V_{SEA} = V_{RELEASED} - V_{BARRIERS} \tag{3}$$

In the E-CoF assessment procedure, only the volume released to sea will be considered. The contained spill on the platform may potentially be a safety hazard, but this will not be covered by the procedure. Hence, it is the volume released to sea which will be significant for the rest of the assessment.

Output from step 5.3.c:

- Volume of oil released to sea (m^3)

5.3.d Density

The first crossroad in the proposed procedure is dividing the spill into either light or heavy oil, as this has a significant impact on its adverse environmental effects. While light oils often contain very toxic substances such as benzene, toluene, ethylbenzene and xylene, they are also very volatile and evaporate quickly (Beyer, 2011). Heavy oils, on the other hand, are less toxic. Still, they often pose a greater threat to the environment, as they have the ability to persist for much longer and are likely to contain compounds such as PAH and alkylphenols, which were described in Section 4.9.b.

There are also other reasons to divide the hydrocarbons based on gravity. As light oils are weathered quickly, no oil spill response will usually be initiated (White, n.d.). In the procedure, an assumption is also made that light oils will not hit shore. This is an approximation, but it will be valid for most of the spills from platform topsides as light oil spills are unlikely to last more than a few days before they are weathered (Fingas, 2001). The assumption of no shore impact is also supported by the fact that the volumes considered in the model are small.

Density of oil is usually denoted in one of two ways. The first is to use its specific gravity (SG) compared to water at 15.5° Celsius (60° Fahrenheit). However, the API degrees (°API) have also become a known standard. The °API notation is an inverse scale, meaning that low density oil will receive a high °API grading. These two notations are related in the following way (API, 2002b):

$$API\ gravity = \frac{141.5}{SG} - 131.5 \qquad (4)$$

$$SG = \frac{141.5}{API\ gravity + 131.5} \qquad (5)$$

Determining what is a light or heavy oil is not an exact science. There are several suggestions regarding this in literature, and some sources also use further categories such as “extra heavy” and “extra light”. In the environmental context, the most important attribute is whether the oil is persistent or not. A critical limit can be set at a density of 0.85 (Robertson et al., 1997). Oils with a higher density than this will be more persistent and the natural degradation will take longer. This definition also corresponds with Figure 4-5, where groups 1-2 will be considered “light” and groups 3-4 “heavy”. Converted to °API, a density of 0.85 will be 35° API.

Two methods are suggested for oil classification:

Method 1

- Simple assessment based on specific gravity or °API

Light oils	Heavy oils
Specific gravity < 0.85 @15.5°C (60°F) °API > 35	Specific gravity > 0.85 @15.5°C (60°F) °API < 35

Table 5-1: Definitions of light and heavy oil

Method 2

- Advanced assessment based on oil properties

If details regarding the properties of the oil and its behaviour are readily available, this may be utilized to get a more correct picture. As an example, light oil with a high wax content will often display the behaviour of heavier oil (Fingas, 2001). Such oil could then be placed in the “heavy” category even if its specific gravity suggests otherwise. Other properties which may influence the fate and behaviour of the oil are its water uptake ability and viscosity.

The result from the oil density evaluation will decide which flowchart to use next. The options are:

- Light oils assessment (Section 5.2.c)
- Heavy oils assessment (Section 5.3.c)

Output from step 5.3.d:

- Classification of released oil: either as light or heavy.

5.3.e Oil spill response

An oil spill response action has two basic purposes:

- Collecting as much oil as possible before it can do any harm, thus minimizing the environmental impact
- Preventing the spill from reaching fragile areas such as shores and habitats

As the proposed E-CoF assessment procedure is intended as a general procedure, it does not differentiate between different times of year. Oil spill response will be hampered by bad weather and high waves such as winter storms, but these conditions will have to be evaluated on a general basis.

In Section 4.7, the barrier principle used by NOFO was described. In Norwegian waters, the response system is usually sufficient to set up all barriers within reasonable time limits. Hence, the effectiveness of the oil spill response can be estimated on a system level, with a formula provided by NOFO (OLF/NOFO, 2007):

$$\textit{System efficiency} = (\alpha * (87 - 9.80 * H_S)) + ((1-\alpha) * 0.65 * (87 - 9.80 * H_S)) \qquad (6)$$

where:

α = Fraction of operational light within a 24h period (decimal, e.g. 0.5 for 12 hours of light)
H_s = Significant wave height (m)

Based on practical oil-on-water exercises, it is estimated that the boom loss is minimum 20%. Hence, the maximum system efficiency shall be set to 80% if the formula yields a value above this (OLF/NOFO, 2007).

A requirement for using Equation 6 is that the first barrier is set up before the oil spreads out in a large area. No precise time limit is set for this due to the various drift scenarios on the fields, but around three hours seems fair to assume based on a review of environmental risk and response assessments (Revus Energy/DNV, 2008; ENI Norge/DNV, 2006).

If barrier 1 cannot be established within this time frame, efforts must be made to set up barrier 2 instead. The second barrier should be in place within 6-12 hours, and will have approximately 50% of the efficiency of barrier 1 (OLF/NOFO, 2007). Hence, the result from the given efficiency formula must be divided by two.

To estimate whether the necessary response assets are close enough to set up the barriers within the given time limits, NOFO has provided guidance for estimating response time, found in Table 5.2.

Travel time	When calculating travel time, a speed of 14 knots should be assumed. In cases where specific vessels are used for emergency preparedness, vessel-specific values may be utilized.
Unloading	An unloading time of six hours should be the basis of all vessels at a NOFO base.
Preparation	A preparation time of four hours should be the basis of all vessels at a NOFO base.
Travel time to NOFO base	For NOFO bases with more than one system, it is assumed that one system is at the base, one system is within six hours from base, and another is within 12 hours from base.
Area emergency preparedness	Area response vessels will be mobilized immediately when needed.

Table 5-2: Presumptions for assessing response time (OLF/NOFO, 2007)

Within reasonable distance from well developed areas, there will usually be response vessels on site in time for the first barrier, or at least the second one. This is due to the large number of response vessels found in the Norwegian Sea. For distant areas, such as the Arctic, this may not be the case. Area-specific considerations must then be taken into account.

In this procedure, barriers 3 & 4 will not be evaluated. The effectiveness of these is hard to estimate, and their main purpose is to prevent the oil from reaching fragile and coastal areas. Hence, the amount of recovered oil will depend just as much on priorities as the actual capacity.

Two methods are suggested for estimating oil spill response effectiveness:

Method 1:

- Reference-based approach

Use analyses from nearby fields to yield a representative estimate of oil spill response effectiveness.

Method 2:

- Semi-quantitative estimation of recovery using the following steps:
    1. Find the response time of the nearest vessel, using information from NOFO web pages (NOFO, 2011) and Table 5-2.
    2. Find appropriate values for α (operational daylight) and H_s (significant wave height) in the area. This may be obtained from NOFO web pages (NOFO, 2008b), or from meteorological data. As daylight and wave height will change according to seasons, conservative values should be used.
    3. Find recovery rate based on first successful barrier, based on Table 5-3.
    4. Estimate whether oil spill response preparedness will be able to prevent oil from reaching fragile areas (where applicable).

First successful barrier	Recovery rate
Barrier 1	According to Equation 6
Barrier 2	50% of the result from Equation 6
Barriers 3 & 4	No recovery expected, but evaluate whether shore impact may be avoided.

Table 5-3: Overview of expected recovery rate based on first successful barrier

Output from step 5.3.e:

- Determine recovered oil volume from surface (m^3)
- Determine whether oil spill can be prevented from reaching fragile areas (if applicable)

5.3.f Unhandled volume

The calculation of unhandled volume is done by simply deducting the recovered volume from the oil spill response from the volume released to sea. As described in Section 5.3.e, the maximum recovery from response equipment is 80%. Hence, at least 20% of the release volume must be assumed to bypass the recovery attempts, even in ideal conditions.

$$V_{UNHANDLED} = V_{SEA} - V_{RECOVERED} \quad (7)$$

Output from step 5.3.f:

- Determine unhandled volume from oil spill response operations

5.3.g Impact area

Determining where the oil is likely to spread is crucial for determining the E-CoF. The main reasons for this are:

- The need to evaluate whether the oil will hit shore
- The need to evaluate whether there are any valuable ecological resources (VECs) within the impact area

Determining which path the oil will take is not an easy task, as it is heavily influenced by factors such as wind, current and wave action. Usually, the oil drift is assessed by the use of computer modelling, as described in Section 4.6.

Where available, computer simulations are the preferred means for predicting oil slick movement. However, as conducting such a simulation is quite resource-demanding, it may not be applicable for smaller spills. A more qualitative approach is then needed to provide a rough estimate of the probable impact area of the oil.

Two methods are suggested for estimating the impact area of the spill:

Method 1:

- Reference-based approach based on existing oil drift simulations

If oil drift simulations are available, these can be used to assess the probability of hitting shore. In addition, they may be beneficial to establish where the oil is likely to get stranded. The simulation should preferably be from the field in question, but simulations from nearby fields with similar wind- and current conditions may also be utilized.

As oil drift simulations are often made on the basis of worst-case scenarios, the volumes are usually significantly higher than those found in the RBI analysis. This means that the whole simulation must be "down-sized" to fit the amount in question. In rare cases, the computer program may be available and ready for editing, and the amount may be put in directly and processed. This is, however, unlikely in an RBI context, unless the amounts are high and the shore is close and vulnerable.

In most cases, the simulations must be "down-sized" in a qualitative way. This could be done by looking at the volumes and results from the available simulations, and comparing these with the release volume in question.

Method 2:

- Calculation based on release volume and oil film thickness

The Norwegian oil spill response organization NOFO offers a simpler means of calculating the impact area of a release (NOFO, 2008c). A volume formula is used, which gives the impact area as a function of release volume and the oil film thickness (Eq. 8).

$$A_{IMPACT} = \frac{V_{RELEASE}}{t_{OIL\ FILM}} \quad (8)$$

where:
A = Impact area [m^2]
V = Release volume [m^3]
t = Oil film thickness [m]

In this proposed procedure, the unhandled volume to sea is already known from Section 5.3.f. However, a film thickness must be assumed for the formula to work. In an analysis of a hypothetical spill of 1,500 barrels of oil in Cook inlet, Alaska, the oil film thickness was simulated over time by the use of SINTEF's oil weathering model (Prentki et al., 2004). The initial thickness was calculated to 2.3mm, which reduced to 1.3mm after three days and finally to 1.0mm after ten days. The simulation was conducted for a summer season spill originating from a platform topside, and hence it is considered as representative for a typical release evaluated in RBI.

Based on the above analysis, a film thickness of 1mm will be assumed for the impact area estimations. Further, it is assumed that a radius from the spill origin will be more helpful to analysts than an area given in km^2. Hence, the impact area will be given as radius from the source in this guidance.

The radius is found by reversing the area formula of a circle, giving the radius as:

$$r = \sqrt{\frac{A}{\pi}} \quad (9)$$

However, it must be kept in mind that a spill will rarely be formed as a circle around its origin, as discussed in Section 4.6.a. Based on the wind and current, the released oil is likely to form quite a thin line, as illustrated in Figure 5-4.

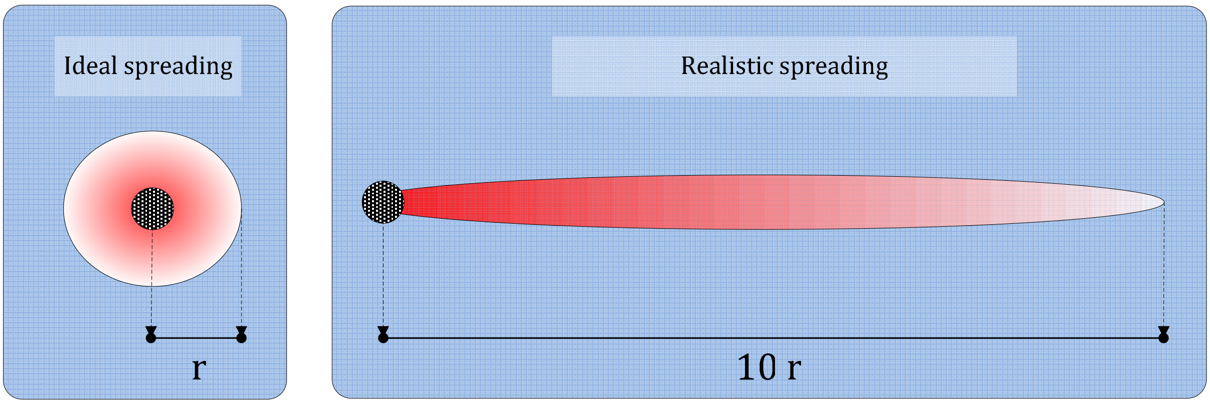


Figure 5-4: Illustration of ideal spreading of an oil slick vs. realistic spreading

This is solved in this procedure by multiplying the radius with a factor of 10 to obtain a safety margin. The factor of 10 is an assumption, but it seems a fair estimate based on a selection of existing drift models (ENI Norge/DNV, 2006; Revus Energy/DNV, 2008; StatoilHydro/DNV, 2008). This yields the impact radius from the output as a function of release volume, shown in Figure 5-5.

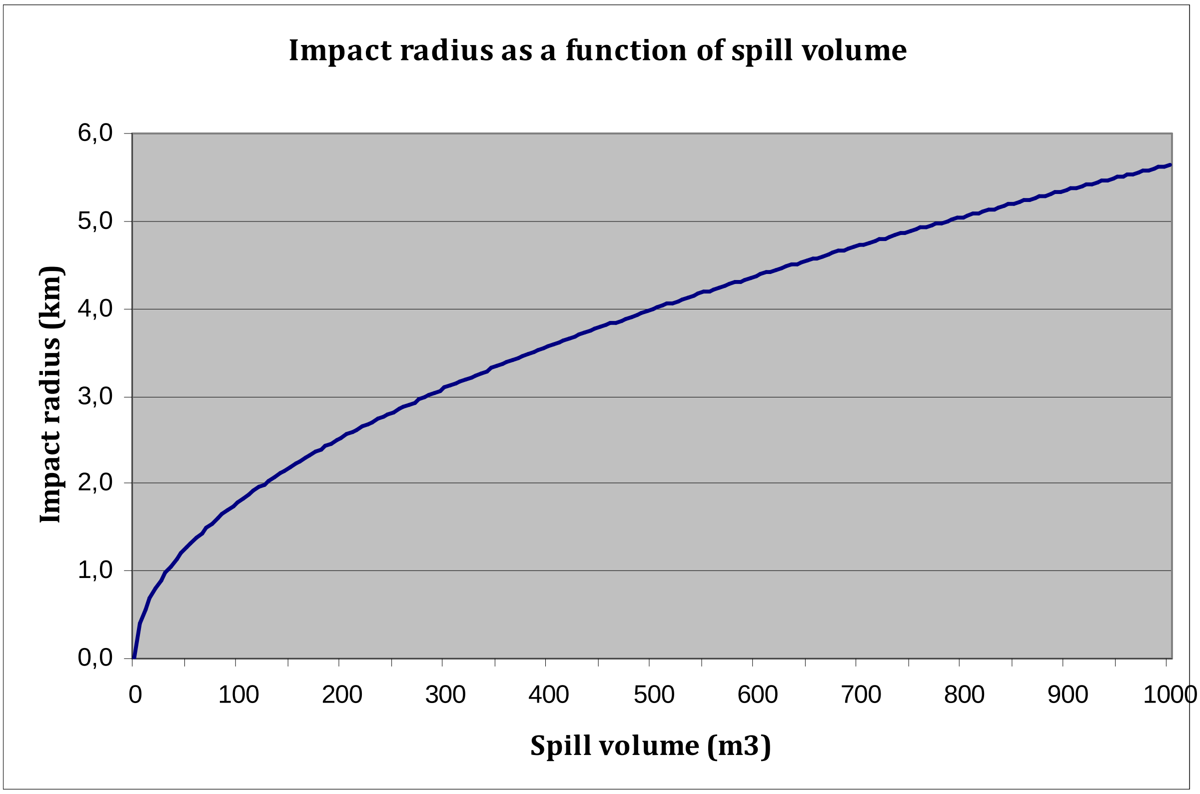


Figure 5-5: Impact radius as a function of spill volume

Output from step 5.3.g:

- Determine the impact radius from spill site

5.3.h Shore impact

The assessment of possible shore impact is conducted by comparing the spill impact radius to the distance to shore. If the distance to shore is shorter than the radius, shore impact should be considered a possibility. If detailed knowledge regarding local wind- and current conditions is available, qualitative judgement may be used to yield a more accurate result.

Output from step 5.3.h:

- Determine whether the spill is likely to hit shore (Yes/No)

5.3.i Valuable ecological components in area

Valuable Ecological Component (VEC) is a term taken from the MIRA method described in Section 3.5. The purpose of VEC is to have a standardized method for selecting important natural resources.

From MIRA (DNV, 2007), a VEC is defined as a resource or environmental feature which:

- Is important for the local population, or
- Has a national or international interest, or
- If changed, will impact how the environmental effects of the analysed asset are viewed, and which kind of mitigation measures are used

Some features of a VEC are also listed in MIRA (DNV, 2007):

- A VEC is a population or stock, a society or a habitat
- A VEC must have a high sensitivity for oil pollution (year around or seasonal)
- A VEC must be represented in large numbers in the influence area
- A VEC must be present at most times of the year
- A VEC must have a high probability of being exposed to the oil

In practice, a VEC is often related to breeding grounds for fish or nesting colonies for seabirds. Most species tend to have their favourite places for breeding, and hence they are gathered in great numbers at such locations.

It should, however, be noted that some species may roam in great distances from the breeding place in search of food. While some common birds such as eider will normally hunt for food in the coastal areas nearby, some pelagic birds may be found more than 100km out at sea from their breeding colonies (BG Norge, 2010). Similar behaviour may be expected from marine mammals as well, and this should be considered when assessing VECs in the impact area.

Three methods are proposed to gather information regarding VECs in the area:

Method 1:

- Consulting local authorities for information about vulnerable species and habitats

Local authorities are likely to possess some information regarding VECs in the area. Hence, they may be able to assist in the pursuit for relevant information.

Method 2:

- Utilization of map resources

Maps which show the location of the most important VECs along the coast are available for Norwegian waters. Several interactive maps of this kind are available through NOFO's web pages (NOFO, n.d.)

Method 3:

- Reference-based approach

If an environmental consequence assessment has previously been carried out in the same area, results from this analysis may be used to identify possible VECs. However, the impact area of the spill must be considered, as existing E-CoF assessments are often based on much larger spills than the volumes considered in this procedure.

Output from step 5.3.i:

- Determine if a VEC is present in impact area (Yes/No)

5.4 Consequence rating for environmental consequence of failure

The end of the procedure yields a consequence rating based on the input factors, as seen in the flowcharts presented in Section 5.2. There are five different consequence ratings:

- Very low
- Low
- Medium
- High
- Very high

Dividing into five different categories has been chosen as it corresponds with existing DNV practice (DNV, 2009) as well as several other practices. MIRA (DNV, 2007) uses four different ratings for the consequences.

A significant difference, however, is that the likes of DNV recommended practice and MIRA give an explanation for each rating. As an example, DNV describes the "low" consequence as a "minor local effect" (DNV, 2009). MIRA, on the other hand, uses restitution time as a basis for the ratings.

The E-CoF in the proposed procedure lacks this explanation for each rating, as no requirements for each consequence rating have been given. This is a common problem for environmental consequence assessment compared to safety and economics, which has established units such as Fatal Accident Rate (FAR) and monetary values to lean on. After all, the definitions in DNV recommended practice are rather vague as well, as "minor local effect" can be defined in many ways.

The following reasoning is behind the choice for consequence ratings in this proposed procedure:

- ***The whole spectrum of consequence rating is used***
  - Even though events such as blowouts will lead to higher E-CoF than any scenario in the RBI context described, the whole spectrum from "very low" to "very high" has been used. Hence, "very high" E-CoF will indicate a major consequence in the context of topside leaks.

- ***The consequences are balanced in relation to each other***
  - Even though no firm justification can be given as to why a certain E-CoF has been assigned to its rating, they are balanced in relation to each other. As an example, it can be shown from the theory and calculations in the procedure that a "high" E-CoF is in fact worse than a "medium".

Based on the given reasoning, the consequences have been assigned according to best knowledge. However, the consequence classes may be adapted to reflect their significance compared to other possible events, such as safety consequences, economy and larger spills.

CHAPTER 6

Proposed Procedure for Cost Estimation

6.1 Introduction

Traditionally, E-CoF has often been calculated in monetary values (DNV, 2009; API, 2002a). This thesis has aimed to put more emphasis on the environmental values, by neglecting the cost term in the proposed procedure. However, the need for cost estimation should be recognized, as a spill may in fact have severe consequences on the economy of a company. Also, calculating cost brings a familiar unit into the considerations. Using cost to estimate E-CoF makes it easily comparable to other consequences, and the monetary unit should be well known to everyone.

This chapter presents a procedure which aims to work as a guideline when estimating the cost from a liquid hydrocarbon spill. As it is difficult to compare cost and environmental harm, this procedure has been made independent of the actual E-CoF assessment procedure. However, a matrix is provided in Section 6.4 to combine the result from the two procedures into a common E-CoF rating.

It should be noted that the costs estimated in this chapter are not the same as the “business” consequence category in the DNV recommended practice (2009). The business consequence is concerned with loss due to downtime, repairs etc., while the cost in this context refers to expenses which are directly related to a hydrocarbon spill.

The currency selected for the cost estimation procedure is Euro (€), as this complies with DNV recommended practice (2009). For volumes, cubic metres (m^3) will be used. Where the sources for calculations use tonnes (t), these will be directly translated to m^3 in a 1:1 ratio. This is an approximation, but it will be considered valid as most oils are close to such a ratio. It also prevents further complication of the procedure.

6.2 Factors determining the cost of a spill

The factors included are based on the practices from DNV (2009) and API (2002a), and the following have been selected:

- Clean-up costs (Section 6.2.a)
- Fines and penalties from authorities (Section 6.2.b)
- Loss of product (Section 6.2.c)
- Compensation for damage to commercial interests or recreational grounds (Section 6.2.d)

An important factor, which has not been included in this chapter, is the loss of reputation which a company may experience after being involved in an incident. Though the volumes considered in this thesis are small, media coverage and investigations may put the responsible company in the spotlight after a spill. Possible effects are loss of contracts, decrease in stock prices and a general reputation loss among the public. These effects should not be underestimated, but they are difficult to quantify in terms of financial value. For this reason, loss of reputation is not included in the cost estimation. However, the effect will often tend to be proportional with the environmental harm. Hence, an incident with a severe environmental consequence will often lead to a severe loss of reputation.

6.2.a Clean-up costs

The clean-up costs are arguably the greatest financial concern after a spill. A large number of vessels, specialized equipment and manpower are needed in the effort to minimize the damage from releases into the sea, and the cleaning may last for weeks or months. The costs could easily reach millions of Euro; a substantial amount even for the largest of companies. However, a successful clean-up could potentially reduce the consequences for wildlife. Also, a good cleaning effort could limit the other economic consequences.

The problem with clean-up cost, however, is that it is very complex to predict in advance. ITOPF (n.d.) states that "Various technical factors in combination determine the actual costs of any particular incident and simplistic comparisons between different events based on a single parameter such as quantity of oil spilled can be highly misleading" . In other words, the potential clean-up cost of spills cannot be predicted from single parameters. Two factors still seem to stand out as decisive for cost: density of the spilled oil and proximity to shore. Denser oils will be more persistent and harder to clean, and spills which reach the shoreline will always complicate the clean-up process and increase the severity of the spill (ITOPF, n.d.).

The DNV recommended practice (2009) suggests that the clean-up costs may vary between $700 and $50,000 per tonne released, with a conservative estimate of $10,000 per tonne for use in rough estimates. Based on this, the proposed estimate per m^3 of oil in this procedure is €7,000.

If more details are known about the spill response cost in the area, or if the installation is located in remote areas, the cost per m^3 may be adjusted to reflect the actual expenses.

Output from step 6.2a:

- Use a cost of €7,000 for each m^3 of spilled oil

6.2.b Fines and penalties from authorities

A company which is responsible for an oil spill release is likely to be fined by the local authorities. The size of the fine will probably depend on the circumstances of the spill, as well as the released volume.

To estimate a cost per unit released, research has been carried out to find suitable examples in the Norwegian offshore industry. As there have in fact been very few incidents with larger accidental spills, the data set is small. Still, there is a certain correlation in the cost per m^3 from the found examples, as shown in Table 6-1 and Figure 6-1. Based on this, a fine of €750 per m^3 of spilled oil is considered a fair estimate.

Location, year	Release volume	Size of fine	Fined amount in €/m³
Draugen, 2003	750 m^3	NOK 4,000,000	€ 678
Norne, 2005	340 m^3	NOK 2,000,000	€ 747
Statfjord A, 2007	4,400 m^3	NOK 25,000,000	€ 722

Table 6-1: Examples of some releases from Norwegian platforms and the corresponding fines (Dagsavisen, 2007; Ree, 2009; Bjørheim, 2010)

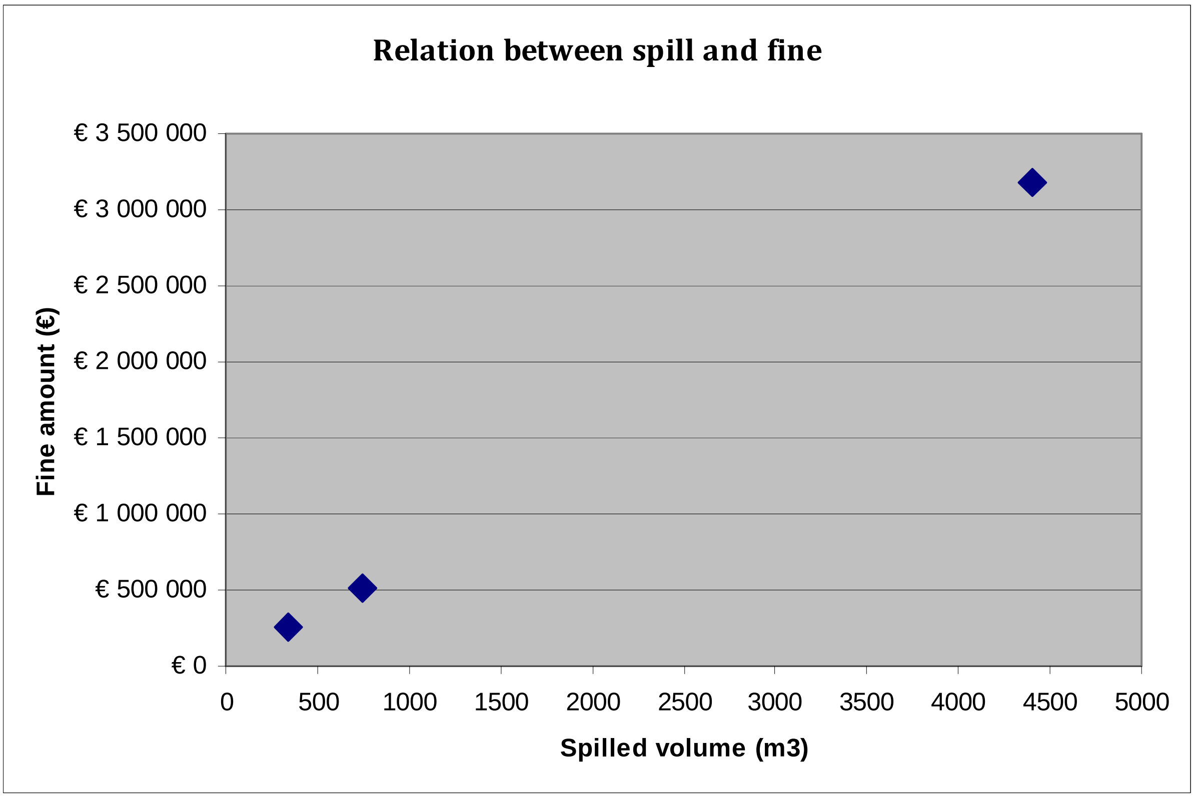


Figure 6-1: Plot showing the relation between spill and fines. The dots represent the data from Table 6-1, and show a certain correlation between spilled volume and fined amount.

Output from step 6.2.b:

- Use a cost of €750 per m^3 of spilled oil

6.2.c Loss of product

The hydrocarbons which are released during a spill are considered lost, along with their value to the owners. Hence, a cost may be calculated by multiplying the value of the product per m^3 with the release volume.

Output from step 6.2.c:

- Use the value of the spilled oil in euro (€) per m^3 of spilled oil

6.2.d Compensation for damage to commercial interests or recreational grounds

Damage to commercial interest such as fish farms, important fishing grounds and shore facilities is likely to trigger a claim for compensation. Besides the claims from private companies, the authorities may also decide to fine pollution of recreational areas, such as public beaches. Fishing vessels may have their equipment damaged by oil, but a more serious concern is the tainting of fish from oil or chemical spills. “Tainting” is defined by OSPAR as “the ability of a substance to impart a foreign flavour or odour to the flesh of fish or shellfish” (OSPAR, 2003). Tainting in fish is not necessarily harmful for the fish or consumers, but it will still not be accepted by customers. Hence, fishing in the area may be halted for several years, leaving the fishermen unemployed. If large fish stocks are affected, the compensation claim may be substantial.

The cost of such compensation claims is hard to predict, as it varies with the characteristics of the area. An approximate value can be found by comparing the impact radius of the spill with commercial and public interests in the area, and estimating a conservative value for compensation.

<u>Output from step 6.2.d:</u>

- Estimate a compensation cost in euro (€) for the impact area of the spill

6.3 Consequence rating based on cost

Based on the reasoning in Section 6.2, Equation 10 is suggested to calculate the costs involved with an oil spill:

$$E - CoF\ Cost = (V_{RELEASED} \times (C_{CLEAN-UP} + C_{LOST\ PRODUCT} + C_{FINES})) + C_{COMPENSATION} \qquad (10)$$

The currency selected in the procedure is Euro (€), to comply with existing DNV practices.

When a value has been estimated, this can be assigned to a consequence rating based on the DNV recommended practice (2009). The categories are taken from the “business rating”; i.e. the consequence classification normally used for costs involved with a breakdown.
Five categories are given:

Very low - <€ 1.000
Low - < € 10,000
Medium - < € 100,000
High - < € 1,000,000
Very high - <€ 10,000,000

6.4 Combining consequence ratings for environmental damage and cost

A common problem for E-CoF assessments is that they cannot be directly compared to cost. While cost is measured in € or another known currency, E-CoF does not have a common unit to rely on. In this thesis, the costs related to oil spills have been treated separately from the actual E-CoF assessment.

Since both are divided into five different consequence categories, this allows a certain comparison between them. RBI analyses often use the principle of applying the worst consequence in calculation. Hence, if the E-CoF is worse than the safety consequence, E-CoF will be decisive for determining inspection intervals. This principle could also be applied in an E-CoF context, where the environmental consequence and the corresponding cost could be compared and the most severe one applied. Another suggestion is to combine the two in a matrix. This will allow contributions from both consequences to be highlighted. A suggestion for such a combination matrix is shown in Figure 6-2.

E-CoF	**Total E-CoF including cost**				
Very high	**VERY HIGH**	**VERY HIGH**	**VERY HIGH**	**VERY HIGH**	**VERY HIGH**
High	**HIGH**	**HIGH**	**HIGH**	**HIGH**	**VERY HIGH**
Medium	**MEDIUM**	**MEDIUM**	**MEDIUM**	**HIGH**	**VERY HIGH**
Low	**LOW**	**LOW**	**MEDIUM**	**HIGH**	**VERY HIGH**
Very low	**VERY LOW**	**LOW**	**MEDIUM**	**HIGH**	**VERY HIGH**
Cost	Very low <€1,000	Low <€10,000	Medium <€100,000	High <€1,000,000	Very High <€10,000,000

Figure 6-2: Matrix for combining E-CoF and cost from spills

CHAPTER 7

Conclusions

This thesis presents the study carried out to develop a new procedure for assessing the environmental consequences of failure (E-CoF) on static process equipment. Existing procedures are either incomplete or inaccurate, or they are too comprehensive and data-intensive to be applied in an RBI setting. Hence, there is a need for a simple procedure which also has the ability to yield reliable results.

In this thesis, a literature study has first been carried out to review the existing practices and models on the subject. The most important factors affecting environmental consequence have then been identified and discussed.

Based on the identified factors, an assessment procedure for E-CoF is suggested. The procedure is presented in the form of flowcharts for clarity, with a reference in each step pointing to a guideline for assessment and calculation for each factor. The procedure has been made flexible with regard to available input data, by allowing both quantitative and qualitative inputs to most steps. If detailed data is readily available, it may be used directly in the procedure. If this is not the case, then a qualitative judgement may be done with help from the included guide.

Traditionally, E-CoF has often been calculated in terms of cost for clean-up, lost product and fines. The proposed assessment procedure in this thesis has aimed to focus more on environmental values, and hence the cost term is excluded from the proposed procedure. Still, as cost calculation is important, a separate procedure has been proposed for cost estimation.

Both procedures gives the result as a consequence rating in five steps ranging from very low to very high, compliant with existing DNV practice. A matrix is also provided to combine the two ratings.

The result from this work is a procedure for environmental consequence assessment which is simple and flexible, yet sensitive enough to yield reliable results for RBI purposes. It is expected that the procedure could well lay the foundation for a future E-CoF assessment model for DNV.

CHAPTER 8

Suggestions for Further Work

The aim of this thesis has been to identify the factors which should be included in an environmental consequence assessment for RBI analysis, as well as putting them together in a procedure to yield an E-CoF rating.

All of the factors described individually represent a vast field of research, and each of them could have been the basis of a separate Master's thesis. It is believed that most important factors have been covered, but a more in-depth look at each of them would have been favourable to increase the accuracy of the procedure.

Further, this thesis has only covered spills of liquid hydrocarbons. Other potential dangers for the environment are gas emissions and chemicals, which have not been described. These should also be evaluated. A suggestion for chemical releases is to use the OSPAR ranking of chemicals (2003), as it offers a pre-made hazard ranking of most applicable chemicals. The OSPAR ranking is also being used in the activity regulations (PTIL, 2011), which are the regulations applied for offshore activity in Norway.

The cost estimation procedure which has been presented in this thesis could also benefit from more detailed studies. The compensation part, which covers the damage to commercial or public interest, has a particular potential for improvement.

Further studies are also suggested to balance the consequence ratings in relation to other consequence classes used in RBI, such as safety and business.

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