OCS Study MMS 2002-047

FINAL REPORT

VOLUME I

Alternative Oil Spill Occurrence Estimators for the Beaufort and Chukchi Seas – Fault Tree Method

MMS Contract Number 01-00-PO-17199

August, 2002

By

Bercha International Inc.
Calgary, Alberta, Canada

U.S. Department of the Interior
Minerals Management Service
Alaska Outer Continental Shelf Region

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ABSTRACT

Oil spill occurrence estimates were generated for several expected future oil and gas development scenarios (including exploration, production, and abandonment) in the Beaufort and Chukchi Seas Offshore Continental Shelf (OCS) lease sale regions. Because sufficient historical data on offshore oil spills for these regions do not exist, an oil spill occurrence model based on fault tree methodology was developed and applied. Using the fault trees, base data from the Gulf of Mexico were modified and augmented to represent expected Arctic offshore oil spillage frequencies. Three principal spill occurrence indicators, as follows, were quantified:

- Annual spill frequency
- Annual spill frequency per barrel produced
- Spill index, the product of spill size and spill frequency

These indicators were quantified for the following spill sizes:

- Small - = 50 < 100 bbl
- Medium - = 100 < 1,000 bbl
- Large - = 1,000 < 10,000 bbl
- Huge - = 10,000 bbl

Quantification was carried out for each future year for four different Beaufort Sea development scenarios, ranging in duration up to 38 years, and for two Chukchi Sea scenarios of 10-year duration. In addition, comparative scenarios for non-Arctic locations were formulated and analyzed for oil spill occurrence. Generally, it was found that the non-Arctic spill indicators were likely to be significantly higher than those for similar scenarios in the Arctic. The computations were carried out using a Monte Carlo process to permit the inclusion of estimated uncertainties in the Arctic effects. A wide range of details for each scenario was generated, including the following:

- Expected time history of spill occurrences over the scenario life.
- Spill occurrence variations by spill volumes in the above spill size ranges.
- Spill occurrence variation by spill cause such as boat anchoring or ice gouging.
- Spill occurrence contribution from each main facility type, including pipelines, platforms, and wells.
- Comparison of spill occurrence predictions between Arctic and non-Arctic scenarios.
- The variability in the results due to uncertainties in the Arctic effects introduced, expressed as cumulative distribution functions and statistical measures.

In the final report, a detailed description of the methodology, results, and conclusions and recommendations is given, as well as a section on limitations of the study.

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- Dennis Hinnah, Office of Field Operations

This work was carried out by the Bercha Group with assistance from S.L. Ross Environmental Consultants on the historical data assimilation. Key personnel on the project team were as follows:

- Dr. Frank G. Bercha, Project Manager and Principal Engineer, Bercha Group
- Dr. Seymour L. Ross, Oil Spill Specialist, S.L. Ross Environmental Consultants
- Dr. Norman Davies, Statistical Specialist, Cambridge University, UK
- Milan Cerovšek, Reliability Engineering Specialist, Bercha Group
- Archie C. Churcher, Offshore Operations Specialist, Bercha Group
- Wesley Abel, Offshore Engineering Specialist, Bercha Group

This work is dedicated to the memory of Dr. Norman Davies, who regrettably passed away before its completion.

EXECUTIVE SUMMARY

A. Summary of Work Done

Oil spill occurrence estimators were generated for several expected future oil and gas development scenarios (including exploration, production, and abandonment) in the Beaufort and Chukchi Seas Offshore Continental Shelf (OCS) lease sale regions. Because sufficient historical data on offshore oil spills for these regions do not exist, an oil spill occurrence model based on fault tree methodology was developed and applied. Using the fault trees, base data from the Gulf of Mexico were modified and augmented to represent expected Arctic offshore oil spillage frequencies. Three principal spill occurrence indicators, as follows, were quantified:

- Annual spill frequency
- Annual spill frequency per barrel produced
- Spill index, the product of spill size and spill frequency

These indicators were quantified for the following spill sizes:

- Small (S) - = 50 < 100 bbl
- Medium (M) - = 100 < 1,000 bbl
- Large (L) - = 1,000 < 10,000 bbl
- Huge (H) - = 10,000 bbl

Quantification was carried out for each future year for four different Beaufort Sea development scenarios, ranging in duration up to 38 years, and for two Chukchi Sea scenarios of 10-year duration. In addition, comparative scenarios for non-Arctic locations were formulated and analyzed for oil spill occurrence. Generally, it was found that the non-Arctic spill indicators were likely to be significantly higher than those for similar scenarios in the Arctic. The computations were carried out using a Monte Carlo process to permit the inclusion of estimated uncertainties in the Arctic effects. A wide range of details for each scenario was generated, including the following:

- Expected time history of spill occurrences over the scenario life.
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- Comparison of spill occurrence predictions between Arctic and non-Arctic scenarios.

- The variability in the results due to uncertainties in the Arctic effects introduced, expressed as cumulative distribution functions and statistical measures.

In the final report, a detailed description of the methodology, results, and conclusions and recommendations is given, as well as a section on limitations of the study.

B. Conclusions

B.1 Conclusions on Spill Indicator Trends

The three spill occurrence indicators – annual frequency, annual frequency per barrel produced, and spill index – exhibit a wide range of values varying with location, scenario year, facility composition, and spill size. For the Beaufort Sea and Chukchi Sea locations, comparative non-Arctic scenarios were also postulated and analyzed.

B.1.1 Spill Occurrence Indicator Variations by Spill Size and Location

How do spill indicators for the different scenarios and for their non-Arctic counterparts vary by spill size and location? Table 1 summarizes the spill indicator values for representative years. Representative years are chosen as the peak production years. Figures 1 and 2 show the spill size composition associated with each scenario representative year chosen. The total values of each spill index are also given in a rectangle in the bottom right hand corner of each pie chart. The following can be observed from Figures 1 and 2 and Table 1.

- Each spill indicator for Beaufort Sea Sale 1, 2, and 3 is similar in value. The indicators are higher for the composite "Sale All" scenario (Table 1).
- Chukchi Sea spill indicators are all higher than Beaufort Sea indicators (Table 1).
- Spill frequency per year and per barrel produced decreases significantly with increasing spill size for all scenarios (Figures 1 and 2). The spill frequency and spill frequency per barrel proportions are the same for any given year. Their absolute value differs only because the latter is divided by the annual production volume.
- The spill index increases dramatically with spill size for all scenarios (Table 1 and Figures 1 and 2).
- All non-Arctic scenario spill indicators are greater than their Arctic counterparts. Non-Arctic spill frequencies are approximately 40% greater; spill indices, 8% greater for the non-Arctic scenarios (Table 1).

In addition, the unit Arctic oil spill frequencies for pipelines show a decrease with increasing water depth. That is, pipeline failures per km-yr are highest for shallow water and lowest for deep water. Thus, given the same size and length of pipeline in shallow and deep water, the spill indicators for deep water pipelines would be lower than those for shallow water pipelines. The opposite trend was observed to apply to platforms. No water depth effect was introduced for wells.

Table 1
Summary of Spill Indicators for All Scenarios

SPILL INDICATORS Spill Size bbl x 1000		Beaufort Sea					Chukchi Sea		
		Year 2016	Year 2019	Year 2024	Year 2020	Year 2020	Year 2010	Year 2010	Year 2010
		Sale 1	Sale 2	Sale 3	Sale All	Sale All Non Arctic	Base Case	High Case	High C Non Arctic
Spill Frequency per 10^3 years	SM	9.97	10.17	9.84	29.98	43.90	37.66	70.18	95.17
	L	4.53	4.42	4.07	13.02	17.83	15.23	25.34	36.70
	H	2.39	2.34	2.21	6.93	8.31	7.68	14.38	17.85
	All	**16.88**	**16.93**	**16.12**	**49.93**	**70.04**	**60.58**	**109.91**	**149.72**
Spill Frequency per 10^9 bbl produced	SM	0.21	0.24	0.25	0.40	0.59	0.41	0.31	0.42
	L	0.10	0.11	0.11	0.17	0.24	0.17	0.11	0.16
	H	0.05	0.06	0.06	0.09	0.11	0.08	0.06	0.08
	All	**0.36**	**0.40**	**0.42**	**0.67**	**0.94**	**0.66**	**0.48**	**0.66**
Spill Index [bbl] (Product of spill frequency and mean spill size)	SM	2	2	2	6	9	8	13	19
	L	28	27	26	81	102	92	171	218
	H	170	169	165	505	529	534	1150	1211
	All	**200**	**199**	**193**	**592**	**640**	**633**	**1335**	**1448**

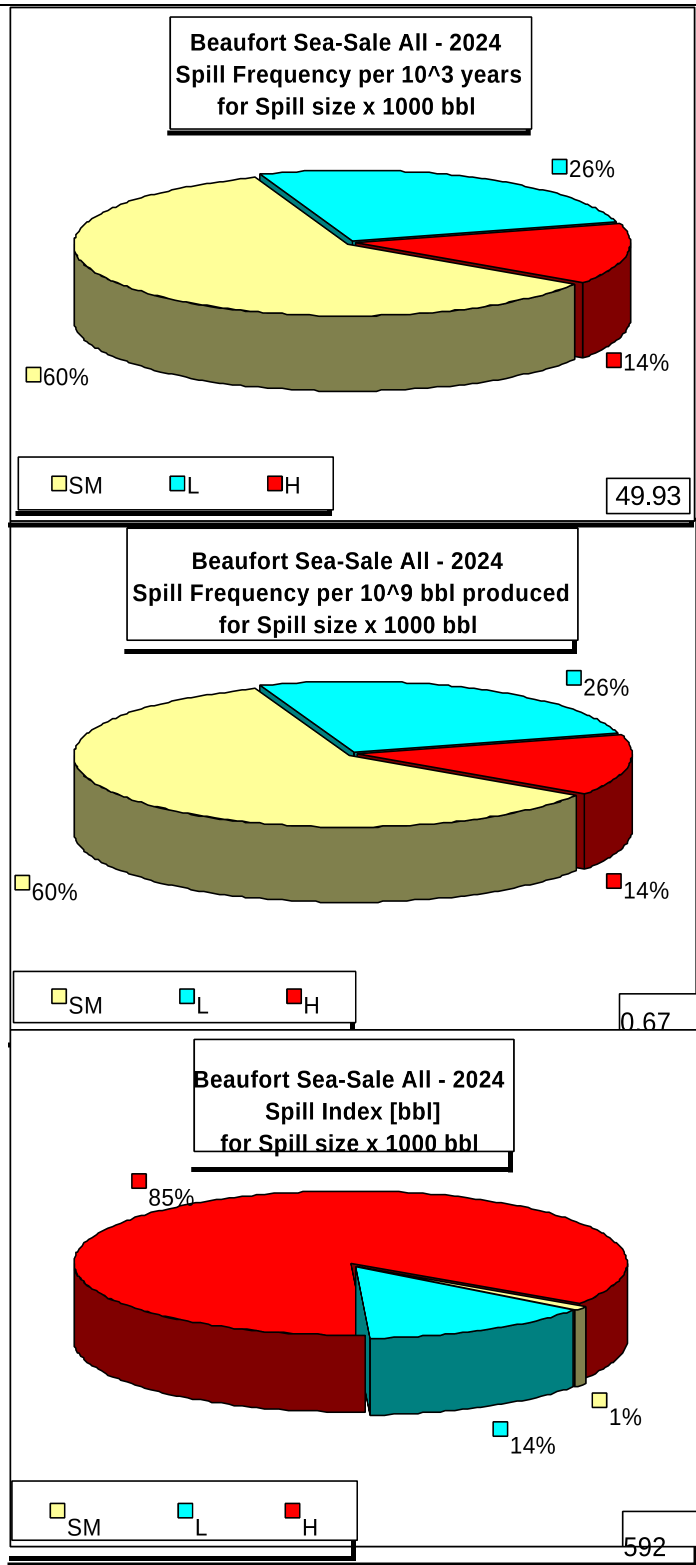


Figure 1
Beaufort Sea 'Sale All' Spill Indicators – Year 2024

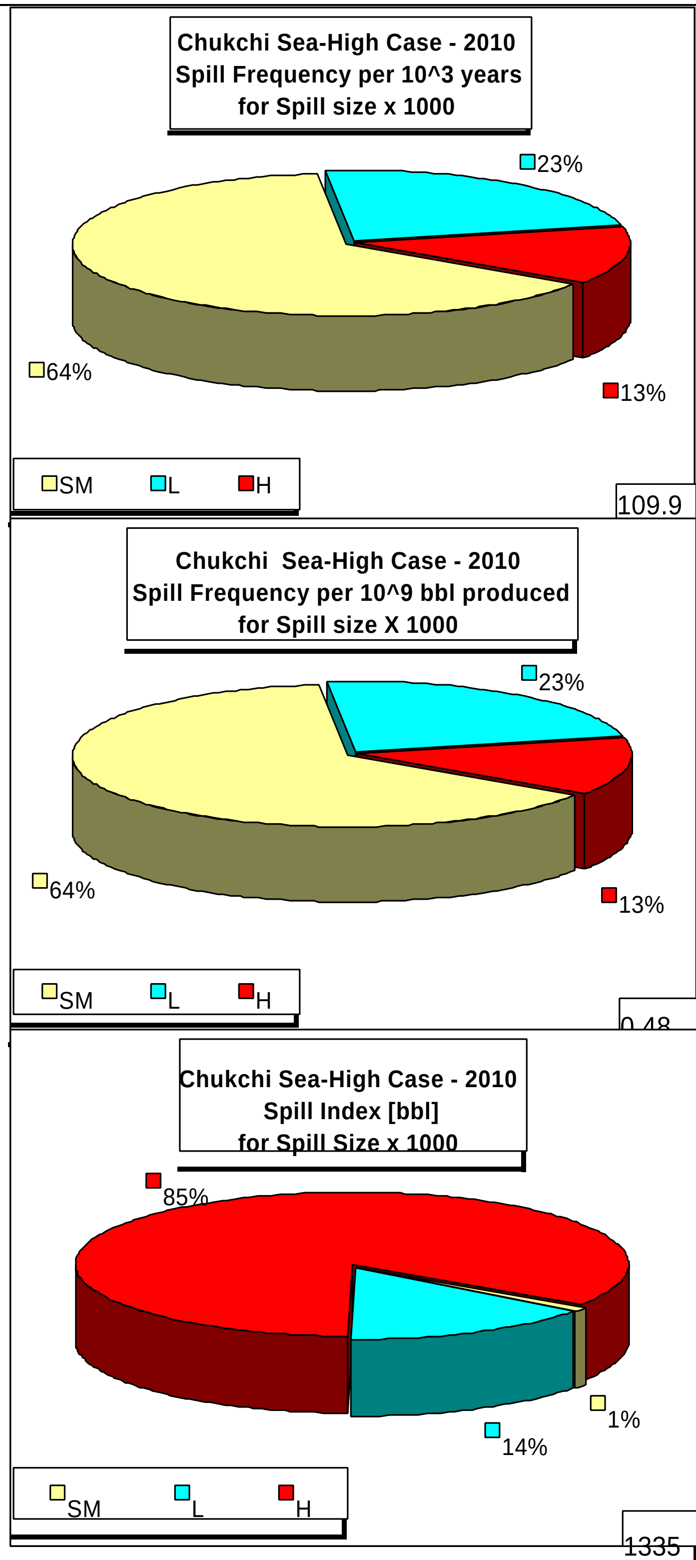


Figure 2
Chukchi Sea 'High Case' Spill Indicators – Year 2010

B.1.2 Facility Contributions to Spill Occurrence Indicators

How do the spill indicators vary by facility type for representative scenarios? The contributions of spill indicators by facility have also been summarized for representative scenario years. Figures 3 and 4 gives the relative component contributions, in absolute value and percent, for each of the main facility types; namely, pipelines (P/L), platforms, and wells. Platform spills do not include blowouts. Blowouts are the only spill events categorized under well spills. The following may be noted from these figures:

- For both the Beaufort and Chukchi scenarios, platforms contribute the most (50% and 61% respectively) to the two spill frequency indicators, but the least (5% and 6% respectively) to the spill index (Figure 3 and 4).
- Pipelines in the Beaufort scenarios are next in relative contribution to spill frequencies (31%) and intermediate in contribution to spill index (10%) (Figure 3).
- The relative contribution of pipelines to spill frequencies in the Chukchi, however, are approximately the same (19%) as contributions of wells (20%) (Figure 4).
- Wells are by far the highest contributors to spill index in the Beaufort and Chukchi Seas, at 85% and 89% respectively, while platforms and wells are each responsible for 10% or less contribution to the spill index (Figures 3 and 4).
- It can be concluded that platforms are likely to have the most, but smaller spills, while wells will have the least number, but largest spills. Pipelines will be in between, with a tendency towards more spills than wells, but less or about the same number as platforms. Pipeline spill volumes will tend to be greater than (in Beaufort) or similar in size (in Chukchi) to platform spills.

B.1.3 Projected Annual Variations of Spill Occurrence Indicators

How do spill indicators vary over the development life cycle? Figure 5 shows the composite Beaufort Sea scenario annual variation in spill indicators over the expected development lifetime. Generally, spill frequencies and the spill index can be seen to follow the facility build-up and phase-out, as they are directly proportional to facility quantities. Spill frequency per barrel produced, however, continues to rise beyond the peak production year. The lack of fall of spills per billion barrels produced in years after peak production is partially artificial. The development scenarios used by MMS in environmental analyses (and used in this report) assume pipelines, platforms, and wells are abandoned at a rate lower than the rate of decrease in production. This leads to the artifact that as production goes to zero, spills per barrel produced increase to infinity. The artifact disappears when spill rates are summed or normalized over the life of the fields.

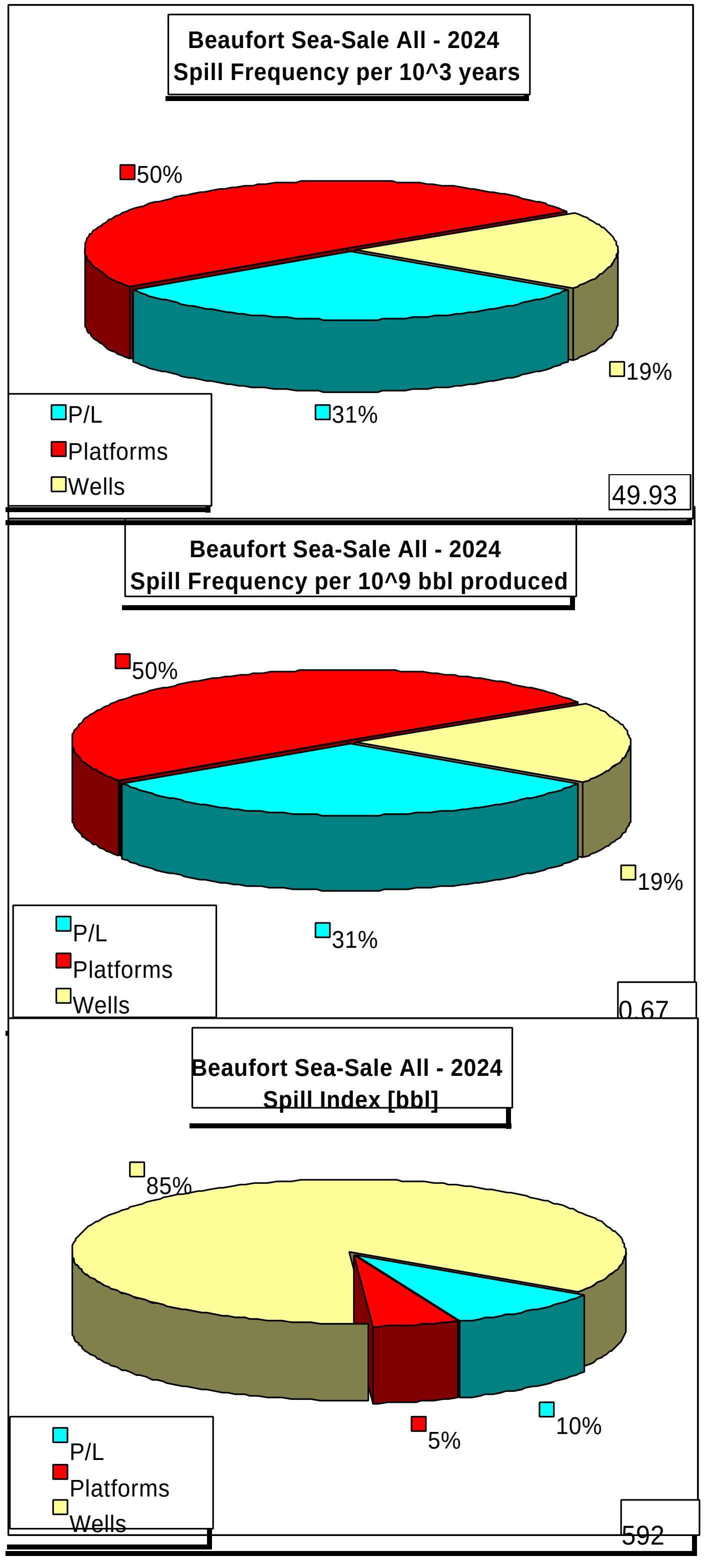
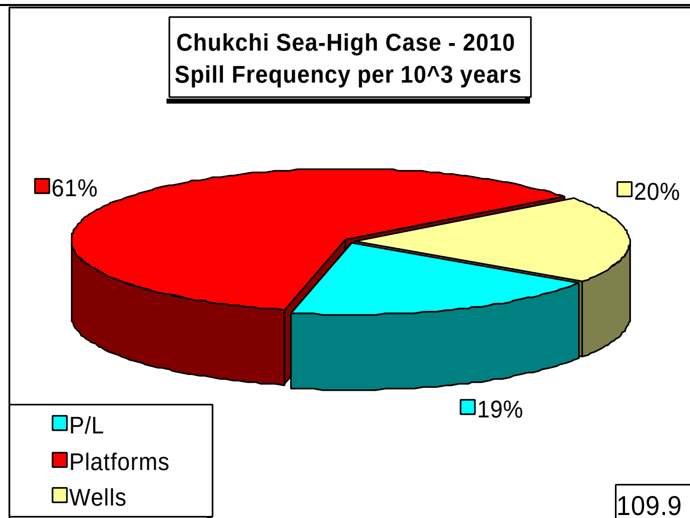
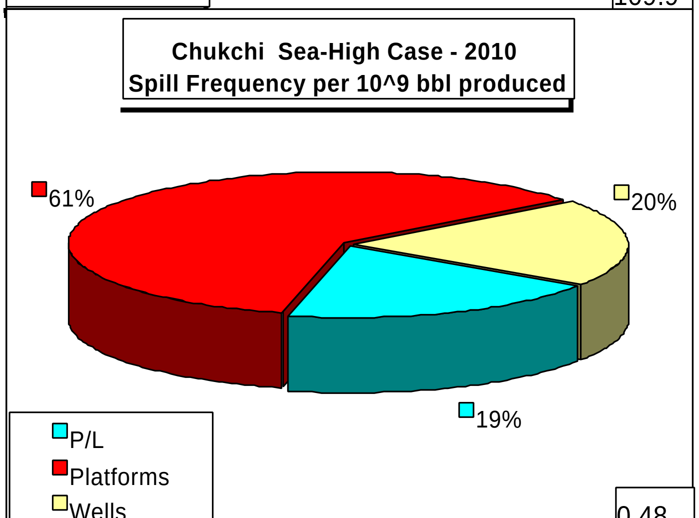


Figure 3
Beaufort Sea 'Sale All' Spill Indicators – Year 2024





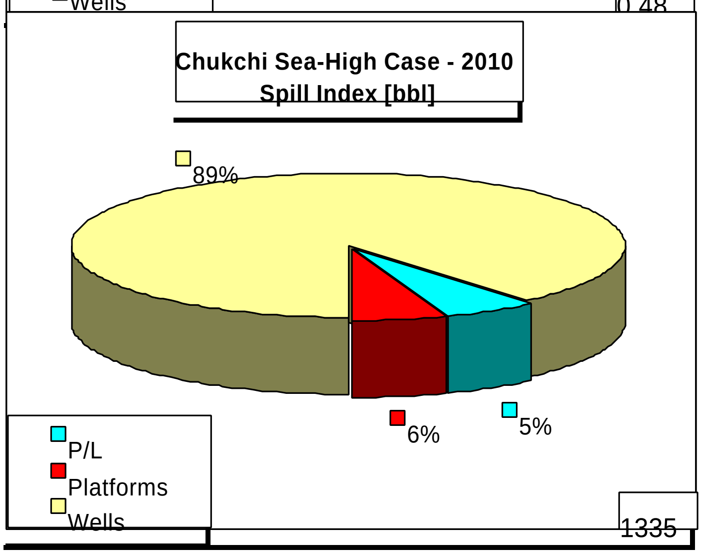


Figure 4
Chukchi Sea 'High Case' Spill Indicators – Year 2010

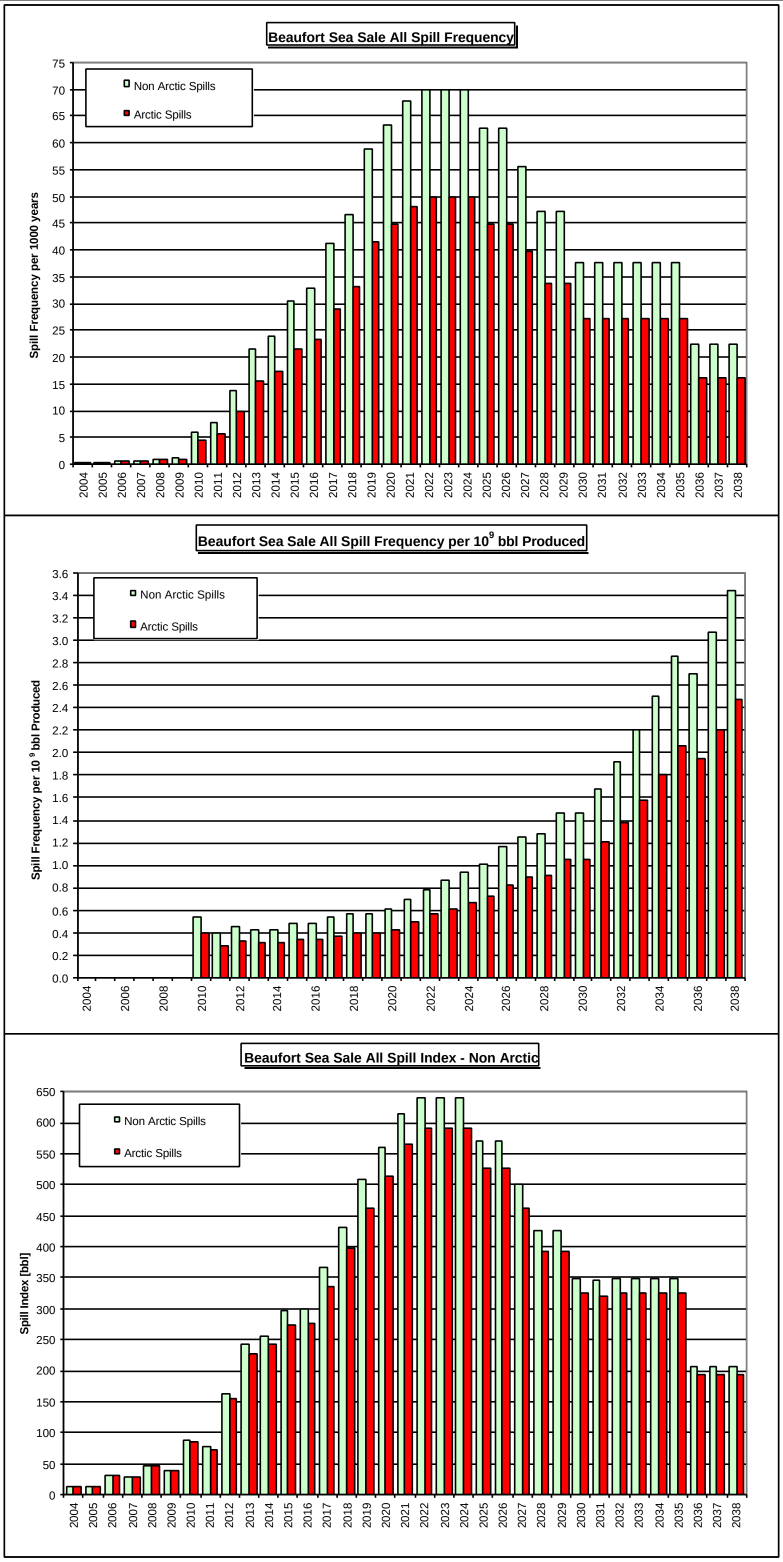


Figure 5
Beaufort Sea Composite Scenario Annual Variation in Arctic and Non-Arctic Spill Occurrence Indicators

B.1.4 Spill Indicator Statistical Variance

The variance introduced into the spill occurrence indicators by the incorporation of Arctic effects was numerically evaluated. Figure 6 shows typical distributions of the resulting indicators, in this case for the Beaufort Sea composite (All Sales) scenario. The slope of each line is an indicator of its variance. Specifically, it was found that for all spills the standard deviation ranged from 12% to 15% of the mean, while the upper and lower bound (95^{th} percentile and 5^{th} percentile, respectively) ranged from 20% to 30%, with the smaller variances corresponding to the Beaufort Sea scenarios and the large ones to the Chukchi Sea scenarios. Upper (95%) and lower (5%) bounds, however, varied as much as 20 to 50% and 20 to 35% of the mean. Since many of the variations in the Arctic inputs ranged in excess of plus or minus 80% of the mean value, the relatively small variance of the indicators suggest that the total model is quite robust; large variances in inputs cause only small variances in outputs. However, this small variance relates only to the Arctic effects; variance in historical spill size and frequency was considered to be zero. Thus, the variances discussed here characterize the uncertainties associated with the Arctic effects incorporated through the fault tree methodology in this study.

B.2 Conclusions on the Methodology and Its Applicability

An analytical tool for the prediction of oil spill occurrence indicators for systems without history has been developed based on the utilization of fault tree methodology. Although the results generated are voluminous, they are essentially transparent, simple, and easy to understand. The analytical tool developed is also quite transparent, very efficient in terms of computer time and input-output capability, and user friendly for users that are generally familiar with the process. In addition, the basic model is setup so that any input variables can be entered as distributions; the model presented in this study only uses distributed values of the Arctic effect inputs.

A wealth of information that can be utilized for the optimal planning and regulation of future developments is generated by the analytical tool. Key aspects of the analytical tool capability may be summarized as follows:

- Ability to generate expected and mean values as well as their variability in rigorous numerical statistical format.
- Use of verifiable input data based on MMS historical spill data and statistics.
- Ability to independently vary the impacts of different causes on the spill occurrences as well as add new causes such as some of those that may be expected for the Arctic or other new environments.
- Ability to generate spill occurrence indicator characteristics such as annual variations, facility contributions, spill size distributions, and spill causes.

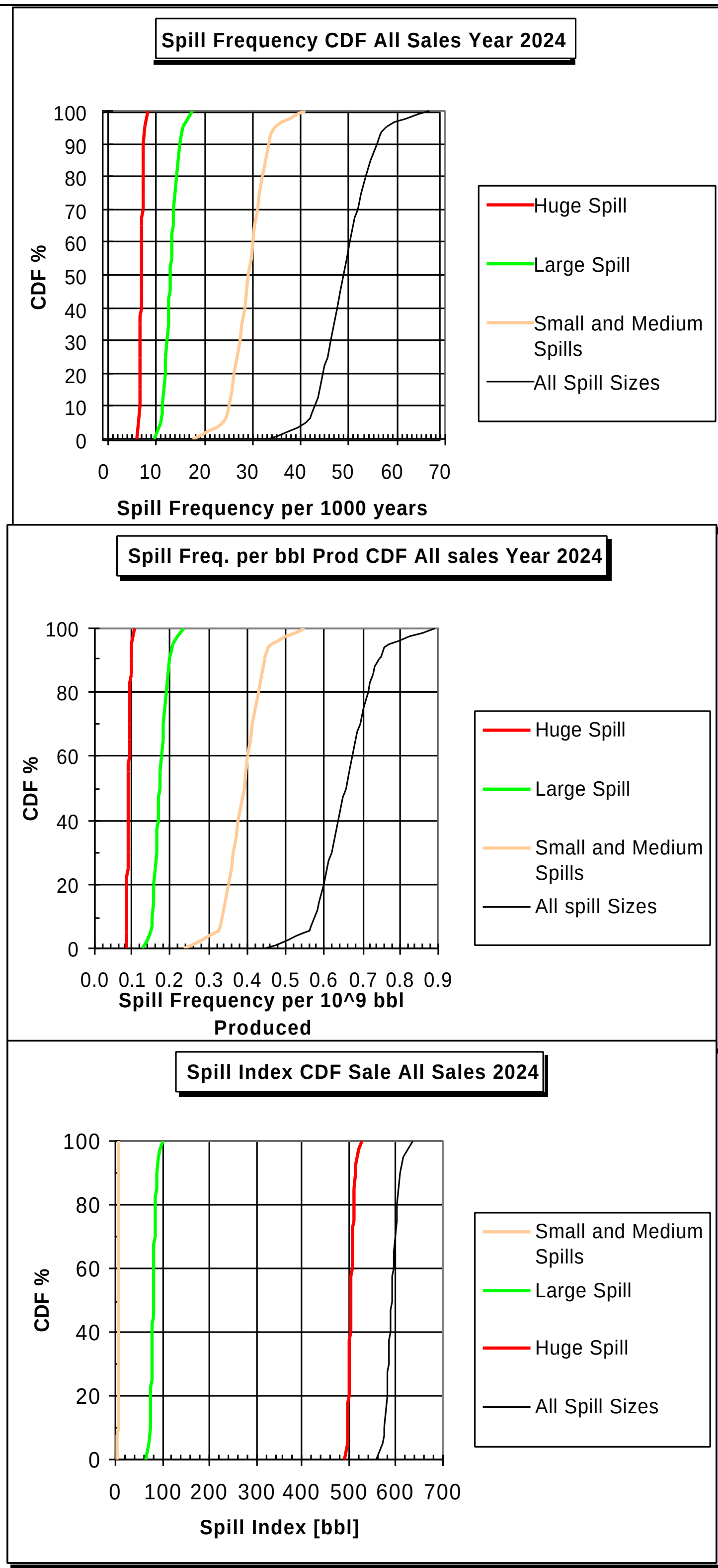


Figure 6
Typical Spill Occurrence Indicator Variance Graphs

- Ability to generate comparative spill occurrence indicators such as those of comparable scenarios in more temperate regions. The model developed provides a basis for estimating each Arctic effect's importance through sensitivity analysis as well as propagation of uncertainties.
- Capability to quantify uncertainties rigorously, together with their measures of variability.

C. Limitations of Methodology and Results

C.1 General Description of Limitations

During the work, a number of limitations in the input data, the scenarios, the application of the fault tree methodology, and finally the oil spill occurrence indicators themselves have been identified. These shortcomings are summarized in the following paragraphs.

C.2 Limitations of Input Data

Two categories of input data were used; namely the historical spill data and the Arctic effect data. Although a verifiable and optimal historical spill data set has been used, the following shortcomings may be noted:

- Gulf of Mexico (OCS) historical data bases were provided by MMS and used as a starting point for the fault tree analysis; however, some inconsistencies were identified in these databases as discussed in Appendix A, Section A.2.4.
- Only the historical spill frequency point value was utilized, since adequate data were not provided to create distributions of these frequencies.
- Several ranges of spill sizes were analyzed, but only the mean value of each spill size range was used to characterize representative spill size for each range. Spill size distribution data for each spill size range was available, but was not used in the interest of restricting the uncertainties to the Arctic effects.
- The assessment of the variability or statistical properties of the GOM historical data is a significant study in itself, which is expected to be carried out in the companion study being conducted in parallel with the present work
- The Arctic effects include modifications in causes associated with the historical data set as well as additions of spill causes unique to the Arctic environment. Quantification of existing causes for Arctic effects was done in a relative cursory way restricted to engineering judgement.
- A reproducible but relatively elementary analysis of gouging and scour effects was carried out.

- Upheaval buckling and thaw settlement effect assessments were included on the basis of an educated guess; no engineering analysis was carried out for the assessment of frequencies to be expected for these effects.
- No Arctic effects were estimated for the wells, which were considered to blowout with frequencies the same as those for the GOM.

C.3 Scenarios

The scenarios are those developed for use in the MMS Alaska OCS Region Environmental Impact Statements for Oil and Gas Lease Sales. As estimated they appear reasonable and were incorporated in the form provided. There are two possible shortcomings of the scenarios as follows:

- Distributed values for the key quantities were not provided, thus precluding their incorporation as distributions in the Monte Carlo analysis.
- The facility abandonment rate is significantly lower than the rate of decline in production.

C.4 Fault Tree Methodology

Generally, the fault tree methodology was limited primarily by the shortcomings in input data discussed above.

- The primary method for assessing uncertainties was restricted to the fault tree module, which incorporates the uncertainties or bounds assigned to the Arctic effects. The treatment of uncertainties could be expanded to incorporate distributions in volume of spills, and the original historical frequencies.
- The treatment of uncertainties was carried out utilizing a Monte Carlo process, which requires an add-in (called @Risk©) to the Excel spreadsheet within which the algorithms have been programmed. For some users, this might be slightly arcane; accordingly, it may be desirable to have two versions, the Monte Carlo version which gives more rigorous results and is used for results in the body of this report, and an expected value version, which may be utilized for rough estimates. Appendix C gives the detailed results and calculations for the Monte Carlo model; Appendix D gives those from the expected value model.
- The Monte Carlo results give higher oil spill occurrence indicators than the expected value results. This is due to the skewness of the Arctic effect distributed values, which are inputs to the Monte Carlo calculations.

C.5 Limitations of Indicators Generated

The following comments can be made on limitations associated with the indicators that have been generated.

- The indicators have inherited the deficiencies in the input and scenario data noted above. Indicators should be viewed primarily as trend indicators of the expected values and their distributions for Arctic developments.
- The indicator distribution shows relatively small variability – this is primarily because the only variability introduced is that of the Arctic effects.
- The model generating the indicators is fundamentally a linear model which ignores the effects of scale, of time variations such as the learning and wear-out curves (Bathtub curve), and production volume non-linear effects.
- The expected value (simpler) calculation results (given in Appendix D) should be used with caution since they underestimate the spill indicators. The underestimation ranges from 3 to 76%. Appendix D gives all the expected value calculations. The body of the report is based on the Monte Carlo results given in Appendix C.

D. Recommendations

D.1 Recommendations on Direct Application of Results from This Study

The results of this study can be applied directly in two principal ways; namely, on an annual per barrel produced basis, and on a total production volume basis.

On an annual basis, the peak production year oil spill frequency per barrel produced can be used to calculate corresponding annual spill frequencies for other annual production rate scenarios. This is done simply by multiplying the appropriate spill frequency per billion barrels produced from Table 1 by the subject annual production rate.

To apply the results on a total production volume basis, the following steps can be used:

- For the desired spill size range and facility component (or all facilities), add together the annual spill frequencies for each year of the production life.
- Divide the sum of the frequencies by the total production volume. This provides the number of spills per barrel produced for the entire development.
- For another development, multiply the above spills per barrel produced by the other development's total production volume.
- The resultant is the expected number of spills of the desired spill size range and for the desired facility component for the total production life of the other development.

D.2 General Recommendations

The following recommendations based on the work may be made:

- Utilize the oil spill occurrence indicator model to generate additional model validation information, including direct application to specific non-Arctic scenarios, such as GOM projects, which have an oil spill statistical history.
- Utilize the oil spill occurrence indicator model in a sensitivity mode to identify the importance of different Arctic effect variables introduced to provide a prioritized list of those items having the highest potential impact on Arctic oil spills.
- Use GOM historical data together with its measures of spill size variance and setup the Monte Carlo model to run with these measures of spill size variance.
- Generalize the model so that it can be run both in an expected value and a distributed value (Monte Carlo) form with the intent that expected value form can be utilized without the Monte Carlo add-in for preliminary estimates and sensitivity analyses, while for more comprehensive rigorous studies, the Monte Carlo version can be used. All calculations in this report are based on the Monte Carlo version.
- Finally, convert the current oil spill occurrence indicator model into a user friendly software package, which can be used for the assessment of oil spill occurrence indicators and their characteristics for any designated scenario. The software package should include the following:
  - Modular structure
  - User manual
  - Online help
  - Password protected parameters and algorithms
  - Extensive graphical outputs

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GLOSSARY OF TERMS AND ACRONYMS

Acute Risk	Risk that has an immediate adverse effect due to a single accident such as an oil blowout.
ALARP	**A**s **L**ow **a**s **R**easonably **P**racticable
API	**A**merican **P**etroleum **I**nstitute
ARM	**A**vailability, **R**eliability and **M**aintainability
BOP	**B**low**o**ut **P**reventer
CDF	**C**umulative **D**istribution **F**unction
Chronic Risk	Risk that has an adverse effect only after long-term or repeated occurrences.
Consequence	The direct effect of an accidental event.
DJU	**D**rilling **J**ack-**U**p
ESD	**E**mergency **S**hut**d**own
ESDV	**E**mergency **S**hut**d**own **V**alve
FPSO	**F**loating **P**roduction and **S**torage **O**peration
GBS	**G**ravity **B**ase **S**tructure
GOM	**G**ulf **o**f **M**exico
H_2S	**H**ydrogen **S**ulfide
Hazard	A condition with a potential to create risks such as accidental leakage of natural gas from a pressurized vessel.
HT	**H**igh **T**emperature
HTHP	**H**igh **T**emperature, **H**igh **P**ressure
LFL	**L**ower **F**lammability **L**imit
MAOP	**M**aximum **A**llowable **O**perating **P**ressure. The highest pressure at which a pipeline or vessel can be operated considering design and regulatory conditions.
MMS	**M**inerals **M**anagement **S**ervice, Department of the Interior
Monte Carlo	A numerical method for evaluating algebraic combinations of statistical distributions.
MSL	**M**ean **S**ea **L**evel
NOP	**N**ormal **O**perating **P**ressure. The highest pressure at which a pipeline or vessel can be operated considering design conditions.
NPD	**N**orwegian **P**etroleum **D**irectorate
OCS	**O**ffshore **C**ontinental **S**helf

OIM	**O**ffshore **I**nstallation **M**anager
QRA	**Q**uantitative **R**isk **A**ssessment
Risk	A compound measure of the probability and magnitude of adverse effect.
ROV	**R**emotely **O**perated **V**ehicle
Spill Frequency	The number of spills of a given spill size range per year. Usually expressed as spills per 1,000 years (and so indicated).
Spill Frequency per Barrel Produced	The number of spills of a given spill size range per barrel produced. Usually expressed as spills per billion barrels produced (and so indicated).
Spill Index	The product of spill frequency for a given spill size range and the mean spill size for that spill size range.
Spill Occurrence	Characterization of an oil spill as an annual frequency and associated spill size or spill size range.
Spill Occurrence Indicator	Any of the oil spill occurrence characteristics; namely, spill frequency, spill frequency per barrel produced, or spill index (defined above).
Spill Sizes	Small (S) = 50 < 100 bbl Medium (M) = 100 < 1,000 bbl Large (L) = 1,000 < 10,000 bbl Huge (H) = 10,000 bbl
SPM	**S**ingle **P**oint **M**ooring
SSIV	**S**ub-**S**ea **I**solation **V**alve
SSSV	**S**ub**s**urface **S**afety **V**alve
UFL	**U**pper **F**lammability **L**imit
UKCS	**UK C**ontinental **S**helf

CHAPTER 1

INTRODUCTION

1.1 General Introduction

The MMS Alaska OCS Region uses oil spill occurrence predictions for National Environmental Protection Act assessments for all parts of their area of jurisdiction, ranging from onshore through shallow water, to deeper water. In 1999-2000, a study, OCS Study MMS 2000-007 [22]*, was carried out to collate readily available information on oil industry spills in the Alaska and North Slope and Arctic Canada, to verify spill information for spills of at least 500 barrels and to estimate provisional spill rates for use in the near shore Beaufort Sea OCS. Based on this study, MMS estimated pipeline and facility spill rates from Alaskan North Slope and Trans-Alaska Pipeline onshore oil spill experience to shallow coastal waters and the near shore Beaufort Sea. However, as water depth increases and one moves further from shore, extrapolation of these statistics is not necessarily valid due to the change in operational modes and environmental conditions. There are no adequate historical statistics to characterize spill rates in deeper waters in the Beaufort and Chukchi Seas, for forthcoming lease areas.

Accordingly, MMS implemented the present study to develop and apply alternative methodologies for the assessment of oil spill rates associated with exploration and production facilities and operations in deeper waters in the Chukchi and Beaufort Seas. The prediction of the reliability (or failure) of systems without history can be approached through a variety of mathematical techniques, the most preferable and accepted being fault trees [2, 7, 10, 11, 14, 15, 18, 23, 26, 45, 51, 65], and their possible combination with numerical distribution methods such as Monte Carlo simulation. In the current study, fault tree methodology was applied to the prediction of oil spill rates for oil and gas developments such as those now operational or contemplated for the Beaufort and Chukchi Seas in the Alaska OCS, and used to generate predictions of oil spill occurrence indicators.

1.2 Study Objectives

The objectives of this study are as follows:

- Assimilate and analyze world-wide and US OCS oil spill statistics and evaluate their applicability to deeper lease tracts which could be offered in the upcoming Beaufort Sea sales or in subsequent Chukchi Sea sales.
- Develop the fault tree method for estimating oil spill occurrences from Beaufort Sea and Chukchi Sea developments associated with spills less than and greater than 1,000 bbl.

* Numbers in square brackets refer to citations listed in the "References" section of this report.

- Using the fault tree approach, develop alternative oil spill indicators and assess their robustness.
- Provide statistical support to MMS in evaluation of statistical issues in estimation of oil spill rates.

1.3 Study Area Definition

The geographical study area is the offshore continental shelf in the U.S. Chukchi and Beaufort Seas, as generally illustrated in Figure 1.1. Of interest is the offshore area from landfall to approximately the 60-meter isobath. This area is selected due to the possibility of future oil and gas development within it, based on potential leases. Although a depth greater than 60 meters was originally contemplated as part of the study area, the analysis of development scenarios has indicated that it is highly unlikely that any oil and gas developments will take place in depths greater than 60 meters. More details on the leases and the geology of the study area are described in several MMS publications [35, 36, 37, 38, 39].

Temporally, the study scenarios investigated span into the future by nearly half a century from the present to Year 2038.

1.4 Scope of Work

The scope of work has been subdivided functionally into seven principal tasks as follows:

- Tasks 1 to 4 are the definitive study tasks and are reported in the present report in the Chapters indicated above.
- Task 5 is a service task directed at facilitating the transfer of technology from this study to MMS staff.
- Task 6 is simply the coordination and management process applied throughout.
- Task 7 is reporting. Four Progress Reports were issued throughout the study, but all salient aspects of them are incorporated in this Final Report, so that they need not be referenced.

The general relationship among the principal technical tasks is shown in Figure 1.2. Essentially, following the start-up procedure of the study, including final scope definition and refinement in Task 1, two parallel tasks, Tasks 2 and 3, were conducted. Task 2 dealt with the assimilation of historical data, while Task 3 dealt with the projection of future development scenarios for the next 40 years more or less. Next, the analytical aspects of the work were contained under Task 4, which was subdivided into Task 4A, the fault tree spill frequency analysis, and Task 4B, the oil spill indicator quantification. Task 5 consists of statistical consulting services to MMS. Task 6 entails coordination of the entire project. This report constitutes the principal output from Task 7.

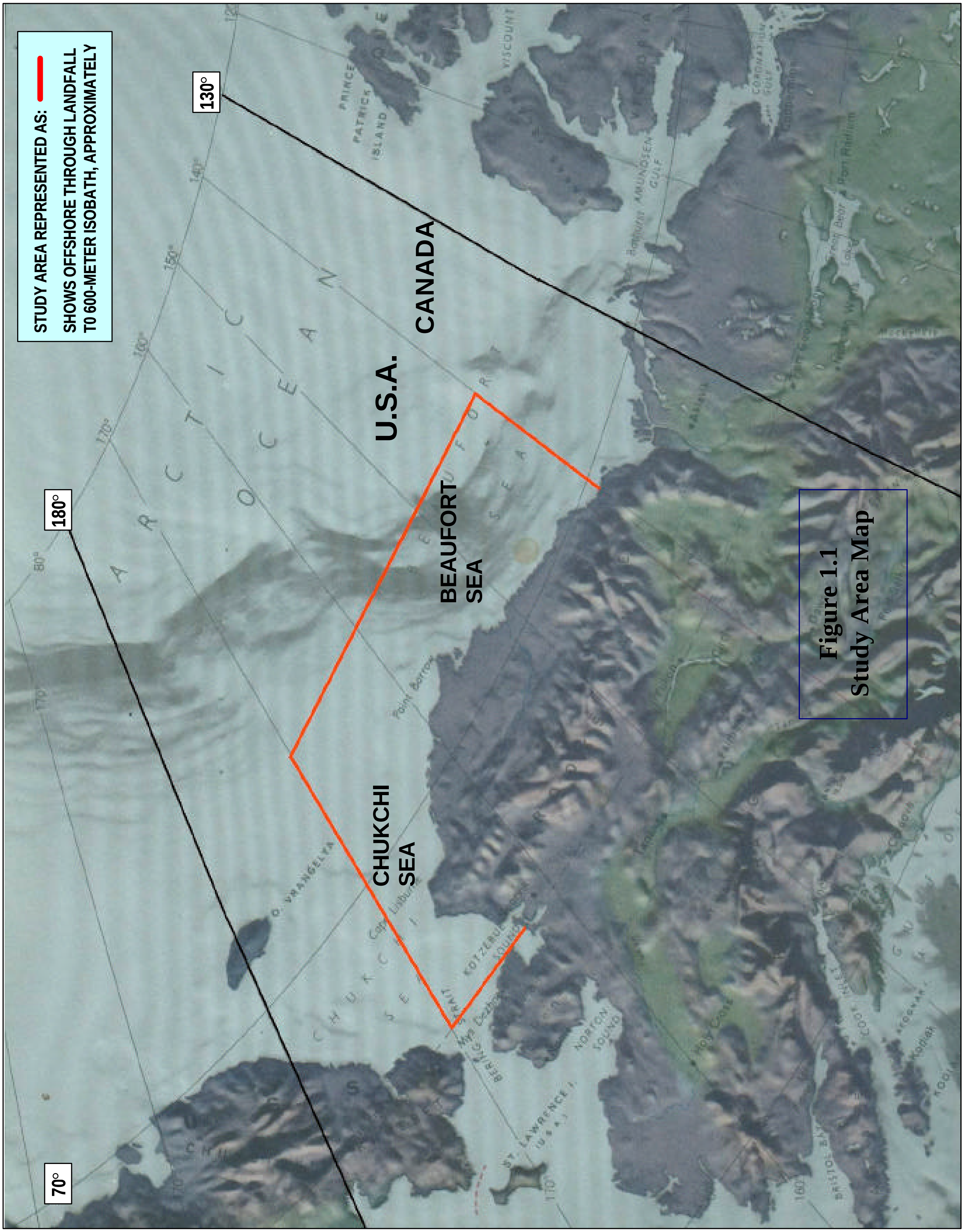


Figure 1.1
Study Area Map

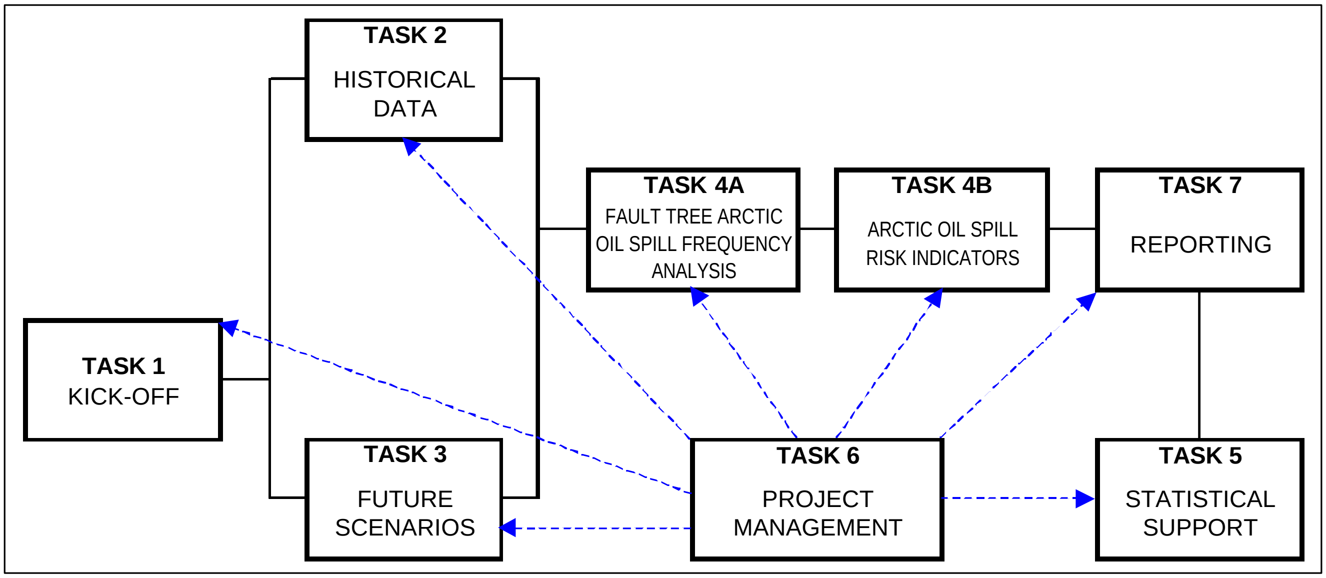


Figure 1.2
Work Flow Schematic

1.5 Work Organization

The present study consisted of statistical and engineering investigations, followed by extensive numerical analysis. Although the assimilation of historical and future scenario data is of indisputable significance to the work, the salient contribution consisted primarily of the analytical work involving fault trees and oil spill occurrence indicator generation. Although the individual calculations are relatively simple, the subdivision of the calculations into realistic representative categories of facilities, spill sizes, and water depth for several development scenarios resulted in a relatively complex mix of computations, generally illustrated in the flow chart in Figure 1.3. Moving from left to right; initially historical data were obtained for each of three principal facility categories, pipelines, platforms, and wells. These facility quantities are referred to as "hazard scenarios", since they are considered to be the primary source of oil spill hazard. Pipelines were further subdivided among < 10 inch and = 10 inch diameter lines. Wells were categorized in two ways: according to producing (production) wells and the drilling (D) of exploration and development wells. For each of the above facility subcategories, spill causes were analyzed for small, medium, large, and huge spills, defined as follows:

- Small (S) - = 50 < 100 bbl
- Medium (M) - = 100 < 1,000 bbl
- Large (L) - = 1,000 < 10,000 bbl
- Huge (H) - = 10,000 bbl

For those spills greater than 10,000 bbl, the term 'huge spill' has been introduced to permit unique designation of each spill category by one letter, rather than the more customary terminology of 'very large' which would require two letters.

In the interests of conciseness and clarity, the above four categories of spill sizes will generally be designated by either their name (small, medium, large, huge) or, when space is limited, by their acronym (S, M, L, H), in the balance of this report.

Next, in the frequency analysis utilizing fault trees, each of three representative water depth ranges was assessed as follows:

- Shallow - < 10 meters
- Medium - = 10 < 30 meters
- Deep - = 30 < 60 meters

Although originally it was anticipated that 'very deep' water would be considered, it was found that none of the development scenarios extended beyond the 60-meter isobath.

A total of six different future development scenarios were defined, four for the Beaufort Sea, and two for the Chukchi Sea. Each scenario was described for each year in its development history, as far as the year 2038 for the longest duration scenarios. In addition, a hypothetical scenario for comparative purposes was developed for each study sub-region on the assumption that it was located in a non-Arctic area. This permitted the comparison of the spill indicator results with and without the application of the fault tree analysis to account for Arctic effects.

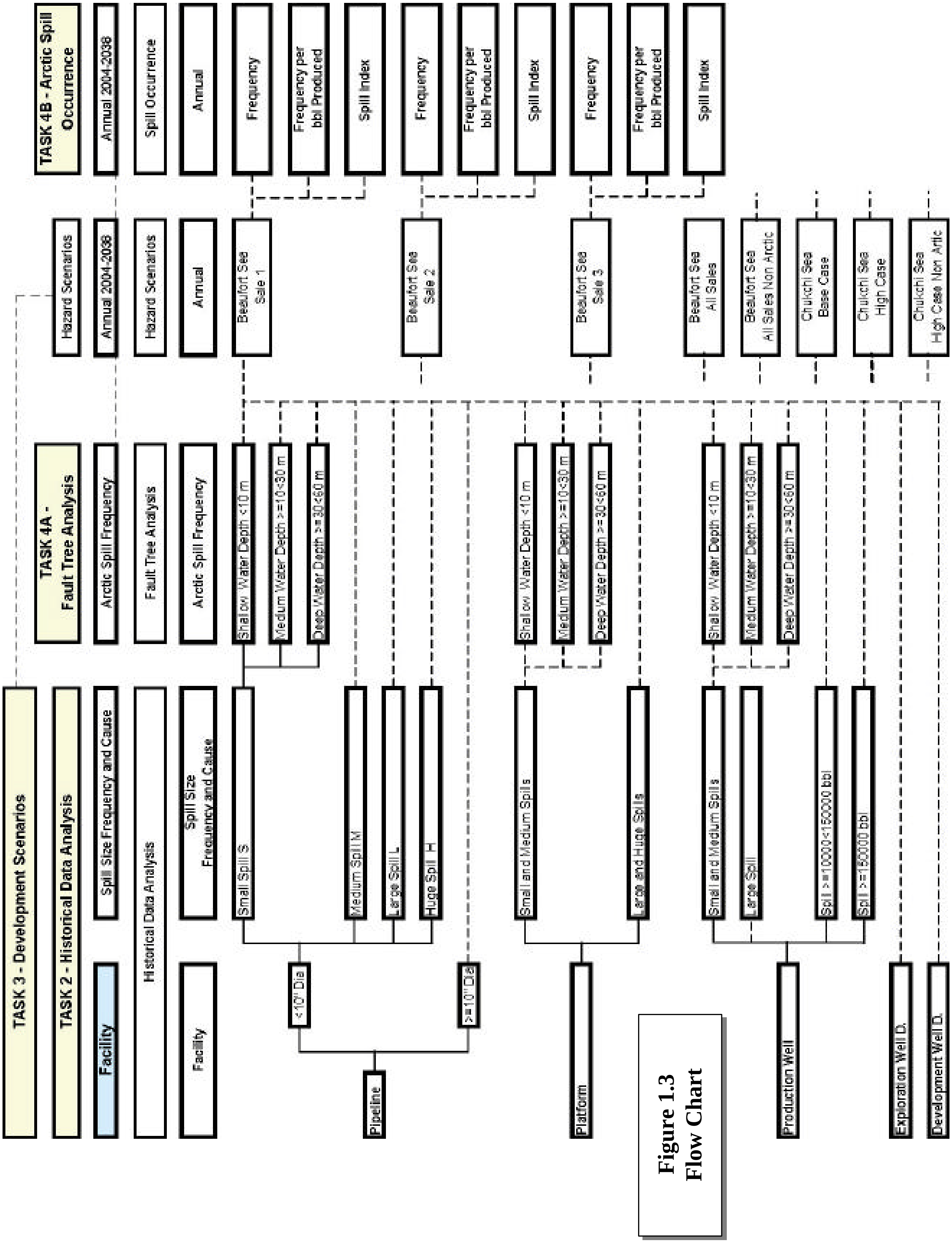


Figure 1.3
Flow Chart

Finally, for each of the combinations considered, three Arctic oil spill occurrence indicators were generated, as follows:

- Oil spill frequency
- Oil spill frequency per barrel produced
- Spill index, which is the product of the oil spill frequency and the mean spill size (for the particular category under consideration)

The flow chart in Figure 1.3, of course, does not show all the different combinations and permutations; rather, it indicates the typical calculations for one case, and suggests the balance by dotted lines. The total number of spill indicator quantifications conducted was 1,728 for each year of the scenario development profile, or approximately 60,000 indicators.

1.6 Outline of Report

Following this brief introductory chapter, Volume I of the final report addresses each of the principal tasks and subtasks in its logical sequence. Accordingly, Chapter 2 describes the historical data assimilation and analysis, Chapter 3 defines the future development scenarios to be utilized, Chapter 4 deals with the fault tree analysis to obtain Arctic oil spill frequencies, while Chapter 5 summarizes the results of the oil spill occurrence indicator computations and their distributions. Chapter 6 summarizes conclusions and recommendations including a section on the benefits and shortcomings of the present study. Extensive references and bibliography are given in the References.

The appendices given in Volume II form an integral part of the work for the reader who wishes to learn about background and calculation details. Accordingly, Appendix A summarizes the historical data assimilated and analyzed. Because Chapter 2, on historical data, is restricted to the data actually utilized in the present computations, Appendix A will be of interest to readers wanting a more comprehensive view of oil spill occurrence statistics including those from other parts of the world as well as ones associated with tanker traffic and operations. Appendix B gives details on the future development scenarios utilized as a basis for the study. Appendix C gives a printout of all the calculation steps utilized in the development of the Arctic oil spill occurrence indicators using the Monte Carlo approach; Appendix D gives the corresponding calculations for the expected value approach.

CHAPTER 2

HISTORICAL DATA

2.1 Approaches to Historical Data

Historical data on offshore oil spills were utilized as a numerical starting point for predicting Arctic offshore oil spill characteristics. Because a statistical history on Arctic offshore oil spills does not exist, oil spill histories for temperate offshore locations were utilized. Although Arctic offshore exploration and production was started in the early 1970s, operations have been sporadic, with very few spills, so that a statistical history cannot be generated.

The following data sets or databases were reviewed:

(a) Gulf of Mexico (GOM) Offshore Continental Shelf (OCS) Pipeline Spills (1972-1999)
(b) GOM OCS Platform Spills (1972-1999)
(c) North Sea Pipeline Spills (1980-1995)
(d) Crude Oil Tanker Spills, Worldwide (1964-1999)
(e) Above Ground Storage Tank Spills, Worldwide (1980-1995)
(f) Gas Blowouts, Worldwide (1955-1993)
(g) Oil Blowouts, Worldwide (1955-1995)

All of the above categories of data are discussed and summarized in Appendix A. The contents of the balance of this chapter are restricted to the presentation and discussion of only those data sets utilized in the balance of the present study. Specifically, the data sets in categories (a), (b), and (g) were selected. None of the development scenarios considered here (see Chapter 3) included tankers; hence, (d) data were not required. Gas blowouts (f) are also not part of this study. Above ground storage tank spills (e) are included in platform spills (b). And finally, the pipeline spill data in category (a) contained a more appropriate level of detail than that from the North Sea in category (c).

2.2 Pipeline Oil Spill Data

The MMS database called *PPL_REPAIRS* was used as a basis for the assessment of subsea pipeline oil spills. This database contains records of all reported spills in the GOM. The database was used to obtain spill records for spills of 50 bbl or more between January 1st, 1972 and December 31st, 1999. The 31 spills reported in this date range were further subdivided into volume, pipeline diameter, pipeline segment length, and pipeline segment depth ranges as summarized in Table 2.1.

Table 2.1
GOM OCS Pipeline Spills Summary (1972-1999)

GOM OCS Pipeline Spills, Categorized 1972-99		Spill Statistics**			Exposure (km-years)	Frequency (spill per 10^4 km-yr)
		Number of Spills	Average Volume (bbl)	Median Volume (bbl)		
By Pipe Diameter	<10"	16	2141	173	142,892	1.1197
	=10"	15	4070	1211	111,011	1.3512
By Pipeline Minimum Depth	Bad Depth Data*	14				
	< 10 m	6	2310	1211	161,966	0.3704
	= 10 m	11	3165	1040	94,641	1.1623
By Segment Length	< 0.5 km	0	0	0	2,359	0.0000
	= 0.5 < 2 km	2	2335	2335	25,484	0.7848
	= 2 < 5 km	7	820	100	35,279	1.9842
	= 5 km	22	3859	850	192,270	1.1442
By Spill Size***	Small	6	58	50	253,903	0.2363
	Medium	12	317	230	253,903	0.4726
	Large	10	4133	4267	253,903	0.3939
	Huge	3	16611	15576	253,903	0.1182
By Diameter, By Spill Size						
<10"	Small	4	58	50	142,892	0.2799
	Medium	7	266	135	142,892	0.4899
	Large	4	4436	4551	142,892	0.2799
	Huge	1	14423	14423	142,892	0.0700
= 10"	Small	2	58	58	111,011	0.1802
	Medium	5	387	312	111,011	0.4504
	Large	6	3932	3600	111,011	0.5405
	Huge	2	17705	17705	111,011	0.1802

* 14 of the 31 records have both MIN_WATER_DEPTH and MAX_WATER_DEPTH set to "0".

** Exposure comes from an analysis of PPL_MASTERS database as published by MMS on February 15, 2001.

*** Spill Sizes:

- Small (S) - = 50 < 100 bbl
- Medium (M) - = 100 < 1,000 bbl
- Large (L) - = 1,000 < 10,000 bbl
- Huge (H) - = 10,000 bbl

Next, 31 GOM OCS pipeline spill records were reviewed and analyzed for causal and spill size distributions. In particular, it was necessary to analyze spill frequencies for spills less than and greater than 1,000 bbl. Table 2.2 shows the summary of the record information, while Table 2.3 summarizes the spill cause distributions for two spill size ranges (small and medium, large and huge).

2.3 Platform Spill Data

Platform spills in the MMS database are given for the period from 1972 to 1999. The platform spill data are given with an exposure of producing well-years. As for pipelines, the spill records themselves were accessed in order to obtain the correlation between spill cause and spill size. Table 2.4 shows the results of the causal and spill size distribution analysis, while Table 2.5 gives the causal distribution as well as the spill frequency per 10,000 well-years.

In order to assess spill occurrence from platform facilities, using the above per well-year frequency, it is necessary to estimate the number of wells per platform. The number of production wells given in each scenario was distributed equally among the production platforms specified (by MMS) for this study.

2.4 Well Oil Blowout Data

The development scenarios considered under this study include the drilling of exploratory and development wells, and the process of producing oil from production wells [12, 69]. Table 2.6 shows a summary of well drilling blowout oil spill data generated in support of the Northstar and Liberty oil development projects [52]. Table 2.7 gives the statistics for production wells. The combination of these statistics together with the cumulative distribution function for oil blowout releases given in [59], generated in support of the Northstar project, permits a blowout spill volume frequency distribution as summarized in Table 2.8. It should be noted that the exposure factor or frequency unit varies between the well drilling activities (where it is per well) and the production activities (where it is per well-year).

2.5 Arctic Effects Historical Data

2.5.1 General Approaches to the Quantification of Arctic Effects

There are essentially two main categories of Arctic effects; namely, those that are unique to the Arctic, such as marine ice effects, and those that are the same types of effects as those in temperate areas, but occurring with a different frequency, such as anchor impacts on subsea pipelines. The first will be termed “unique” effects; the second, “modified” effects. Modified Arctic effects are dealt with in conjunction with the fault tree analysis described in Chapter 4. Only those Arctic effects or hazards unique to the Arctic, and potentially having a historical occurrence database, such as ice gouging, are discussed in the balance of this section.

Table 2.2
Analysis of GOM OCS Spill Data for Causal Distribution and Spill Size

CAUSE CLASSIFICATION	# OF SPILLS	SPILL SIZE BBL										NUMBER OF SPILLS					
		1	2	3	4	5	6	7	8	9	10	S	M	L	H	SM	LH
CORROSION	**4**											**1**	**2**	**1**		**3**	**1**
External	1	80										1				**1**	
Internal	3	100	5000	414									2	1		**2**	**1**
THIRD PARTY IMPACT	**16**											**2**	**5**	**6**	**3**	**7**	**9**
Anchor Impact	10	19833	65	50	300	900	323	15576	2000	800	1211	2	4	2	2	**6**	**4**
Jackup Rig or Spud Barge	1	3200												1			**1**
Trawl/Fishing Net	5	4000	100	14423	4569	4533							1	3	1	**1**	**4**
OPERATION IMPACT	**4**											**3**		**1**		**3**	**1**
Rig Anchoring	1	50										1				**1**	
Work Boat Anchoring	3	50	5100	50								2		1		**2**	**1**
MECHANICAL	**2**												**2**			**2**	
Connection Failure	1	135											1			**1**	
Material Failure	1	210											1			**1**	
NATURAL HAZARD	**4**											**1**	**1**	**2**		**2**	**2**
Mud Slide	3	250	80	8212								1	1	1		**2**	**1**
Storm/ Hurricane	1	3500												1			**1**
ARCTIC																	
Ice Gouging																	
Strudel Scour																	
Upheaval Buckling																	
Thaw Settlement																	
Other																	
UNKNOWN	**1**	119											**1**			**1**	
TOTALS	**31**											**7**	**11**	**10**	**3**	**18**	**13**

Table 2.3
Causal and Spill Size Distribution of GOM OCS Pipeline Spills (1972-1999)

CAUSE CLASSIFICATION	Small and Medium Spills				Large and Huge Spills			
	HIST. DISTRI-BUTION (%)	# OF SPILLS	EXPOSURE (km-yr)	FREQUENCY (spill per 10^4km-yr)	HIST. DISTRI-BUTION (%)	# OF SPILLS	EXPOSURE (km-yr)	FREQUENCY (spill per 10^4km-yr)
CORROSION	**16.67**	**3**	253903	**0.1182**	**7.69**	**1**	253903	**0.0394**
External	5.56	1		0.0394				
Internal	11.11	2		0.0788	7.69	1		0.0394
THIRD PARTY IMPACT	**38.89**	**7**		**0.2757**	**69.23**	**9**		**0.3545**
Anchor Impact	33.33	6		0.2363	30.77	4		0.1575
Jackup Rig or Spud Barge					7.69	1		0.0394
Trawl/Fishing Net	5.56	1		0.0394	30.77	4		0.1575
OPERATION IMPACT	**16.67**	**3**		**0.1182**	**7.69**	**1**		**0.0394**
Rig Anchoring	5.56	1		0.0394				
Work Boat Anchoring	11.11	2		0.0788	7.69	1		0.0394
MECHANICAL	**11.11**	**2**		**0.0788**				
Connection Failure	5.56	1		0.0394				
Material Failure	5.56	1		0.0394				
NATURAL HAZARD	**11.11**	**2**		**0.0788**	**15.38**	**2**		**0.0788**
Mud Slide	11.11	2		0.0788	7.69	1		0.0394
Storm/ Hurricane					7.69	1		0.0394
ARCTIC								
Ice Gouging								
Strudel Scour								
Upheaval Buckling								
Thaw Settlement								
Other								
UNKNOWN	**5.56**	**1**		**0.0394**				
TOTALS	***100.00***	***18***		***0.7089***	***100.00***	***13***		***0.5120***

Table 2.4
Analysis of GOM OCS Platform Spill Data for Causal Distribution and Spill Size (1972-1999)

CAUSE CLASSIFICATION	# OF SPILLS	SPILL SIZE BBL													NUMBER OF SPILLS					
		1	2	3	4	5	6	7	8	9	10	11	12	13	S	M	L	H	SM	LH
PROCESS FACILITY RLS.	13	130	50	120	104	60	1456	125	50	50	55	400	280	75	6	6	1		12	1
STORAGE TANK RLS.	3	9935	7000	435												1	2		1	2
STRUCTURAL FAILURE	1	58													1				1	
HURRICANE/STORM	2	75	66												2				2	
COLLISION	2	600	108													2			2	
ARCTIC																				
- Ice Force																				
- Facility Low Temperature																				
- Other																				
TOTALS	***21***														***9***	***9***	***3***		***18***	***3***

Table 2.5
Causal and Spill Size Distribution of GOM OCS Platform Spills (1972-1999)

CAUSE CLASSIFICATION	Small and Medium Spills				Large and Huge Spills			
	HIST. DISTRI-BUTION (%)	# OF SPILLS	EXPOSURE (well-yr)	FREQUENCY (spill per 10^4 well-yr)	HIST. DISTRI-BUTION (%)	# OF SPILLS	EXPOSURE (well-yr)	FREQUENCY (spill per 10^4 well-yr)
PROCESS FACILITY RLS.	66.67	12		1.0024	33.33	1		0.0835
STORAGE TANK RLS.	5.56	1		0.0835	66.67	2		0.1671
STRUCTURAL FAILURE	5.56	1	119714	0.0835			119714	
HURRICANE/STORM	11.11	2		0.1671				
COLLISION	11.11	2		0.1671				
TOTALS	***100.00***	***18***		***1.5036***	***100.00***	***3***		***0.2506***

Table 2.6
Well Drilling Blowout Oil Spill Statistics

Event	Historical Frequency	Experience
Development drilling blowout with oil spill > 10,000 bbl	7.8×10^{-5}/wells drilled	worldwide, 1970 - present
Exploration drilling blowout with oil spill > 10,000 bbl	1.5×10^{-4}/wells drilled	worldwide, 1970 - present
Development drilling blowout with oil spill > 150,000 bbl	3.9×10^{-5}/wells drilled	worldwide, 1970 - present
Exploration drilling blowout with oil spill > 150,000 bbl	5.5×10^{-5}/wells drilled	worldwide, 1970 - present

Table 2.7
Producing Well Blowout Oil Spill Statistics

Event	Historical Frequency	Experience
Blowout during production and workovers involving some oil discharge >1 bbl	6.5×10^{-5}/well-years	U.S. OCS, 1964 - 1995
Production/workover blowout with oil spill > 10,000 bbl	2.5×10^{-5}/well-year	worldwide, 1970 - present
Production/workover blowout with oil spill > 150,000 bbl	1.0×10^{-5}/well-year	worldwide, 1970 - present

Table 2.8
Oil Spill Size Distribution for Well Blowouts

EVENT	FREQUENCY UNIT	SPILL SIZE				
		Small & Medium	Large	Small, Medium, & Large	Spill = 10,000 < 150,000 bbl	Spill = 150,000 bbl
		HISTORICAL FREQUENCY				
PRODUCTION WELL	spill per 10^5 well-years	0.50	3.50	4.00	1.50	1.00
EXPLORATION WELL DRILLING	spill per 10^5 wells	3.16	22.11	25.27	9.50	5.50
DEVELOPMENT WELL DRILLING	spill per 10^5 wells	1.30	9.08	10.38	3.90	3.90

2.5.2 Ice Gouging

Ice gouging occurs when a moving ice feature contacts the sea bottom and penetrates into it, generally as it moves against a positive sea bottom slope. The ice feature can be a multiyear ridge, a hummock, or ice rafting formation. Various studies have been conducted on the frequency and depth distribution of ice gouges [8, 27, 29, 30, 46, 67, 68], and a number of assessments of the likelihood of resultant subsea pipeline failure [8, 29] have also been carried out. Pipeline failure frequencies at different water depth regimes as a result of ice gouging in this study have been estimated on the basis of the historical ice gouge characteristics [29] together with an analytical assessment [8, 68] of their likelihood to damage a pipeline.

According to Weeks [67, 68], a relationship between the expected probability of pipeline failure from ice gouging and ice gouging local characteristics may be expressed as follows:

$$N = e^{-kx}\, H_S\; ?\; F\; ?\; T\; ?\; L_P\; ?\, sin? \qquad \textbf{(2.1)}$$

Where:

- N = Number of pipeline failures at burial depth of cover x (meters)
- k = Inverse of mean scour depth (m^{-1})
- H_S = Probability of pipeline failure given ice gouge impact or hit
- F = Scour flux per km-yr
- L_P = Length of pipeline (km)
- $?$ = Gouge orientation (degrees) from pipeline centerline

For the Northstar project, according to [30], the mean scour depth is 0.4 m giving a k factor of 2.5. In addition, a good estimate of scour flux for shallow water is 4 gouges/km-yr. Using an average pipeline depth of cover of 2.5 m, an average directional angle of 45°, a conditional failure probability (H_S) of 0.8, gives a frequency of 5.23 x 10^{-6}/km-yr. For the purposes of the analysis, this frequency must be distributed among different spill size consequences. Due to the difficulty of containing spills under ice, one can expect that the majority of spills would be in the large and huge categories. However, huge spills would be limited by segment length. Thus, a conditional probability (given a spill) of 50% has been assigned to large spills, and one of 14% to huge spills. Least likely are small spills, and accordingly they have been given a probability of 13%. The remaining probability of 23% has been assigned to medium sized spills. The resultant distribution of expected frequencies of spill sizes associated with ice gouging is given in Table 2.9.

Also, high and low values have been assigned in order to permit an analysis of the likely distribution of the effects. Essentially, these variations in effect probability were obtained through a parametric sensitivity analysis using Equation 2.1 for a range of likely values of depth of cover from 2.0 m to 3.0 m (with an expected value of 2.5 m). These resultant low and high values are also summarized in Table 2.9. For medium water depth, an analogous process was carried out with a reduced gouge flux of 2 gouges/km-yr. For deep water (= 30 m) no gouging is expected.

Table 2.9
Summary of Arctic Effect Inputs

Cause Classification	Spill Size	*Water Depth*								
		Shallow			Medium			Deep		
		Frequency Increment per 10^5 km-yr								
		Low	Expected	High	Low	Expected	High	Low	Expected	High
Ice Gouging	**S**	0.0060	0.0680	0.8290	0.0030	0.0340	0.4145			
	M	0.0090	0.1210	1.4670	0.0045	0.0605	0.7335			
	L	0.0210	0.2610	3.1900	0.0105	0.1305	1.5950			
	H	0.0060	0.0730	0.8930	0.0030	0.0365	0.4465			
Strudel Scour	**S**	0.0004	0.0012	0.0044						
	M	0.0006	0.0020	0.0078						
	L	0.0014	0.0045	0.0170						
	H	0.0004	0.0012	0.0048						
Upheaval Buckling	**S**	0.00007	0.00023	0.00088	0.00007	0.00023	0.00088	0.00007	0.00023	0.00088
	M	0.00013	0.00041	0.00156	0.00013	0.00041	0.00156	0.00013	0.00041	0.00156
	L	0.00028	0.00089	0.00340	0.00028	0.00089	0.00340	0.00028	0.00089	0.00340
	H	0.00008	0.00025	0.00095	0.00008	0.00025	0.00095	0.00008	0.00025	0.00095
Thaw Settlement	**S**	0.00004	0.00012	0.00044	0.00004	0.00012	0.00044	0.00004	0.00012	0.00044
	M	0.00006	0.00020	0.00078	0.00006	0.00020	0.00078	0.00006	0.00020	0.00078
	L	0.00014	0.00045	0.00170	0.00014	0.00045	0.00170	0.00014	0.00045	0.00170
	H	0.00004	0.00012	0.00048	0.00004	0.00012	0.00048	0.00004	0.00012	0.00048

2.5.3 Strudel Scour

When fresh water collecting on top of the ice sheet generally from rivers running into the Arctic seas, and drains through a hole in the ice, its hydrodynamic effect on the ocean floor below forms a depression which is called a strudel scour. Numerous studies have been conducted on strudel scour [29, 30], so that a prediction on the number of strudel scours per unit area can be made on the basis of historical data. Strudel scours are restricted to shallow water. With an average strudel scour frequency of 4 scours/mi^2 (1.5 scours/km^2) [30], the methodology in [30] can be utilized to predict a possible failure rate of subsea pipelines in shallow waters due to strudel scour of approximately 8.9 x 10^{-8}/km-yr. Using reasoning similar to that for the distribution of spill sizes for ice gouging, and assigning limits based on parametric sensitivity studies, the distribution of strudel scour frequencies for shallow water as shown in Table 2.9 can be derived. Strudel scours are not expected in water depths greater than 10 m.

2.5.4 Upheaval Buckling

Upheaval buckling occurs in a pipeline as a result of its thermal expansion which causes it to buckle upwards to accommodate the extra length generated from thermal effects. Unfortunately, there appears to be no defensible analytical method for calculating the probability of upheaval buckling of Arctic subsea pipelines in general. Accordingly, upheaval buckling has been taken simply as a percentage of the strudel scour effects. Assuming that a upheaval buckling occurs 20% as often as strudel scour, the distribution shown in Table 2.9 can be derived. Upheaval buckling is expected to be independent of water depth; accordingly, the same values have been used for each water depth range.

2.5.5 Thaw Settlement

Thaw settlement occurs when a permafrost lens or formation over which the pipeline was installed melts as a result of the heat generated by the pipeline and ceases to support the pipeline so that the pipeline overburden loads the pipeline and causes it to deflect downwards. As for the case of upheaval buckling, writers are not aware of any method for defensibly calculating the probability of pipeline failures from thaw settlement. Accordingly, resort is again made to the percentage of a known phenomenon approach and thaw settlement has been assumed to occur at a rate equal to 10% of that associated with strudel scour. The resultant distribution is shown in Table 2.9. Like upheaval buckling, thaw settlement is expected to be independent of water depth.

CHAPTER 3

FUTURE DEVELOPMENT SCENARIOS

3.1 Approaches to Future Development Scenarios

For the purposes of the fault tree analysis utilized in this study, future offshore oil and gas development scenarios need to include the following characteristics:

- Water depth range, particularly for pipelines
- Physical quantities of individual facilities (e.g., production wells, pipelines) on an annual basis in correspondence with the baseline data exposure factors (e.g., per well year or per km-yr)
- Associated oil production volumes
- Other characteristics such as pipeline diameter or type of well drilled

Table 3.1 shows the Classification of Development Scenarios by water depth range and operation type. The salient aspect of this classification is subdivision into water depth ranges among which Arctic hazard characteristics (such as ice gouging rates) may change. The following water depth categories have been used:

- Shallow - < 10 meters
- Medium - = 10 < 30 meters
- Deep - = 30 < 60 meters
- Very Deep - = 60 meters

In Table 3.1, an indication is given of the types of facilities that might be utilized in each of the principal types of oil and gas activities, exploration, production, or transportation. As will be seen in this chapter, current forecasts for development scenarios over the next 40 years exclude very deep locations, in excess of 60 m. Accordingly, any suggestions for facilities under the very deep scenario would be speculative and will not be used in the current study.

In general, the scenarios described in this chapter were developed to an appropriate level and type of detail to match the type of unit spill data and statistics available as a basis for the oil spill occurrence indicator quantification.

The principal regions of interest within the study area are the Beaufort Sea Lease Areas shown in Figure 3.1 and the Chukchi Sea Lease Areas illustrated in Figure 3.2.

Table 3.1
Classification of Development Scenarios

PRINCIPAL ACTIVITY	WATER DEPTH (m)			
	SHALLOW (< 10)	**MEDIUM (= 10 < 30)**	**DEEP (= 30 < 60)**	**VERY DEEP (= 60)**
EXPLORATION	▪ Artificial island ▪ Drill barge ▪ Ice island	▪ Artificial island ▪ Drill ship (summer) ▪ Caisson	▪ Drill ship (summer) ▪ Semisubmersible (summer)	▪ Drill ship (summer) ▪ Semisubmersible (summer)
PRODUCTION	▪ Artificial island ▪ Caisson island	▪ Caisson island ▪ Gravity Base Structure (GBS)	▪ Caisson island ▪ Gravity Base Structure (GBS)	▪ New design structure ▪ Submarine habitat
TRANSPORT	▪ Subsea pipeline	▪ Subsea pipeline	▪ Subsea pipeline ▪ Storage & tankers	▪ Subsea pipeline ▪ Submarine storage ▪ Icebreaking tankers ▪ Submarine tankers

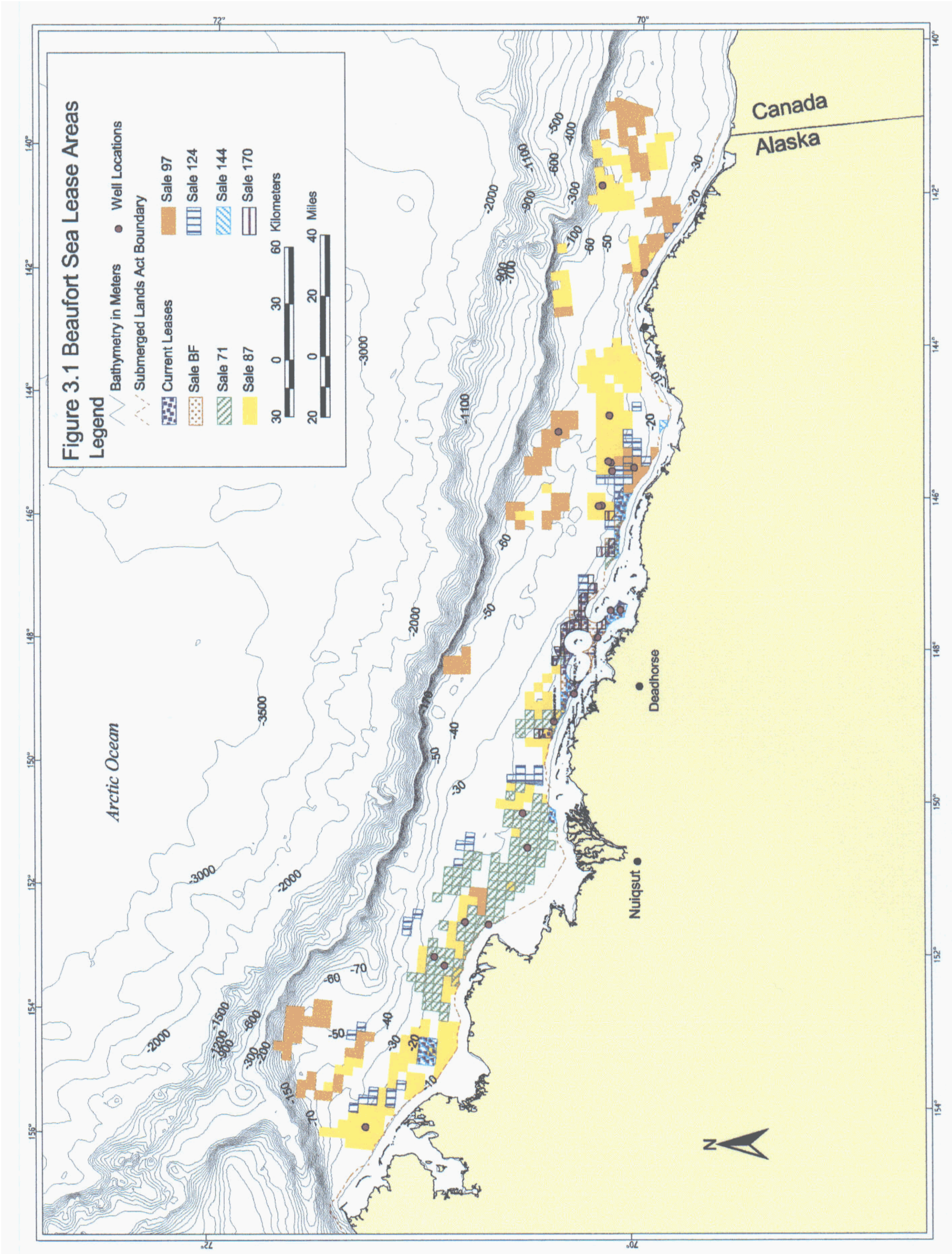


Figure 3.1 Beaufort Sea Lease Areas

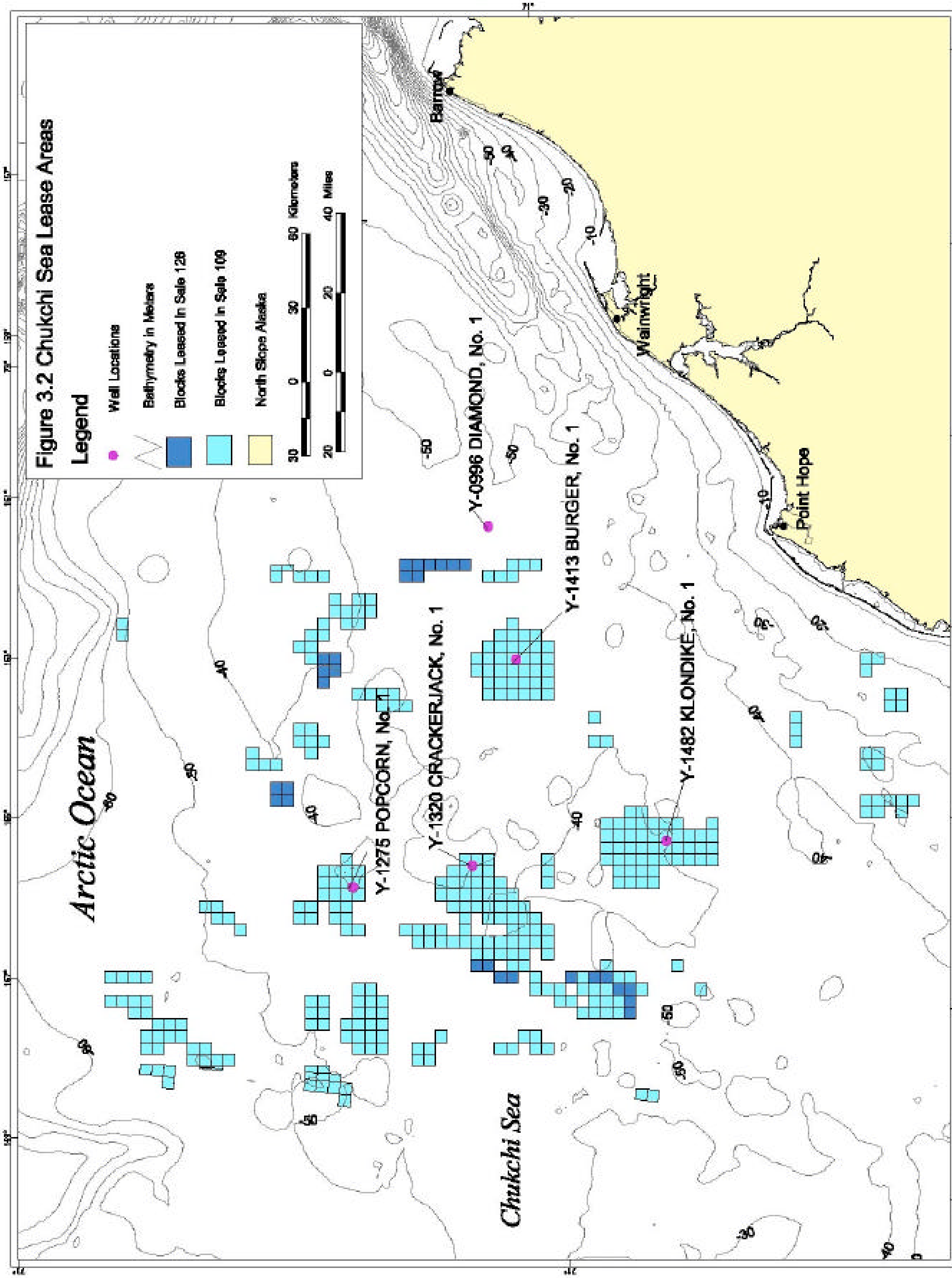


Figure 3.2 Chukchi Sea Lease Areas

3.2 Beaufort Sea Development Scenarios

As a basis for the current analysis, the geographic and water depth distribution of the facilities and its variation over the life of the development is required in order to effectively incorporate the effects of Arctic operations on the oil spill occurrences. The obvious way to approach this, at least for an initial scenario, is to sketch a map of the possible geographic configuration of the facilities. Such a map, based on the composite Beaufort Sea (All Sale) scenario is shown in Figure 3.3. This location map also shows the four water depth zones – shallow, medium, deep, and very deep. As can be seen, no facilities are predicted in the very deep region. The details of the development scenarios, given in Appendix B, were generated by Alaska MMS personnel for three different Beaufort Sea Lease Sale alternatives, Sales 1, 2, and 3, and for a composite of all sales.

Table 3.2 summarizes the complete Beaufort Sea composite (Sale All) scenario including its temporal development from the present to Year 2038, at which time it is forecast to cease production. For items such as exploration and field delineation well drilling, the actual number of wells drilled in a given year were needed, since the statistics of well spill (blowouts) are on a per well drilled exposure unit. For items that continue from year to year, such as production wells or subsea pipelines, both the annual incremental and the cumulative total are needed. Specifically, the following facility quantities by water depth zone were estimated and distributed as shown in Table 3.2:

- Exploration wells drilled – annual
- Delineation wells drilled – annual
- Production platforms – annual increment and cumulative number
- Production/service wells – annual increment and cumulative number
- Pipeline quantities for NPS < 10, and NPS = 10, and total – annual increment and cumulative number of pipeline length in service
- Oil production volumes – annual

As noted above, these quantities match the type of unit spill data that can be made available through the analysis. For example, we have spill data by pipeline diameter only for lines < and = 10”, so a full spectrum of pipeline diameters would be redundant. The important aspect of the information in Table 3.2, however, is the distribution of the facilities by water depth, as there is a significant variation in Arctic hazards by water depth.

Similar tables were developed for Lease Sales 1, 2, and 3. These are given in detail in Appendix B. Peak production for the composite scenario occurs in Year 2020. Accordingly, Table 3.3 summarizes the quantities of facilities and their distribution by water depth for Year 2020, the maximum production year of the composite (Sale All) scenario.

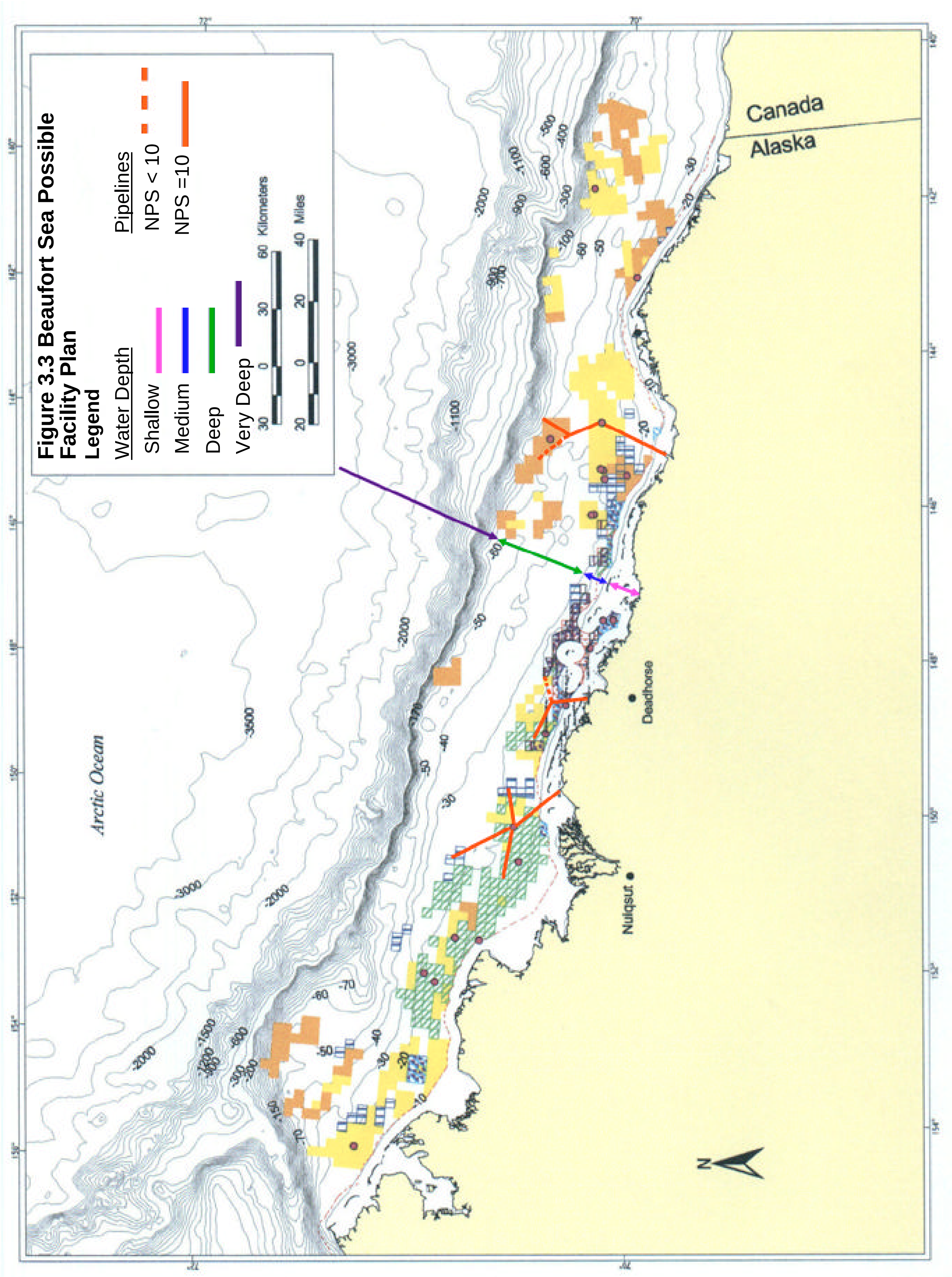


Figure 3.3 Beaufort Sea Possible Facility Plan
Legend
Water Depth
Shallow
Medium
Deep
Very Deep
Pipelines
NPS < 10
NPS =10
Kilometers
Miles
Arctic Ocean
Canada
Alaska
Deadhorse
Nuiqsut

Table 3.2
Beaufort Sea All Sale Production Scenarios

Year	Water Depth	Exploration Wells	Delineation Wells	Production Platforms		Production Wells		In-use Pipeline Length [miles]						Production MMbbl
								Sum<10"		Sum >=10"		Sum All		
				Incr.	Cum.	Incr.	Cum.	Incr.	Cum.	Incr.	Cum.	Incr.	Cum.	
2004	Shallow	1												
	Medium													
	Deep													
	Total	**1**												
2005	Shallow	1												
	Medium													
	Deep													
	Total	**1**												
2006	Shallow	1	2											
	Medium													
	Deep													
	Total	**1**	**2**											
2007	Shallow	2												
	Medium													
	Deep													
	Total	**2**												
2008	Shallow	1	2											
	Medium	1												
	Deep													
	Total	**2**	**2**											
2009	Shallow		2	1	1	3	3							
	Medium	1												
	Deep													
	Total	**1**	**2**	**1**	**1**	**3**	**3**							
2010	Shallow	1			1	10	13			10	10	10	10	10.9
	Medium	1	2											
	Deep													
	Total	**2**	**2**		**1**	**10**	**13**			**10**	**10**	**10**	**10**	10.9
2011	Shallow			1	2	13	26				10		10	19.9
	Medium													
	Deep													
	Total			**1**	**2**	**13**	**26**				**10**		**10**	19.9
2012	Shallow			1	3	13	39			10	20	10	20	30.8
	Medium	2												
	Deep	1												
	Total	**3**		**1**	**3**	**13**	**39**			**10**	**20**	**10**	**20**	30.8
2013	Shallow				3	20	59			15	35	15	35	50.7
	Medium	1	3											
	Deep	1												
	Total	**2**	**3**		**3**	**20**	**59**			**15**	**35**	**15**	**35**	50.7
2014	Shallow				3	10	69				35		35	56.2
	Medium		4	1	1	3	3							
	Deep													
	Total		**4**	**1**	**4**	**13**	**72**				**35**		**35**	56.2

Table 3.2 - *continued*

Year	Water Depth	Exploration Wells	Delineation Wells	Production Platforms		Production Wells		In-use Pipeline Length [miles]						Production MMbbl
								Sum<10"		Sum >=10"		Sum All		
				Incr.	Cum.	Incr.	Cum.	Incr.	Cum.	Incr.	Cum.	Incr.	Cum.	
2015	Shallow				3		69			10	45	10	45	53.3
	Medium		2		1	10	13			10	10	10	10	10.9
	Deep	1												
	Total	**1**	**2**		**4**	**10**	**82**			**20**	**55**	**20**	**55**	64.2
2016	Shallow				3		69				45		45	47.5
	Medium			1	2	13	26				10		10	19.9
	Deep													
	Total			**1**	**5**	**13**	**95**				**55**		**55**	67.4
2017	Shallow				3		69			10	55	10	55	39.1
	Medium			1	3	13	39	5	5	10	20	15	25	38.3
	Deep	1												
	Total	**1**		**1**	**6**	**13**	**108**	**5**	**5**	**20**	**75**	**25**	**80**	77.4
2018	Shallow				3		69				55		55	32.3
	Medium			1	4	24	63		5		20		25	50.6
	Deep	1												
	Total	**1**		**1**	**7**	**24**	**132**		**5**		**75**		**80**	82.9
2019	Shallow				3		69			15	70	15	70	26.7
	Medium			1	5	24	87	5	10	15	35	20	45	77.9
	Deep													
	Total			**1**	**8**	**24**	**156**	**5**	**10**	**30**	**105**	**35**	**115**	104.6
2020	Shallow				3		69				70		70	22.0
	Medium				5	20	107		10		35		45	82.8
	Deep													
	Total				**8**	**20**	**176**		**10**		**105**		**115**	104.8
2021	Shallow				3		69				70		70	18.1
	Medium				5	20	127		10		35		45	80.5
	Deep													
	Total				**8**	**20**	**196**		**10**		**105**		**115**	98.6
2022	Shallow				3		69				70		70	15.0
	Medium				5	10	137		10		35		45	74.2
	Deep													
	Total				**8**	**10**	**206**		**10**		**105**		**115**	89.2
2023	Shallow				3		69				70		70	12.5
	Medium				5		137		10		35		45	68.9
	Deep													
	Total				**8**		**206**		**10**		**105**		**115**	81.4
2024	Shallow				3		69				70		70	10.4
	Medium				5		137		10		35		45	64.4
	Deep													
	Total				**8**		**206**		**10**		**105**		**115**	74.8
2025	Shallow			-1	2	-23	46			-10	60	-10	60	6.5
	Medium				5		137		10		35		45	56.0
	Deep													
	Total			**-1**	**7**	**-23**	**183**		**10**	**-10**	**95**	**-10**	**105**	62.5
2026	Shallow				2		46				60		60	5.5
	Medium				5		137		10		35		45	48.6
	Deep													
	Total				**7**		**183**		**10**		**95**		**105**	54.1
2027	Shallow			-1	1	-23	23			-10	50	-10	50	2.4
	Medium				5		137		10		35		45	42.2
	Deep													
	Total			**-1**	**6**	**-23**	**160**		**10**	**-10**	**85**	**-10**	**95**	44.6
2028	Shallow			-1		-23				-15	35	-15	35	
	Medium				5		137		10		35		45	36.9
	Deep													
	Total			**-1**	**5**	**-23**	**137**		**10**	**-15**	**70**	**-15**	**80**	36.9

Table 3.2 - *continued*

Year	Water Depth	Exploration Wells	Delineation Wells	Production Platforms		Production Wells		In-use Pipeline Length [miles]						Production MMbbl
								Sum<10"		Sum >=10"		Sum All		
				Incr.	Cum.	Incr.	Cum.	Incr.	Cum.	Incr.	Cum.	Incr.	Cum.	
2029	Shallow										35		35	
	Medium				5		137		10		35		45	32.2
	Deep													
	Total				**5**		**137**		**10**		**70**		**80**	32.2
2030	Shallow									-10	25	-10	25	
	Medium			-1	4	-23	114		10	-10	25	-10	35	25.8
	Deep													
	Total			**-1**	**4**	**-23**	**114**		**10**	**-20**	**50**	**-20**	**60**	25.8
2031	Shallow										25		25	
	Medium				4		114		10		25		35	22.6
	Deep													
	Total				**4**		**114**		**10**		**50**		**60**	22.6
2032	Shallow										25		25	
	Medium				4		114		10		25		35	19.7
	Deep													
	Total				**4**		**114**		**10**		**50**		**60**	19.7
2033	Shallow										25		25	
	Medium				4		114		10		25		35	17.2
	Deep													
	Total				**4**		**114**		**10**		**50**		**60**	17.2
2034	Shallow										25		25	
	Medium				4		114		10		25		35	15.1
	Deep													
	Total				**4**		**114**		**10**		**50**		**60**	15.1
2035	Shallow										25		25	
	Medium				4		114		10		25		35	13.2
	Deep													
	Total				**4**		**114**		**10**		**50**		**60**	13.2
2036	Shallow									-10	15	-10	15	
	Medium			-2	2	-46	68	-5	5	-10	15	-15	20	8.3
	Deep													
	Total			**-2**	**2**	**-46**	**68**	**-5**	**5**	**-20**	**30**	**-25**	**35**	8.3
2037	Shallow										15		15	
	Medium				2		68		5		15		20	7.3
	Deep													
	Total				**2**		**68**		**5**		**30**		**35**	7.3
2038	Shallow										15		15	
	Medium				2		68		5		15		20	6.5
	Deep													
	Total				**2**		**68**		**5**		**30**		**35**	6.5

Table 3.3
Summary of Development Scenarios for Year 2020[1]

Sale	Year	Water Depth	Exploration Wells	Delineation Wells	Production Platforms		Production Wells	Prod. / Serv. Wells	In-use Pipeline Length [miles]						Production [MMbbl]
									Sum<10"		Sum >=10"		Sum All		
					Incr.	Cum.	Incr.	Cum.	Incr.	Cum.	Incr.	Cum.	Incr.	Cum.	
1	2020	Shallow				2		46				30		30	12.8
		Medium				1		23				10		10	13.5
		Deep													
		Total				**3**		**69**				**40**		**40**	26.3
2	2020	Shallow				1		23				25		25	9.2
		Medium				2		46		5		10		15	30.7
		Deep													
		Total				**3**		**69**		**5**		**35**		**40**	39.9
3	2020	Shallow										15		15	
		Medium				2	20	38		5		15		20	38.6
		Deep													
		Total				**2**	**20**	**38**		**5**		**30**		**35**	38.6
ALL	2020	Shallow				3		69				70		70	22.0
		Medium				5	20	107		10		35		45	82.8
		Deep													
		Total				**8**	**20**	**176**		**10**		**105**		**115**	104.8

[1] Year 2020 is the maximum production year for All Sale scenario.

3.3 Chukchi Sea Development Scenarios

The data for the Chukchi Sea development scenarios was based on Lease Sale 126 [38] publication. Two scenarios were selected; the base case mid point and the high case mid point, given in that publication.

Figure 3.4 shows a possible pipeline and facility plot plan corresponding to the base case mid point facility peak production (Year 2007) quantities.

The Chukchi Sea base case mid point scenario facility quantities, up to Year 2010, are given in Table 3.4, while the high case mid point scenario is provided in Table 3.5.

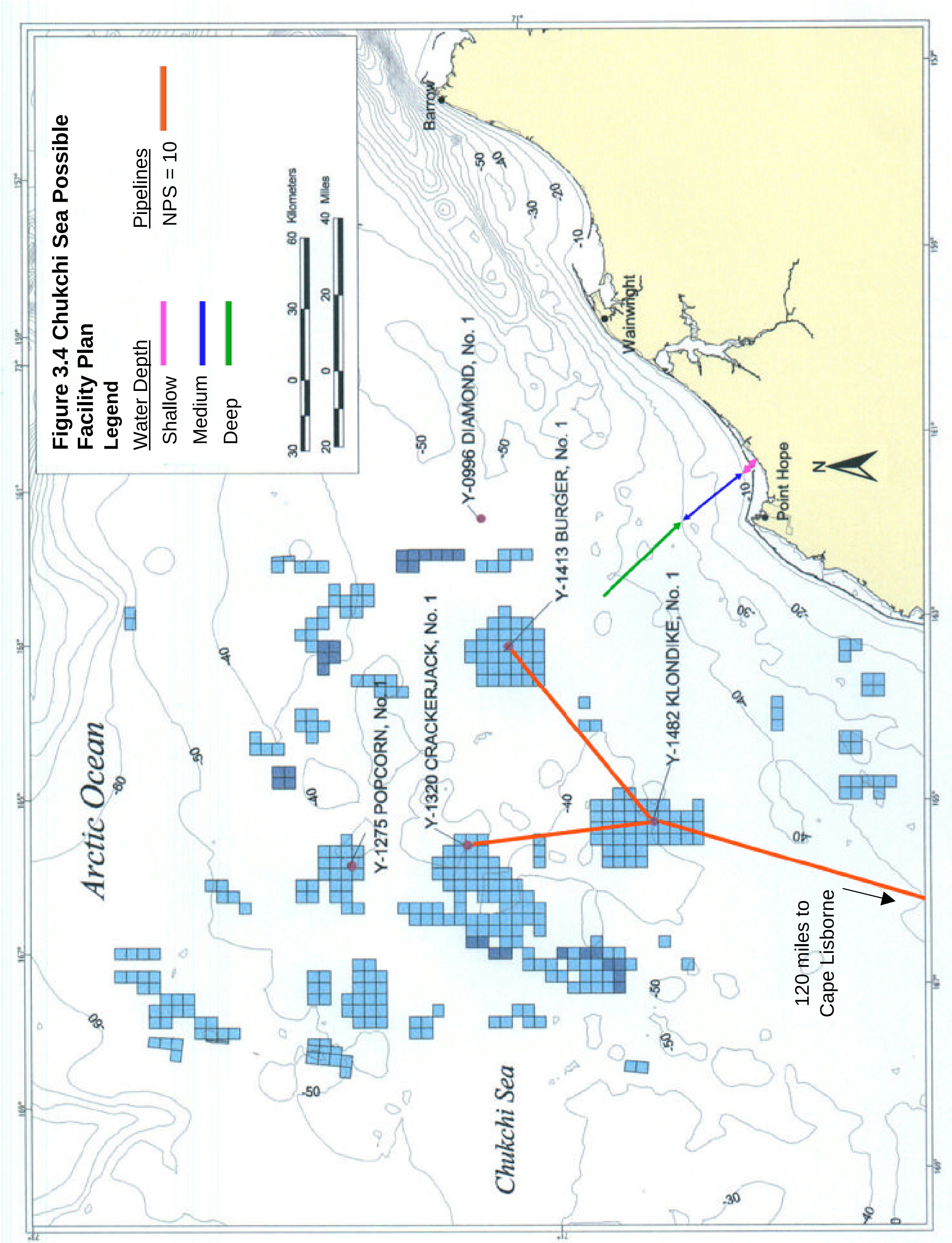


Figure 3.4 Chukchi Sea Possible Facility Plan

Table 3.4
Chukchi Sea Base Case Mid Point Development Scenario

Year	Water Depth	Exploration Wells	Delineation Wells	Production Platforms		Prod./Serv. Wells		Pipeline Length [miles]						Production MMbbl
								Sum<10"		Sum >=10"		Sum All		
				Incr.	Cum.	Incr.	Cum.	Incr.	Cum.	Incr.	Cum.	Incr.	Cum.	
1998	Shallow													
	Medium													
	Deep	2	2											
	Total	**2**	**2**											**0**
1999	Shallow									5	5	5	5	
	Medium									60	60	60	60	
	Deep									135	135	135	135	
	Total									**200**	**200**	**200**	**200**	**0**
2000	Shallow										5		5	
	Medium										60		60	
	Deep			2	2	8	8				135		135	
	Total			**2**	**2**	**8**	**8**				**200**		**200**	**0**
2001	Shallow										5		5	
	Medium										60		60	
	Deep			2	4	40	48				135		135	
	Total			**2**	**4**	**40**	**48**				**200**		**200**	**0**
2002	Shallow										5		5	
	Medium										60		60	
	Deep			2	6	60	108				135		135	
	Total			**2**	**6**	**60**	**108**				**200**		**200**	**101**
2003	Shallow										5		5	
	Medium										60		60	
	Deep				6	80	188				135		135	
	Total				**6**	**80**	**188**				**200**		**200**	**135**
2004	Shallow										5		5	
	Medium										60		60	
	Deep				6	26	214				135		135	
	Total				**6**	**26**	**214**				**200**		**200**	**135**
2005	Shallow										5		5	
	Medium										60		60	
	Deep				6		214				135		135	
	Total				**6**		**214**				**200**		**200**	**135**
2006	Shallow										5		5	
	Medium										60		60	
	Deep				6		214				135		135	
	Total				**6**		**214**				**200**		**200**	**135**
2007	Shallow										5		5	
	Medium										60		60	
	Deep				6		214				135		135	
	Total				**6**		**214**				**200**		**200**	**135**
2008	Shallow										5		5	
	Medium										60		60	
	Deep				6		214				135		135	
	Total				**6**		**214**				**200**		**200**	**119**
2009	Shallow										5		5	
	Medium										60		60	
	Deep				6		214				135		135	
	Total				**6**		**214**				**200**		**200**	**103**
2010	Shallow										5		5	
	Medium										60		60	
	Deep				6		214				135		135	
	Total				**6**		**214**				**200**		**200**	**92**

Table 3.5
Chukchi Sea High Case Mid Point Development Scenario

Year	Water Depth	Exploration Wells	Delineation Wells	Production Platforms		Prod./Serv. Wells		Pipeline Length [miles]						Production MMbbl
								Sum<10"		Sum >=10"		Sum All		
				Incr.	Cum.	Incr.	Cum.	Incr.	Cum.	Incr.	Cum.	Incr.	Cum.	
1998	Shallow													
	Medium													
	Deep	3	1											
	Total	**3**	**1**											**0**
1999	Shallow													
	Medium													
	Deep	2	1											
	Total	**2**	**1**											**0**
2000	Shallow									5	5	5	5	
	Medium									60	60	60	60	
	Deep	2		2	2					135	135	135	135	
	Total	**2**		**2**	**2**					**200**	**200**	**200**	**200**	**0**
2001	Shallow										5		5	
	Medium										60		60	
	Deep			6	8	50	50				135		135	
	Total			**6**	**8**	**50**	**50**				**200**		**200**	**0**
2002	Shallow										5		5	
	Medium										60		60	
	Deep			4	12	80	130				135		135	
	Total			**4**	**12**	**80**	**130**				**200**		**200**	**0**
2003	Shallow										5		5	
	Medium										60		60	
	Deep				12	140	270				135		135	
	Total				**12**	**140**	**270**				**200**		**200**	**223**
2004	Shallow										5		5	
	Medium										60		60	
	Deep				12	140	410				135		135	
	Total				**12**	**140**	**410**				**200**		**200**	**297**
2005	Shallow										5		5	
	Medium										60		60	
	Deep				12	72	482				135		135	
	Total				**12**	**72**	**482**				**200**		**200**	**297**
2006	Shallow										5		5	
	Medium										60		60	
	Deep				12		482				135		135	
	Total				**12**		**482**				**200**		**200**	**297**
2007	Shallow										5		5	
	Medium										60		60	
	Deep				12		482				135		135	
	Total				**12**		**482**				**200**		**200**	**297**
2008	Shallow										5		5	
	Medium										60		60	
	Deep				12		482				135		135	
	Total				**12**		**482**				**200**		**200**	**297**
2009	Shallow										5		5	
	Medium										60		60	
	Deep				12		482				135		135	
	Total				**12**		**482**				**200**		**200**	**262**
2010	Shallow										5		5	
	Medium										60		60	
	Deep				12		482				135		135	
	Total				**12**		**482**				**200**		**200**	**227**

CHAPTER 4

FAULT TREE ANALYSIS FOR ARCTIC OIL SPILL FREQUENCIES

4.1 General Description of Fault Tree Analysis

Fault trees are a method for modeling the occurrence of failures. They are used when an adequate history to provide failure statistics is not available. Developed initially by Rasmussen for the US Nuclear Regulatory Commission in the early 1970s [65, 51], fault trees have become a popular risk analytic tool for predicting risks, assessing relative risks, and quantifying comparative risks [2, 7, 9, 14, 15, 18, 23, 26, 45]. In 1976, fault trees were first used by Bercha to quantify oil spill probabilities in the Canadian Beaufort Sea for the Canadian Department of the Environment [10, 11]. In the present study they are used for the transformation of historical spill statistics for non-Arctic regions to predictive spill statistics for Arctic regions in the study area.

4.2 Fault Tree Methodology

4.2.1 Fault Tree Analysis Basics

The basic symbols used in the graphic depiction of simple (as used here) fault tree networks are illustrated in Figure 4.1. As may be seen, the two types of symbols designate logic gates and event types. The basic fault tree building blocks are the events and associated sub-events, which form a causal network. The elements linking events are the AND and OR gates, which define the logical relationship among events in the network. The output event from an OR gate occurs if any one or more of the input events to the gate occurs. The output event from an AND gate occurs only if all the input events occur simultaneously.

The basic structure of a fault tree is illustrated in Figure 4.2. Because of their connection through an AND gate, Event D and Event E must both occur for the resultant Event B to occur. An OR gate connects Events B and C; therefore, the occurrence of either one or both of Events B and C results in the occurrence of the resultant Event A. As may be seen, the principal fault tree structures are easy to apply; however, the representation of complex problems often requires very large fault trees, which become more difficult to analyze and require more advanced techniques such as minimal cut-set analysis [2, 14, 18, 23, 51]. For the present application, a simple system connected through OR gates only will used.

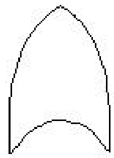
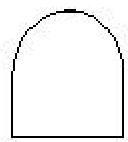
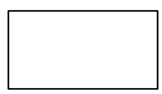
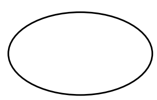
SYMBOL	DESCRIPTION
A. LOGIC	
	EITHER / OR GATE
	AND GATE
B. EVENT	
	RESULTANT EVENT
	BASIC EVENT

Figure 4.1
Basic Fault Tree Symbol Legend

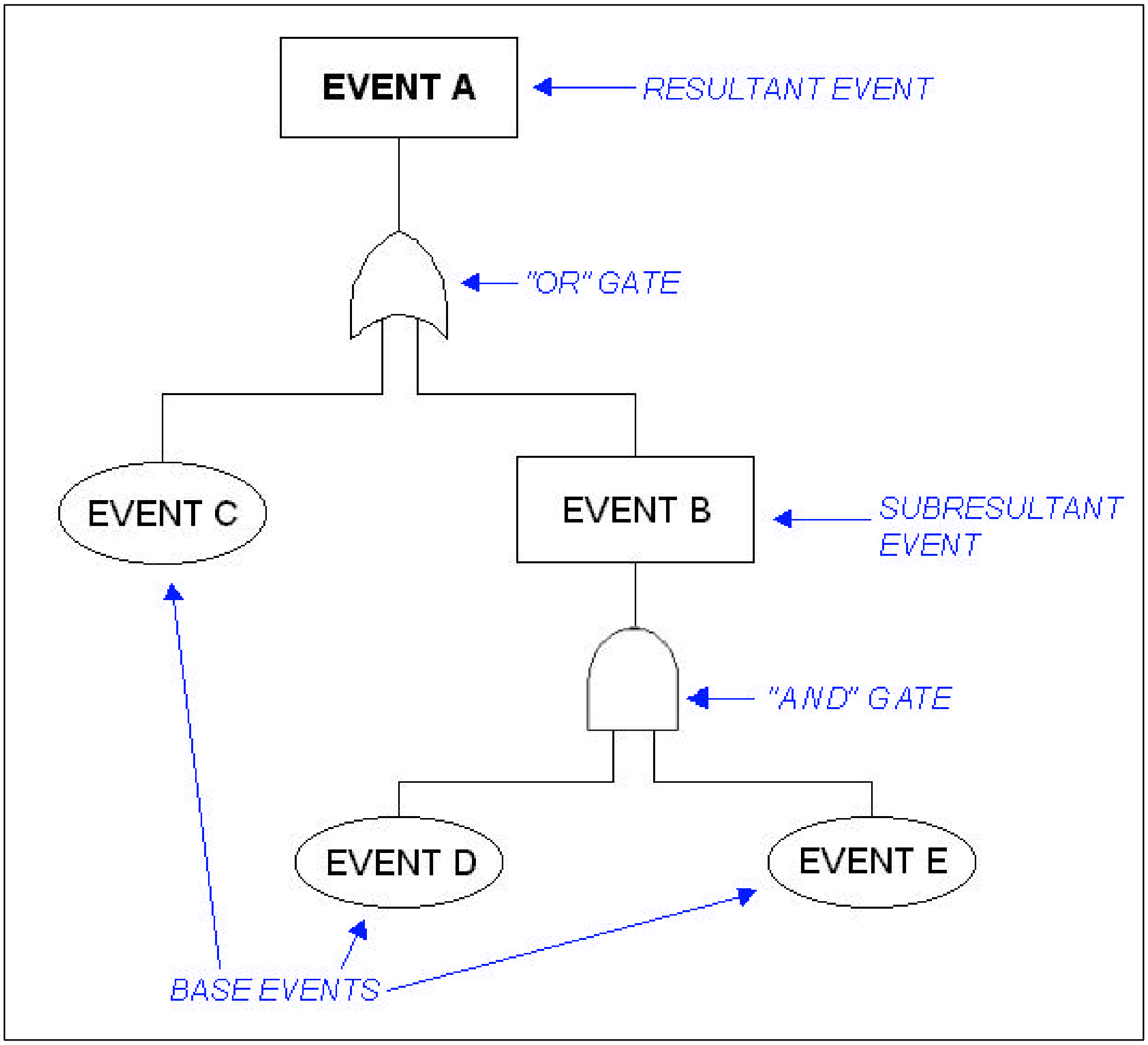


Figure 4.2
Basic Fault Tree Structure

Computationally, the probability of input events joined through an AND gate are multiplied to calculate the probabilities of the output event. The probabilities of input events joined through an OR gate are added to calculate the probability of the output event. The relevant equations and associated assumptions may be summarized as follows:

For AND Gate:

$$P = \prod_{n}^{i=1} P_i \tag{4.1a}$$

Example: Output Event Probability = P_x
Input Events failure probabilities, P_1, P_2, ….

$$P_x = P_1(P_2)(P_3) \tag{4.1b}$$

For OR Gate:

$$P = 1 - \prod_{n}^{i=1}(1 - P_i) \tag{4.2a}$$

Example: Output Event Probability = P_y
Input Event failure probabilities, P_1, P_2, …

$$P_y = 1 - \prod_{n}(1 - P_1)(1 - P_2)(1 - P_3)$$

$$P_y = P_1 + P_2 + P_3; P_i \le 0.1 \tag{4.2b}$$

In more complex fault trees, it is necessary to assure that base events which affect more than one fault tree branch are not numerically duplicated. This is done through the use of minimal cut-set theory [2, 14, 18, 23, 51]. However, as indicated earlier, the fault trees used in this study are sufficiently simple in structure and level of detail to exclude the requirement of using minimal cut-set theory in their computation algorithms.

4.2.2 Current Application of Fault Trees

Figure 4.3 illustrates a two-tier fault tree that can be used to develop pipeline large spill frequencies for the Arctic study area from the historical frequencies. Note that this example is illustrative of the process only, and does not correspond to the same numerical values used in computations later. The type of fault tree shown, to be used extensively later, is a relatively simple fault tree showing the resultant event, the spill, generated from a series of subresultant events corresponding to the pipeline spill causal classification introduced earlier in Tables 2.2 and 2.9. The upper tier of numbers (marked “H”) below each of the events in the fault tree represents the historical frequency (per 100,000 km-yr) while the lower one (marked “A”) represents the modified frequency for Arctic operations. As these fault trees are composed entirely of OR gates, the computation of resultant events is quite simple – consisting of the addition of the probabilities of events at each level of the fault tree to obtain the resultant probability at the next higher value. For example, to obtain the “Natural Hazard” Arctic (“A”) probability of 0.151, add 0.043 and 0.108. Essentially, the fault tree resultant (top event) shows that the Arctic frequency of spills (for the example pipeline category, location, and spill size) is approximately 1 in 100,000 km-yr or 1.015 x 10^{-5}/km-yr. The non-Arctic historical frequency for this spill size, by comparison, is 2.799 x 10^{-5}/km-yr, or approximately 2.8 times higher.

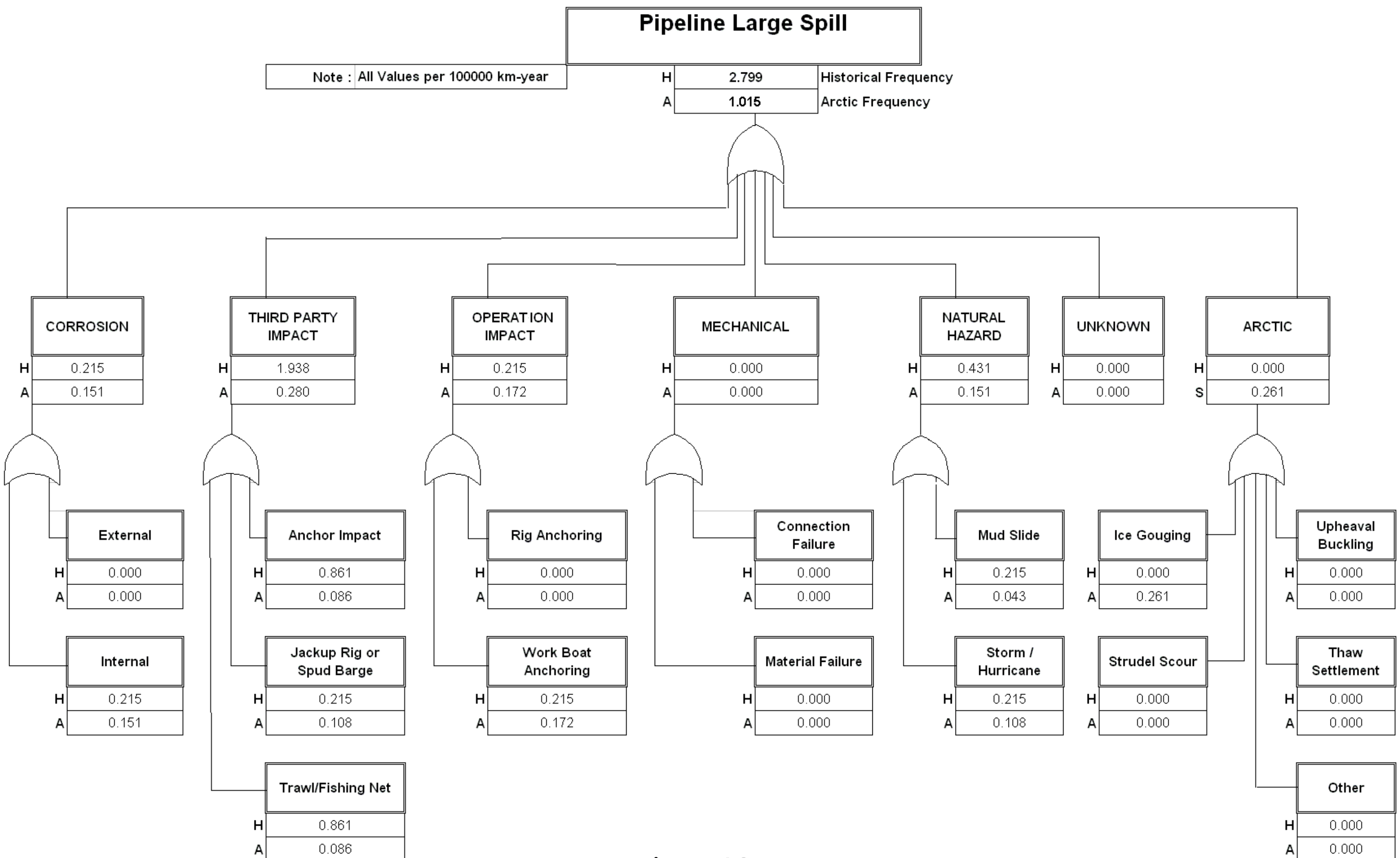


Figure 4.3
Example of Fault Tree to Transform Historical (GOM) to Arctic Spill Frequencies[1]

[1] The input data used here are only illustrative and do not represent the inputs used later in this study.

4.3 Pipeline Fault Tree Analysis

4.3.1 Fault Tree Inputs

The effects of the Arctic environment and operations are reflected in the effect on facility failure rates in two ways; namely, through "Modified Effects", those changing the frequency component of certain fault contributions such as anchor impacts which are common in both Arctic and temperate zones, and through "Unique Effects" or additive elements such as ice gouging which are unique to the Arctic offshore environment. Table 4.1 shows the frequency modifications (in %) and frequency increment additions (per 10^5 km-yr)developed for Arctic pipelines for different spill sizes throughout the three relevant water depth ranges. The right hand column of the table gives a summary of the reasoning behind the effects. For the Arctic unique effects, both the expected value (from Table 2.9) and the median value, determined through the Monte Carlo analysis, are given. The median values differ from the expected values due to skewness of the distributions introduced through the assigned values of the upper and lower bounds (Table 2.9). The following comments can be made for each of the causes described:

- *External corrosion* – Due to the low temperature, limited biological and lowered chemical effects are expected. Coatings will be state of art and high level of quality control will be used during pipeline installation resulting in high integrity levels of coating to prevent external corrosion.
- *Internal corrosion* – Additional (above historical levels) inspection or smart pigging is anticipated.
- *Anchor impact* – The very low traffic densities of third party shipping in the area justify a 90% reduction in anchor impact expectations on the pipeline.
- *Jack-up rig or spud barges* – Associated or other operations are going to be substantially more limited than they are in the historical data population in the Gulf of Mexico.
- *Trawl/Fishing net* – Very limited fishing is expected in the Beaufort Sea. A slight increase in fishing activity might be justifiable in the case of the Chukchi, but this was not done here.
- *Rig anchoring* – Although it is anticipated that no marine traffic except possibly icebreakers will occur during the ice season, an increased traffic density during the four month open water season to resupply the platforms is expected, justifying only a 20% decrease in this failure cause.
- *Workboat anchoring* – The same applies to workboat anchoring as to rig anchoring.
- *Mechanical connection failure or material failure* – No change was made to account for Arctic effects.
- *Mudslide* – A relatively low gradient resulting in limited mudslide potential is anticipated. A gradual increase in the mudslide potential (reflected by smaller decreases in failure frequency) ranging from 80% for shallow water to only 40% in deep water was included to account for the anticipated increase in gradient as deeper waters are encountered.

Table 4.1
Pipeline Fault Tree Analysis Input Rationalization

CAUSE CLASSIFICATION	Spill Size	Shallow	Medium	Deep	Reason
		Frequency Change %			
ARCTIC MODIFIED					
CORROSION					
External	**All**	(50)	(50)	(50)	Limited temperature and bio effects. Extra smart pigging.
Internal	**All**	(30)	(30)	(30)	Extra smart pigging.
THIRD PARTY IMPACT					
Anchor Impact	**All**	(90)	(90)	(90)	Low traffic.
Jackup Rig or Spud Barge	**All**	(50)	(50)	(50)	Low facility density.
Trawl/Fishing Net	**All**	(90)	(90)	(90)	Low fishing activity.
OPERATION IMPACT					
Rig Anchoring	**All**	(20)	(20)	(20)	No marine traffic during ice season (8 months).
Work Boat Anchoring	**All**	(20)	(20)	(20)	No work boat traffic during ice season (8 months).
MECHANICAL					
Connection Failure	**All**				
Material Failure	**All**				
NATURAL HAZARD					
Mud Slide	**All**	(80)	(60)	(40)	Gradient low. Mud slide potential (gradient) increases with water depth.
Storm/ Hurricane	**All**	(50)	(50)	(50)	Fewer severe storms.

ARCTIC UNIQUE		Freq. Inc. per 10^5 km-yr			
		Median	Median	Median	
		Expected	Expected	Expected	
Ice Gouging	**S**	0.3495	0.1747		Ice gouge failure rate calculated using exponential failure distribution for 2.5-m cover, 0.2-m average gouge depth, 4 gouges per km-yr flux. Spill size Distribution explained in text Section 2.5.2
		0.0680	0.0340		
	M	0.6178	0.3089		
		0.1210	0.0605		
	L	1.3438	0.6719		
		0.2610	0.1305		
	H	0.3762	0.1881		
		0.0730	0.0365		
Strudel Scour	**S**	0.0021			Only in shallow water. Average frequency of 4 scours/mile² and 100 ft of bridge length with 10% conditional P/L failure probability. The same spill size distribution as above.
		0.0012			
	M	0.0038			
		0.0020			
	L	0.0082			
		0.0045			
	H	0.0023			
		0.0012			
Upheaval Buckling	**S**	0.0004	0.0004	0.0004	All water depth. The failure frequency is 20% of that of Strudel Scour.
		0.0002	0.0002	0.0002	
	M	0.0008	0.0008	0.0008	
		0.0004	0.0004	0.0004	
	L	0.0016	0.0016	0.0016	
		0.0009	0.0009	0.0009	
	H	0.0005	0.0005	0.0005	
		0.0002	0.0002	0.0002	
Thaw Settlement	**S**	0.0002	0.0002	0.0002	All water depth. The failure frequency is 10% of that of Strudel Scour.
		0.0001	0.0001	0.0001	
	M	0.0004	0.0004	0.0004	
		0.0002	0.0002	0.0002	
	L	0.0008	0.0008	0.0008	
		0.0004	0.0004	0.0004	
	H	0.0002	0.0002	0.0002	
		0.0001	0.0001	0.0001	
Other	**S**	0.0881	0.0438	0.0002	To be assessed as 25% of above.
		0.0174	0.0086	0.0001	
	M	0.1557	0.0775	0.0003	
		0.0309	0.0153	0.0002	
	L	0.3386	0.1686	0.0006	
		0.0667	0.0330	0.0003	
	H	0.0948	0.0472	0.0002	
		0.0187	0.0092	0.0001	

- *Storms* – Considerably fewer severe storms are anticipated on an annual basis in the Arctic than in GOM, due to damping of the ocean surface by ice cover.
- *Arctic effects* – Arctic effects are effects which are unique to the Arctic and are not reflected in the historical fault tree itself. Arctic effects were discussed in detail in Chapter 2, Section 2.5. The discussion in that section is summarized in the right hand column of Table 4.1. The frequency increments in this table are given as both the "expected" values and the "median" values. The expected values are the expected values given in Table 2.9. The median values, however, are those calculated using the Monte Carlo method with the low, expected, and high values from Table 2.9, as inputs to the Monte Carlo. These median values are clearly considerably higher than the expected values. This lack of coincidence between expected and median values is due to the skewness of the distribution.

4.3.2 Arctic Pipeline Fault Tree Frequency Calculations

Incorporation of the frequency effects as variations in and additions to the historical frequencies can be represented in a fault tree, as shown for the large spill size for Arctic pipelines in Figure 4.4. In this figure, the historical frequency as well as that associated with small, medium, and deep-water zones are shown under each of the event boxes. Each box is further split into two, for pipelines < and = 10" diameter as represented in the historical database. Such fault trees were developed for all of the pipeline spill sizes, and these additional spill size fault trees, for small, medium, and huge spills are presented in Appendix C, where the complete calculations are given.

Of greatest importance, however, are the pipeline failure frequencies or failure rates per km-yr. These failure rates for the entire range of spill sizes, small, medium, large, and huge, are given in Tables 4.2, 4.3, 4.4, and 4.5, respectively.

Indeed, a huge array of numbers is shown in these tables. Consider Table 4.4 (page 4.12), which is the frequency calculation corresponding to the large spill size fault tree shown in Figure 4.4. Consider the bottom line opposite totals. What the table tells us is that the total spill frequency for pipelines less than 10" diameter was, as we well know, 2.799 (per 10^5 km-yr) historically. With the frequency changes attributable to Arctic effects, this frequency is reduced to 2.636 for shallow water, to 1.812 for medium depth water, and to 1.015 for deep water. A similar trend in the reduction of failure frequencies with increasing water depth for pipelines greater than 10" is manifested in the right hand side of the table. Because the frequencies per unit pipeline length and operating year are the key drivers in the balance of the analysis, they have been given in the body of the report (in Tables 4.2 to 4.5) for each of the spill sizes for pipelines.

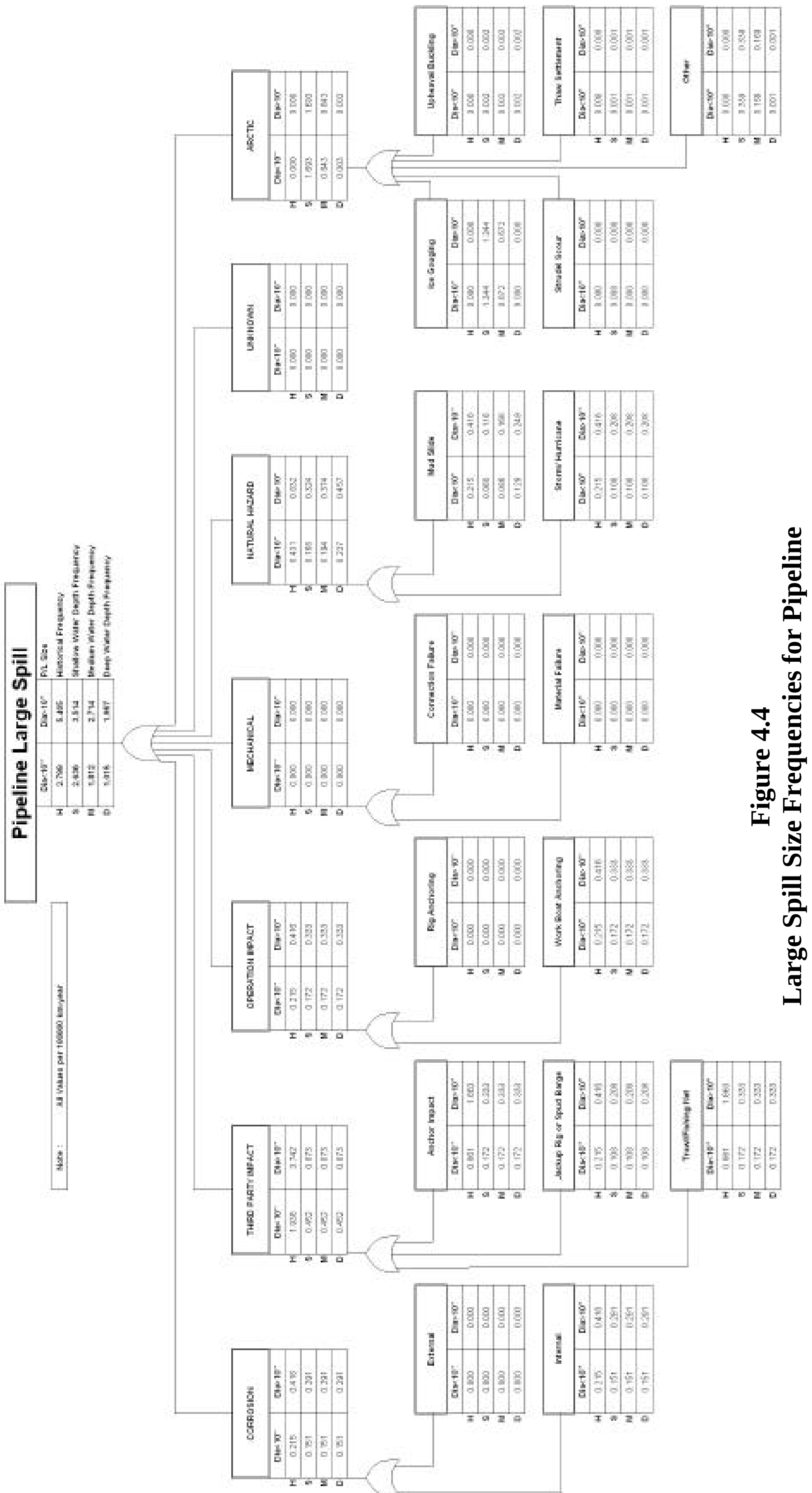


Figure 4.4
Large Spill Size Frequencies for Pipeline

Table 4.2
Pipeline Small Spill Size Frequencies

CAUSE CLASSIFICATION	HISTORICAL DISTRIBUTION %	SMALL SPILL*																			
		Pipeline Diameter <10"										Pipeline Diameter = 10"									
			Shallow			Medium			Deep				Shallow			Medium			Deep		
		FREQUENCY (spill per 10^5 km-yr)	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %	FREQUENCY (spill per 10^5 km-yr)	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %
CORROSION	**16.67**	**0.467**	**(0.171)**	**0.295**	**15.71**	**(0.171)**	**0.295**	**17.42**	**(0.171)**	**0.295**	**19.18**	**0.300**	**(0.110)**	**0.190**	**13.91**	**(0.110)**	**0.190**	**16.25**	**(0.110)**	**0.190**	**19.18**
External	5.56	0.156	(0.078)	0.078	4.14	(0.078)	0.078	4.58	(0.078)	0.078	5.05	0.100	(0.050)	0.050	3.66	(0.050)	0.050	4.28	(0.050)	0.050	5.05
Internal	11.11	0.311	(0.093)	0.218	11.58	(0.093)	0.218	12.83	(0.093)	0.218	14.13	0.200	(0.060)	0.140	10.25	(0.060)	0.140	11.98	(0.060)	0.140	14.13
THIRD PARTY IMPACT	**38.89**	**1.089**	**(0.871)**	**0.218**	**11.58**	**(0.871)**	**0.218**	**12.83**	**(0.871)**	**0.218**	**14.13**	**0.701**	**(0.561)**	**0.140**	**10.25**	**(0.561)**	**0.140**	**11.98**	**(0.561)**	**0.140**	**14.13**
Anchor Impact	33.33	0.933	(0.746)	0.187	9.93	(0.746)	0.187	11.00	(0.746)	0.187	12.11	0.601	(0.480)	0.120	8.79	(0.480)	0.120	10.26	(0.480)	0.120	12.11
Jackup Rig or Spud Barge																					
Trawl/Fishing Net	5.56	0.156	(0.124)	0.031	1.65	(0.124)	0.031	1.83	(0.124)	0.031	2.02	0.100	(0.080)	0.020	1.46	(0.080)	0.020	1.71	(0.080)	0.020	2.02
OPERATION IMPACT	**16.67**	**0.467**	**(0.093)**	**0.373**	**19.85**	**(0.093)**	**0.373**	**22.00**	**(0.093)**	**0.373**	**24.23**	**0.300**	**(0.060)**	**0.240**	**17.57**	**(0.060)**	**0.240**	**20.53**	**(0.060)**	**0.240**	**24.22**
Rig Anchoring	5.56	0.156	(0.031)	0.124	6.62	(0.031)	0.124	7.33	(0.031)	0.124	8.08	0.100	(0.020)	0.080	5.86	(0.020)	0.080	6.84	(0.020)	0.080	8.07
Work Boat Anchoring	11.11	0.311	(0.062)	0.249	13.23	(0.062)	0.249	14.67	(0.062)	0.249	16.15	0.200	(0.040)	0.160	11.71	(0.040)	0.160	13.69	(0.040)	0.160	16.15
MECHANICAL	**11.11**	**0.311**		**0.311**	**16.54**		**0.311**	**18.33**		**0.311**	**20.19**	**0.200**		**0.200**	**14.64**		**0.200**	**17.11**		**0.200**	**20.19**
Connection Failure	5.56	0.156		0.156	8.27		0.156	9.17		0.156	10.10	0.100		0.100	7.32		0.100	8.55		0.100	10.09
Material Failure	5.56	0.156		0.156	8.27		0.156	9.17		0.156	10.10	0.100		0.100	7.32		0.100	8.55		0.100	10.09
NATURAL HAZARD	**11.11**	**0.311**	**(0.224)**	**0.087**	**4.62**	**(0.187)**	**0.124**	**7.33**	**(0.124)**	**0.187**	**12.11**	**0.200**	**(0.144)**	**0.056**	**4.09**	**(0.120)**	**0.080**	**6.84**	**(0.080)**	**0.120**	**12.11**
Mud Slide	11.11	0.311	(0.224)	0.087	4.62	(0.187)	0.124	7.33	(0.124)	0.187	12.11	0.200	(0.144)	0.056	4.09	(0.120)	0.080	6.84	(0.080)	0.120	12.11
Storm/ Hurricane																					
ARCTIC			**0.440**	**0.440**	**23.42**	**0.219**	**0.219**	**12.92**	**0.001**	**0.001**	**0.05**		**0.440**	**0.440**	**32.21**	**0.219**	**0.219**	**18.74**	**0.001**	**0.001**	**0.08**
Ice Gouging			0.3495	0.3495	18.59	0.1747	0.1747	10.30					0.3495	0.3495	25.56	0.1747	0.1747	14.93			
Strudel Scour			0.0021	0.0021	0.11								0.0021	0.0021	0.16						
Upheaval Buckling			0.0004	0.0004	0.02	0.0004	0.0004	0.03	0.0004	0.0004	0.03		0.0004	0.0004	0.03	0.0004	0.0004	0.04	0.0004	0.0004	0.04
Thaw Settlement			0.0002	0.0002	0.01	0.0002	0.0002	0.01	0.0002	0.0002	0.01		0.0002	0.0002	0.02	0.0002	0.0002	0.02	0.0002	0.0002	0.02
Other			0.0881	0.0881	4.68	0.0438	0.0438	2.58	0.0002	0.0002	0.01		0.0881	0.0881	6.44	0.0438	0.0438	3.75	0.0002	0.0002	0.02
UNKNOWN	**5.56**	**0.156**		**0.156**	**8.27**		**0.156**	**9.17**		**0.156**	**10.10**	**0.100**		**0.100**	**7.32**		**0.100**	**8.55**		**0.100**	**10.09**
TOTALS	***100.00***	***2.799***	***(0.919)***	***1.880***	***100.00***	***(1.103)***	***1.697***	***100.00***	***(1.259)***	***1.540***	***100.00***	***1.802***	***(0.435)***	***1.367***	***100.00***	***(0.632)***	***1.170***	***100.00***	***(0.810)***	***0.992***	***100.00***

* Small (S) - = 50 < 100 bbl

Table 4.3
Pipeline Medium Spill Size Frequencies

CAUSE CLASSIFICATION	HISTORICAL DISTRIBUTION %	MEDIUM SPILL*																			
		Pipeline Diameter <10"										Pipeline Diameter = 10"									
			Shallow			Medium			Deep				Shallow			Medium			Deep		
		FREQUENCY (spill per 10^5 km-yr)	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %	FREQUENCY (spill per 10^5km-yr)	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %
CORROSION	**16.67**	**0.816**	**(0.299)**	**0.517**	**15.68**	**(0.299)**	**0.517**	**17.39**	**(0.299)**	**0.517**	**19.18**	**0.751**	**(0.275)**	**0.475**	**15.36**	**(0.275)**	**0.475**	**17.20**	**(0.275)**	**0.475**	**19.18**
External	5.56	0.272	(0.136)	0.136	4.13	(0.136)	0.136	4.58	(0.136)	0.136	5.05	0.250	(0.125)	0.125	4.04	(0.125)	0.125	4.53	(0.125)	0.125	5.05
Internal	11.11	0.544	(0.163)	0.381	11.55	(0.163)	0.381	12.82	(0.163)	0.381	14.13	0.500	(0.150)	0.350	11.32	(0.150)	0.350	12.67	(0.150)	0.350	14.13
THIRD PARTY IMPACT	**38.89**	**1.905**	**(1.524)**	**0.381**	**11.55**	**(1.524)**	**0.381**	**12.82**	**(1.524)**	**0.381**	**14.13**	**1.752**	**(1.401)**	**0.350**	**11.32**	**(1.401)**	**0.350**	**12.67**	**(1.401)**	**0.350**	**14.13**
Anchor Impact	33.33	1.633	(1.306)	0.327	9.90	(1.306)	0.327	10.98	(1.306)	0.327	12.11	1.501	(1.201)	0.300	9.70	(1.201)	0.300	10.86	(1.201)	0.300	12.11
Jackup Rig or Spud Barge																					
Trawl/Fishing Net	5.56	0.272	(0.218)	0.054	1.65	(0.218)	0.054	1.83	(0.218)	0.054	2.02	0.250	(0.200)	0.050	1.62	(0.200)	0.050	1.81	(0.200)	0.050	2.02
OPERATION IMPACT	**16.67**	**0.816**	**(0.163)**	**0.653**	**19.80**	**(0.163)**	**0.653**	**21.97**	**(0.163)**	**0.653**	**24.23**	**0.751**	**(0.150)**	**0.601**	**19.40**	**(0.150)**	**0.601**	**21.72**	**(0.150)**	**0.601**	**24.23**
Rig Anchoring	5.56	0.272	(0.054)	0.218	6.60	(0.054)	0.218	7.32	(0.054)	0.218	8.08	0.250	(0.050)	0.200	6.47	(0.050)	0.200	7.24	(0.050)	0.200	8.08
Work Boat Anchoring	11.11	0.544	(0.109)	0.435	13.20	(0.109)	0.435	14.65	(0.109)	0.435	16.15	0.500	(0.100)	0.400	12.93	(0.100)	0.400	14.48	(0.100)	0.400	16.15
MECHANICAL	**11.11**	**0.544**		**0.544**	**16.50**		**0.544**	**18.31**		**0.544**	**20.19**	**0.500**		**0.500**	**16.17**		**0.500**	**18.10**		**0.500**	**20.19**
Connection Failure	5.56	0.272		0.272	8.25		0.272	9.15		0.272	10.10	0.250		0.250	8.08		0.250	9.05		0.250	10.10
Material Failure	5.56	0.272		0.272	8.25		0.272	9.15		0.272	10.10	0.250		0.250	8.08		0.250	9.05		0.250	10.10
NATURAL HAZARD	**11.11**	**0.544**	**(0.392)**	**0.152**	**4.61**	**(0.327)**	**0.218**	**7.32**	**(0.218)**	**0.327**	**12.11**	**0.500**	**(0.361)**	**0.140**	**4.52**	**(0.300)**	**0.200**	**7.24**	**(0.200)**	**0.300**	**12.11**
Mud Slide	11.11	0.544	(0.392)	0.152	4.61	(0.327)	0.218	7.32	(0.218)	0.327	12.11	0.500	(0.361)	0.140	4.52	(0.300)	0.200	7.24	(0.200)	0.300	12.11
Storm/ Hurricane																					
ARCTIC			**0.778**	**0.778**	**23.60**	**0.388**	**0.388**	**13.04**	**0.001**	**0.001**	**0.05**		**0.778**	**0.778**	**25.15**	**0.388**	**0.388**	**14.02**	**0.001**	**0.001**	**0.06**
Ice Gouging			0.6178	0.6178	18.73	0.3089	0.3089	10.39					0.6178	0.6178	19.96	0.3089	0.3089	11.17			
Strudel Scour			0.0038	0.0038	0.11								0.0038	0.0038	0.12						
Upheaval Buckling			0.0008	0.0008	0.02	0.0008	0.0008	0.03	0.0008	0.0008	0.03		0.0008	0.0008	0.02	0.0008	0.0008	0.03	0.0008	0.0008	0.03
Thaw Settlement			0.0004	0.0004	0.01	0.0004	0.0004	0.01	0.0004	0.0004	0.01		0.0004	0.0004	0.01	0.0004	0.0004	0.01	0.0004	0.0004	0.02
Other			0.1557	0.1557	4.72	0.0775	0.0775	2.61	0.0003	0.0003	0.01		0.1557	0.1557	5.03	0.0775	0.0775	2.80	0.0003	0.0003	0.01
UNKNOWN	**5.56**	**0.272**		**0.272**	**8.25**		**0.272**	**9.15**		**0.272**	**10.10**	**0.250**		**0.250**	**8.08**		**0.250**	**9.05**		**0.250**	**10.10**
TOTALS	***100.00***	***4.899***	***(1.600)***	***3.298***	***100.0***	***(1.926)***	***2.973***	***100.00***	***(2.203)***	***2.696***	***100.00***	***4.504***	***(1.409)***	***3.095***	***100.00***	***(1.739)***	***2.765***	***100.00***	***(2.025)***	***2.479***	***100.00***

* Medium (M) - = 100 < 1,000 bbl

Table 4.4
Pipeline Large Spill Size Frequencies

CAUSE CLASSIFICATION	HISTORICAL DISTRIBUTION %	LARGE SPILL*																					
		P/L Dia <10"										P/L Dia >10"											
			Shallow			Medium			Deep				Shallow			Medium			Deep				
		FREQUENCY (spill per 10^5km-yr)	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %	FREQUENCY (spill per 10^5km-yr)	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %
CORROSION	**7.69**	**0.215**	**(0.065)**	**0.151**	**5.72**	**(0.065)**	**0.151**	**8.32**	**(0.065)**	**0.151**	**14.85**	**0.4158**	**(0.125)**	**0.291**	**8.28**	**(0.125)**	**0.291**	**10.72**	**(0.125)**	**0.291**	**14.87**
External																					
Internal	7.69	0.215	(0.065)	0.151	5.72	(0.065)	0.151	8.32	(0.065)	0.151	14.85	0.4158	(0.125)	0.291	8.28	(0.125)	0.291	10.72	(0.125)	0.291	14.87
THIRD PARTY IMPACT	**69.23**	**1.938**	**(1.486)**	**0.452**	**17.15**	**(1.486)**	**0.452**	**24.96**	**(1.486)**	**0.452**	**44.54**	**3.7419**	**(2.869)**	**0.873**	**24.85**	**(2.869)**	**0.873**	**32.17**	**(2.869)**	**0.873**	**44.61**
Anchor Impact	30.77	0.861	(0.689)	0.172	6.53	(0.689)	0.172	9.51	(0.689)	0.172	16.97	1.6631	(1.330)	0.333	9.47	(1.330)	0.333	12.26	(1.330)	0.333	16.99
Jackup Rig or Spud Barge	7.69	0.215	(0.108)	0.108	4.08	(0.108)	0.108	5.94	(0.108)	0.108	10.61	0.4158	(0.208)	0.208	5.92	(0.208)	0.208	7.66	(0.208)	0.208	10.62
Trawl/Fishing Net	30.77	0.861	(0.689)	0.172	6.53	(0.689)	0.172	9.51	(0.689)	0.172	16.97	1.6631	(1.330)	0.333	9.47	(1.330)	0.333	12.26	(1.330)	0.333	16.99
OPERATION IMPACT	**7.69**	**0.215**	**(0.043)**	**0.172**	**6.53**	**(0.043)**	**0.172**	**9.51**	**(0.043)**	**0.172**	**16.97**	**0.4158**	**(0.083)**	**0.333**	**9.47**	**(0.083)**	**0.333**	**12.26**	**(0.083)**	**0.333**	**16.99**
Rig Anchoring																					
Work Boat Anchoring	7.69	0.215	(0.043)	0.172	6.53	(0.043)	0.172	9.51	(0.043)	0.172	16.97	0.4158	(0.083)	0.333	9.47	(0.083)	0.333	12.26	(0.083)	0.333	16.99
MECHANICAL																					
Connection Failure																					
Material Failure																					
NATURAL HAZARD	**15.38**	**0.431**	**(0.263)**	**0.168**	**6.37**	**(0.237)**	**0.194**	**10.70**	**(0.194)**	**0.237**	**23.33**	**0.8315**	**(0.507)**	**0.324**	**9.22**	**(0.457)**	**0.374**	**13.79**	**(0.374)**	**0.457**	**23.37**
Mud Slide	7.69	0.215	(0.155)	0.060	2.28	(0.129)	0.086	4.75	(0.086)	0.129	12.73	0.4158	(0.300)	0.116	3.31	(0.249)	0.166	6.13	(0.166)	0.249	12.75
Storm/ Hurricane	7.69	0.215	(0.108)	0.108	4.08	(0.108)	0.108	5.94	(0.108)	0.108	10.61	0.4158	(0.208)	0.208	5.92	(0.208)	0.208	7.66	(0.208)	0.208	10.62
ARCTIC			**1.693**	**1.693**	**64.23**	**0.843**	**0.843**	**46.52**	**0.003**	**0.003**	**0.30**		**1.693**	**1.693**	**48.18**	**0.843**	**0.843**	**31.06**	**0.003**	**0.003**	**0.16**
Ice Gouging			1.3438	1.3438	50.98	0.6719	0.6719	37.08					1.3438	1.3438	38.24	0.6719	0.6719	24.76			
Strudel Scour			0.0082	0.0082	0.31								0.0082	0.0082	0.23						
Upheaval Buckling			0.0016	0.0016	0.06	0.0016	0.0016	0.09	0.0016	0.0016	0.16		0.0016	0.0016	0.05	0.0016	0.0016	0.06	0.0016	0.0016	0.08
Thaw Settlement			0.0008	0.0008	0.03	0.0008	0.0008	0.05	0.0008	0.0008	0.08		0.0008	0.0008	0.02	0.0008	0.0008	0.03	0.0008	0.0008	0.04
Other			0.3386	0.3386	12.85	0.1686	0.1686	9.30	0.0006	0.0006	0.06		0.3386	0.3386	9.64	0.1686	0.1686	6.21	0.0006	0.0006	0.03
UNKNOWN																					
TOTALS	***100.00***	***2.799***	***(0.163)***	***2.636***	***100.00***	***(0.987)***	***1.812***	***100.00***	***(1.784)***	***1.015***	***100.00***	***5.4050***	***(1.891)***	***3.514***	***100.00***	***(2.691)***	***2.714***	***100.00***	***(3.448)***	***1.957***	***100.00***

* Large (L) - = 1,000 < 10,000 bbl

Table 4.5
Pipeline Huge Spill Size Frequencies

CAUSE CLASSIFICATION	HISTORICAL DISTRIBUTION %	HUGE SPILL*																			
		P/L Dia <10"										P/L Dia >10"									
			Shallow			Medium			Deep				Shallow			Medium			Deep		
		FREQUENCY (spill per 10^5 km-yr)	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %	FREQUENCY (spill per 10^5 km-yr)	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %
CORROSION	**7.69**	**0.054**	**(0.016)**	**0.038**	**5.31**	**(0.016)**	**0.038**	**7.88**	**(0.016)**	**0.038**	**14.84**	**0.1386**	**(0.042)**	**0.097**	**8.98**	**(0.042)**	**0.097**	**11.29**	**(0.042)**	**0.097**	**14.87**
External																					
Internal	7.69	0.054	(0.016)	0.038	5.31	(0.016)	0.038	7.88	(0.016)	0.038	14.84	0.1386	(0.042)	0.097	8.98	(0.042)	0.097	11.29	(0.042)	0.097	14.87
THIRD PARTY IMPACT	**69.23**	**0.485**	**(0.372)**	**0.113**	**15.93**	**(0.372)**	**0.113**	**23.64**	**(0.372)**	**0.113**	**44.53**	**1.2475**	**(0.956)**	**0.291**	**26.93**	**(0.956)**	**0.291**	**33.86**	**(0.956)**	**0.291**	**44.62**
Anchor Impact	30.77	0.215	(0.172)	0.043	6.07	(0.172)	0.043	9.01	(0.172)	0.043	16.96	0.5545	(0.444)	0.111	10.26	(0.444)	0.111	12.90	(0.444)	0.111	17.00
Jackup Rig or Spud Barge	7.69	0.054	(0.027)	0.027	3.79	(0.027)	0.027	5.63	(0.027)	0.027	10.60	0.1386	(0.069)	0.069	6.41	(0.069)	0.069	8.06	(0.069)	0.069	10.62
Trawl/Fishing Net	30.77	0.215	(0.172)	0.043	6.07	(0.172)	0.043	9.01	(0.172)	0.043	16.96	0.5545	(0.444)	0.111	10.26	(0.444)	0.111	12.90	(0.444)	0.111	17.00
OPERATION IMPACT	**7.69**	**0.054**	**(0.011)**	**0.043**	**6.07**	**(0.011)**	**0.043**	**9.01**	**(0.011)**	**0.043**	**16.96**	**0.1386**	**(0.028)**	**0.111**	**10.26**	**(0.028)**	**0.111**	**12.90**	**(0.028)**	**0.111**	**17.00**
Rig Anchoring																					
Work Boat Anchoring	7.69	0.054	(0.011)	0.043	6.07	(0.011)	0.043	9.01	(0.011)	0.043	16.96	0.1386	(0.028)	0.111	10.26	(0.028)	0.111	12.90	(0.028)	0.111	17.00
MECHANICAL																					
Connection Failure																					
Material Failure																					
NATURAL HAZARD	**15.38**	**0.108**	**(0.066)**	**0.042**	**5.91**	**(0.059)**	**0.048**	**10.13**	**(0.048)**	**0.059**	**23.32**	**0.2772**	**(0.169)**	**0.108**	**9.99**	**(0.152)**	**0.125**	**14.51**	**(0.125)**	**0.152**	**23.37**
Mud Slide	7.69	0.054	(0.039)	0.015	2.12	(0.032)	0.022	4.50	(0.022)	0.032	12.72	0.1386	(0.100)	0.039	3.58	(0.083)	0.055	6.45	(0.055)	0.083	12.75
Storm/ Hurricane	7.69	0.054	(0.027)	0.027	3.79	(0.027)	0.027	5.63	(0.027)	0.027	10.60	0.1386	(0.069)	0.069	6.41	(0.069)	0.069	8.06	(0.069)	0.069	10.62
ARCTIC			**0.474**	**0.474**	**66.78**	**0.236**	**0.236**	**49.34**	**0.001**	**0.001**	**0.34**		**0.474**	**0.474**	**43.85**	**0.236**	**0.236**	**27.45**	**0.001**	**0.001**	**0.13**
Ice Gouging			0.3762	0.3762	53.00	0.1881	0.1881	39.33					0.3762	0.3762	34.80	0.1881	0.1881	21.88			
Strudel Scour			0.0023	0.0023	0.32								0.0023	0.0023	0.21						
Upheaval Buckling			0.0005	0.0005	0.06	0.0005	0.0005	0.10	0.0005	0.0005	0.18		0.0005	0.0005	0.04	0.0005	0.0005	0.05	0.0005	0.0005	0.07
Thaw Settlement			0.0002	0.0002	0.03	0.0002	0.0002	0.05	0.0002	0.0002	0.09		0.0002	0.0002	0.02	0.0002	0.0002	0.03	0.0002	0.0002	0.04
Other			0.0948	0.0948	13.36	0.0472	0.0472	9.87	0.0002	0.0002	0.07		0.0948	0.0948	8.77	0.0472	0.0472	5.49	0.0002	0.0002	0.03
UNKNOWN																					
TOTALS	***100.00***	***0.700***	***0.010***	***0.710***	***100.00***	***(0.222)***	***0.478***	***100.00***	***(0.446)***	***0.254***	***100.00***	***1.8020***	***(0.721)***	***1.081***	***100.00***	***(0.942)***	***0.860***	***100.00***	***(1.150)***	***0.652***	***100.00***

* Huge (H) - = 10,000 bbl

4.3.3 Arctic Pipeline Frequency Input Uncertainty Variations

In order to assess the impact of uncertainties in the Arctic hazard effects incorporated fault trees, ranges around the expected value have been estimated for all the Arctic effects, both modified and unique for Arctic effects. The numerical distributions generated through these perturbations in the expected values are modeled as triangular distributions and input to the Monte Carlo simulation analysis conducted as part of the result generation. Table 4.6 shows the unique effect perturbations about the expected value, indicated as low and high. In fact, the low value is defined as the 90% probability of exceedance, while the high one is at the 10% probability of exceedance. The variations in the modified effects were estimated utilizing engineering judgement. For the unique effects, however, the ranges were estimated as described in Section 2.5.2, using parametric analysis.

4.4 Platform Fault Tree Analysis

4.4.1 Arctic Platform Fault Tree Inputs

Table 4.7 summarizes the variations in the modified and unique Arctic effect inputs for platforms. As for pipeline unique effects, both the expected and Monte Carlo median values are given.

The first three modified cause classifications, the process facility release, storage tank release, and structural failure were reduced by 30 to 50% primarily as a result of the state-of-art engineering, construction, and operational standards and practices expected. As before, storms tend to be less severe in the Arctic, and certainly during the ice season would have limited impact on the facility. Due to the extremely low traffic density, as for the case of pipelines, the ship collision cause has been reduced by 90 percent.

Unique effects are also included. Relatively small increments in facility spills were attributed to ice force, low temperature effects, and unknown effects which were taken as a percentage of the other unique Arctic effects. Ice force effect calculations were based on the 1/10,000 year ice force (1/250,000 well year) causing spills, predominantly small and medium. Ice forces are also considered to increase as a contributor to oil spill occurrences with water depth, due to the increasing severity of ice loads as one moves towards the edge of the landfast ice zone with increasing water depth. Increase of low temperature effects with water depth was estimated as 10% of historical process facility spill rates.

Table 4.6
Arctic Pipeline Impact Uncertainty Variations

CAUSE CLASSIFICATION	Spill Size	Water Depth								
		Shallow			Medium			Deep		
		Frequency Change %								
		Low	Expected	High	Low	Expected	High	Low	Expected	High
ARCTIC MODIFIED										
CORROSION										
External	**All**	(25)	(50)	(75)	(25)	(50)	(75)	(25)	(50)	(75)
Internal	**All**	(15)	(30)	(45)	(15)	(30)	(45)	(15)	(30)	(45)
THIRD PARTY IMPACT										
Anchor Impact	**All**	(60)	(90)	(95)	(60)	(90)	(95)	(60)	(90)	(95)
Jackup Rig or Spud Barge	**All**	(25)	(50)	(75)	(25)	(50)	(75)	(25)	(50)	(75)
Trawl/Fishing Net	**All**	(60)	(90)	(95)	(60)	(90)	(95)	(60)	(90)	(95)
OPERATION IMPACT										
Rig Anchoring	**All**	(10)	(20)	(30)	(10)	(20)	(30)	(10)	(20)	(30)
Work Boat Anchoring	**All**	(10)	(20)	(30)	(10)	(20)	(30)	(10)	(20)	(30)
MECHANICAL										
Connection Failure	**All**									
Material Failure	**All**									
NATURAL HAZARD										
Mud Slide	**All**	(50)	(80)	(90)	(30)	(60)	(90)	(20)	(40)	(60)
Storm/ Hurricane	**All**	(25)	(50)	(75)	(25)	(50)	(75)	(25)	(50)	(75)
		Frequency Increment per 10^5 km-year								
ARCTIC UNIQUE										
Ice Gouging	**S**	0.0060	0.0680	0.8290	0.0030	0.0340	0.4145			
	M	0.0090	0.1210	1.4670	0.0045	0.0605	0.7335			
	L	0.0210	0.2610	3.1900	0.0105	0.1305	1.5950			
	H	0.0060	0.0730	0.8930	0.0030	0.0365	0.4465			
Strudel Scour	**S**	0.0004	0.0012	0.0044						
	M	0.0006	0.0020	0.0078						
	L	0.0014	0.0045	0.0170						
	H	0.0004	0.0012	0.0048						
Upheaval Buckling	**S**	0.00007	0.00023	0.00088	0.00007	0.00023	0.00088	0.00007	0.00023	0.00088
	M	0.00013	0.00041	0.00156	0.00013	0.00041	0.00156	0.00013	0.00041	0.00156
	L	0.00028	0.00089	0.00340	0.00028	0.00089	0.00340	0.00028	0.00089	0.00340
	H	0.00008	0.00025	0.00095	0.00008	0.00025	0.00095	0.00008	0.00025	0.00095
Thaw Settlement	**S**	0.00004	0.00012	0.00044	0.00004	0.00012	0.00044	0.00004	0.00012	0.00044
	M	0.00006	0.00020	0.00078	0.00006	0.00020	0.00078	0.00006	0.00020	0.00078
	L	0.00014	0.00045	0.00170	0.00014	0.00045	0.00170	0.00014	0.00045	0.00170
	H	0.00004	0.00012	0.00048	0.00004	0.00012	0.00048	0.00004	0.00012	0.00048
Other	**S**	0.00162	0.01738	0.20869	0.00078	0.00859	0.10396	0.00003	0.00009	0.00033
	M	0.00246	0.03092	0.36929	0.00117	0.01528	0.18396	0.00005	0.00015	0.00059
	L	0.00571	0.06670	0.80303	0.00273	0.03296	0.40003	0.00011	0.00033	0.00128
	H	0.00163	0.01865	0.22480	0.00078	0.00922	0.11198	0.00003	0.00009	0.00036

Table 4.7
Platform Fault Tree Input Rationalization

CAUSE CLASSIFICATION	Spill Size	Frequency Change %			Reason
		Shallow	Medium	Deep	
ARCTIC MODIFIED					
PROCESS FACILITY RLS.	**All**	(50)	(50)	(50)	State of the art now, High QC, High Inspection and Maintenance Requirements
STORAGE TANK RLS.	**All**	(30)	(30)	(30)	State of the art now, High QC, High Inspection and Maintenance Requirements
STRUCTURAL FAILURE	**All**	(30)	(30)	(30)	High safety factor, Monitoring Programs
HURRICANE/STORM	**All**	(80)	(80)	(80)	Less severe storms.
COLLISION	**All**	(90)	(90)	(90)	Very low traffic density.
		Freq. Increment per 10^4 well-year			
		Median	**Median**	**Median**	
		Expected	**Expected**	**Expected**	
ARCTIC UNIQUE					
Ice Force	**SM**	0.1447	0.2170	0.3256	Assumed 1/10000 years ice force causes spill. 85% of the spills are SM.
		0.0340	0.0510	0.0765	
	HL	0.0255	0.0383	0.0575	
		0.0060	0.0090	0.0135	
Facility Low Temperature	**SM**	0.1000	0.1000	0.1000	Assumed 10% of Historical Process Facilities release frequency and corresponding spill size distribution.
		0.1000	0.1000	0.1000	
	HL	0.0080	0.0080	0.0080	
		0.0080	0.0080	0.0080	
Other	**SM**	0.0244	0.0316	0.0424	10% of above.
		0.0134	0.0151	0.0177	
	HL	0.0033	0.0046	0.0065	
		0.0014	0.0017	0.0022	

4.4.2 Arctic Platform Fault Tree Spill Frequency Calculations

Figure 4.5 shows the fault tree developed for Arctic platform spills for the different water depth zones for large and huge spill sizes, which were grouped together as described for platforms in Chapter 2. Again, the fault tree gives the historical value, together with the calculated values for shallow, medium, and deep water. In the case of this particular fault tree, there was room to represent both the small and medium or less than 1,000 bbl and the large and huge or greater than 1,000 bbl spills. Like pipelines, it is evident that platforms manifest a somewhat lower frequency for both spill size categories for the Arctic conditions. Tables 4.8 and 4.9 show the frequency calculations for platforms for small and medium and large and huge spill sizes, respectively.

4.4.3 Platform Arctic Effect Frequency Input Variations

Again, for the calculation of probability distributions of the effects of the frequency changes attributable to the Arctic environment and operations, variations about the expected value were estimated. Table 4.10 shows this range of variations for the platform spill frequencies. These are later utilized in the development of probability distributions for the oil spill occurrence indicator using a Monte Carlo process.

4.3 Blowout Frequency Analysis

As the base case blowout values have not been altered for Arctic effects, no fault tree for well blowouts is required. However, a summary of the historical frequencies to be used in blowout oil spill occurrence calculations is given in Table 4.11.

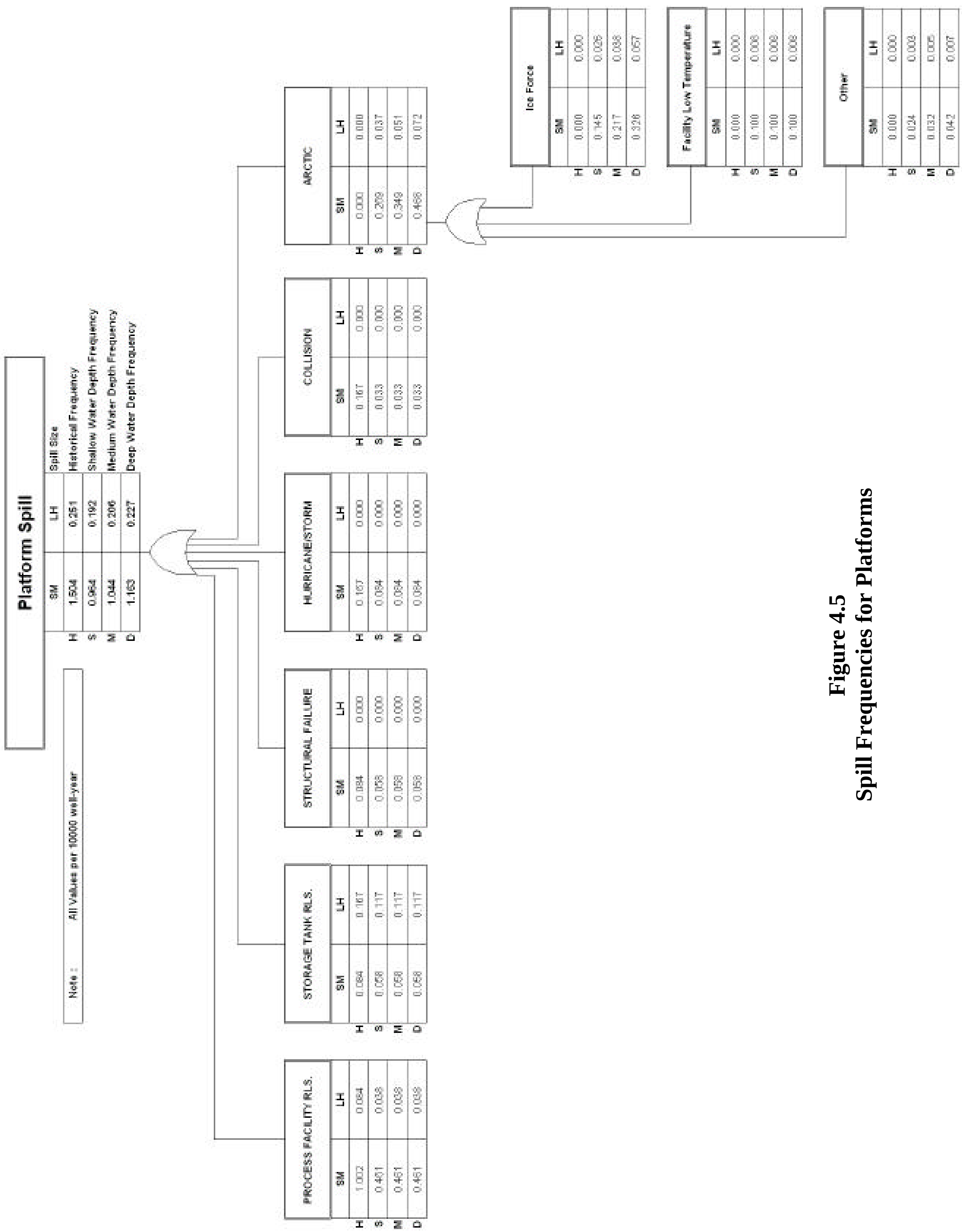


Figure 4.5
Spill Frequencies for Platforms

Table 4.8
Platform Small and Medium Spill Size Frequencies

CAUSE CLASSIFICATION	HISTORICAL DISTRIBUTION %	SMALL AND MEDIUM SPILLS									
			Shallow			Medium			Deep		
		FREQUENCY (spill per 10⁴well-yr)	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %
PROCESS FACILITY RLS.	**66.67**	**1.002**	**(0.541)**	**0.461**	**47.85**	**(0.541)**	**0.4615**	**44.20**	**(0.541)**	**0.4615**	**39.67**
STORAGE TANK RLS.	**5.56**	**0.084**	**(0.025)**	**0.058**	**6.06**	**(0.025)**	**0.0585**	**5.60**	**(0.025)**	**0.0585**	**5.03**
STRUCTURAL FAILURE	**5.56**	**0.084**	**(0.025)**	**0.058**	**6.06**	**(0.025)**	**0.0585**	**5.60**	**(0.025)**	**0.0585**	**5.03**
HURRICANE/STORM	**11.11**	**0.167**	**(0.084)**	**0.084**	**8.66**	**(0.084)**	**0.0835**	**8.00**	**(0.084)**	**0.0835**	**7.18**
COLLISION	**11.11**	**0.167**	**(0.134)**	**0.033**	**3.46**	**(0.134)**	**0.0334**	**3.20**	**(0.134)**	**0.0334**	**2.87**
ARCTIC			**0.269**	**0.269**	**27.90**	**0.349**	**0.3486**	**33.39**	**0.468**	**0.4680**	**40.23**
Ice Force			0.145	0.145	15.00	0.217	0.2170	20.79	0.326	0.3256	27.98
Facility Low Temperature			0.100	0.100	10.37	0.100	0.1000	9.58	0.100	0.1000	8.60
Other			0.024	0.024	2.53	0.032	0.0316	3.03	0.042	0.0424	3.65
TOTALS	**100.00**	**1.504**	**(0.539)**	**0.964**	**100.00**	**(0.460)**	**1.0440**	**100.00**	**(0.340)**	**1.1634**	**100.00**

Table 4.9
Platform Large and Huge Spill Size Frequencies

CAUSE CLASSIFICATION	HISTORICAL DISTRIBUTION %	LARGE AND HUGE SPILLS									
			Shallow			Medium			Deep		
		FREQUENCY (spill per 10⁴well-yr)	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %
PROCESS FACILITY RLS.	**33.33**	**0.0835**	**(0.045)**	**0.0385**	**20.00**	**(0.045)**	**0.0385**	**18.64**	**(0.045)**	**0.0385**	**16.91**
STORAGE TANK RLS.	**66.67**	**0.1671**	**(0.050)**	**0.1169**	**60.82**	**(0.050)**	**0.1169**	**56.68**	**(0.050)**	**0.1169**	**51.43**
STRUCTURAL FAILURE											
HURRICANE/STORM											
COLLISION											
ARCTIC			**0.037**	**0.0369**	**19.18**	**0.051**	**0.0509**	**24.68**	**0.072**	**0.0720**	**31.66**
Ice Force			0.026	0.0255	13.28	0.038	0.0383	18.56	0.057	0.0575	25.27
Facility Low Temperature			0.008	0.0080	4.16	0.008	0.0080	3.88	0.008	0.0080	3.52
Other			0.003	0.0033	1.74	0.005	0.0046	2.24	0.007	0.0065	2.87
TOTALS	**100.00**	**0.2506**	**(0.058)**	**0.1923**	**100.00**	**(0.044)**	**0.2063**	**100.00**	**(0.023)**	**0.2274**	**100.00**

Table 4.10
Platform Arctic Effects Frequency Variations

CAUSE CLASSIFICATION	Spill Size	Shallow			Medium			Deep		
		Frequency Change %								
		Low	Expected	High	Low	Expected	High	Low	Expected	High
ARCTIC MODIFIED										
PROCESS FACILITY RLS.	**All**	(30)	(50)	(80)	(30)	(50)	(80)	(30)	(50)	(80)
STORAGE TANK RLS.	**All**	(20)	(30)	(40)	(20)	(30)	(40)	(20)	(30)	(40)
STRUCTURAL FAILURE	**All**	(20)	(30)	(40)	(20)	(30)	(40)	(20)	(30)	(40)
HURRICANE/STORM	**All**	(25)	(50)	(75)	(25)	(50)	(75)	(25)	(50)	(75)
COLLISION	**All**	(60)	(90)	(95)	(60)	(90)	(95)	(60)	(90)	(95)
		Frequency Increment per 10^4 well-year								
ARCTIC UNIQUE										
- Ice Force	**SM**	0.003	0.034	0.340	0.005	0.051	0.510	0.008	0.077	0.765
	HL	0.001	0.006	0.060	0.001	0.009	0.090	0.001	0.014	0.135
- Facility Low Temperature	**SM**	0.050	0.100	0.150	0.050	0.100	0.150	0.050	0.100	0.150
	HL	0.004	0.008	0.012	0.004	0.008	0.012	0.004	0.008	0.012
- Other	**SM**	0.005	0.013	0.049	0.006	0.015	0.066	0.006	0.018	0.092
	HL	0.000	0.001	0.007	0.000	0.002	0.010	0.001	0.002	0.015

Table 4.11
Blowout Frequencies

EVENT	FREQUENCY UNIT	SMALL AND MEDIUM SPILLS							LARGE SPILL						
			Shallow		Medium		Deep			Shallow		Medium		Deep	
		HISTORICAL FREQUENCY	Frequency Change	New Frequency	Frequency Change	New Frequency	Frequency Change	New Frequency	HISTORICAL FREQUENCY	Frequency Change	New Frequency	Frequency Change	New Frequency	Frequency Change	New Frequency
PRODUCTION WELL	spill per 10^5 well-year	0.500		0.500		0.500		0.500	3.500		3.500		3.500		3.500
EXPLORATION WELL	spill per 10^5 wells	3.160		3.160		3.160		3.160	22.110		22.110		22.110		22.110
DEVELOPMENT WELL	spill per 10^5 wells	1.300		1.300		1.300		1.300	9.080		9.080		9.080		9.080

EVENT	FREQUENCY UNIT	SPILL SIZE - 10000 - 150000 BBL							SPILL SIZE - > 150000 BBL						
			Shallow		Medium		Deep			Shallow		Medium		Deep	
		HISTORICAL FREQUENCY	Frequency Change	New Frequency	Frequency Change	New Frequency	Frequency Change	New Frequency	HISTORICAL FREQUENCY	Frequency Change	New Frequency	Frequency Change	New Frequency	Frequency Change	New Frequency
PRODUCTION WELL	spill per 10^5 well-year	1.500		1.500		1.500		1.500	1.000		1.000		1.000		1.000
EXPLORATION WELL	spill per 10^5 wells	9.500		9.500		9.500		9.500	5.500		5.500		5.500		5.500
DEVELOPMENT WELL	spill per 10^5 wells	3.900		3.900		3.900		3.900	3.900		3.900		3.900		3.900

CHAPTER 5

OIL SPILL OCCURRENCE INDICATOR QUANTIFICATION

5.1 Definition of Oil Spill Occurrence Indicators

Three primary oil spill occurrence indicators (generally referred to as "spill indicators" after this) were quantified in this study. These are as follows:

- Frequency in spills per year.
- Frequency in spills per barrel produced in each year.
- Spill index, the product of spill frequency and associated average spill size.

The spill indicators defined above are subdivided as follows for this study:

- By scenario (eight scenarios).
- By water depth (three ranges).
- By facility type (six types).
- By spill size (four sizes).
- By year (between 10 and 38 years depending on scenario).

The above combinations translate into 576 sets of spill indicators, for a total of 1,728 individual indicators. Given that these are calculated for each year, with most of the scenarios lasting roughly for 35 years, gives 60,480 indicators. In this chapter, we will try to summarize only the salient results of the indicators; Appendix C gives the full calculation printouts for the Monte Carlo results used in the body of this report, while Appendix D gives the expected value calculations and results.

5.2 Oil Spill Occurrence Indicator Calculation Process

The oil spill occurrence indicator calculation process is shown in the flow chart originally given in Figure 1.3, and again presented as Figure 5.1. The steps corresponding to Tasks 2, 3, and 4A have been described in Chapters 2, 3, and 4, respectively. This chapter deals with Task 4B.

Essentially, this chapter addresses the combining of the development scenarios described in Chapter 3 with the unit-spill frequency distributions presented in Chapter 4 to provide measures of oil spill occurrence, the oil spill indicators. Although the calculation is complex because of the many combinations considered (approximately 60,000), in principle, it is a simple process of accounting. Essentially, the quantities of potential oil spill sources are multiplied by their appropriate unit oil spill frequency to give the total expected spill distributions. To develop the probability distributions by the Monte Carlo process, each of the 60,000 combinations needs to be sampled, in this case a sampling of 5,000 iterations was carried out for each combination studied. This translates into roughly 300 million arithmetic operations to generate the Monte Carlo results.

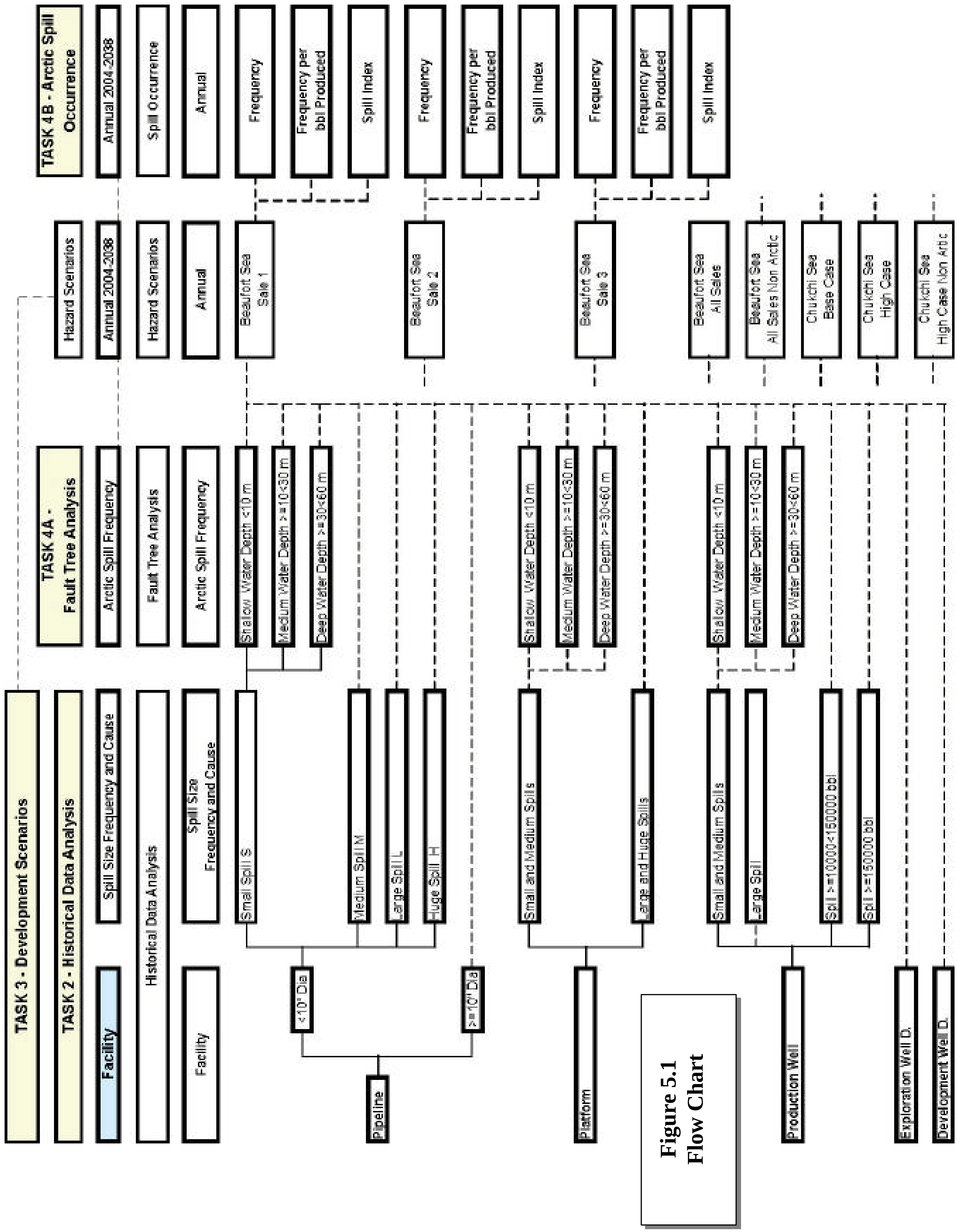


Figure 5.1
Flow Chart

5.3 Summary of Beaufort Sea Oil Spill Occurrence Indicators

5.3.1 Beaufort Sea Sale 1 Oil Spill Occurrence Indicators

Each of the principal oil spill occurrence indicators calculated for the composite of facilities under Sale 1 is given in Figures 5.2, 5.3, and 5.4.

As can be seen, each of these figures spans the development scenario to year 2029 described in Chapter 3. Further, each of the indicators has been subdivided into three segments for each year, those corresponding to spills < 1,000 bbl (small and medium), spills = 1,000 < 10,000 bbl (large), and spills =10,000 bbl (huge). It should be noted that the spill frequency associated with each spill size is only the increment shown in each of the bars. Thus, for example, for the year 2020, small and medium spills are approximately 10.0 per thousand years. Next, in that year, large spills are approximately 4.5 per thousand years, as shown in the second bar increment (i.e., 14.5 - 10 = 4.5). Finally, the top increment corresponds to huge spills, and is approximately 2.5 per thousand years. The same form of presentation applies for spills per barrel produced and for the spill index shown in Figures 5.3 and 5.4. Clearly, the spill index is dominated by the huge spills, which have an average spill size of 20,000 bbl. The spills per barrel produced continue to rise beyond the peak production year of 2016, because the facility quantities (and hence spill rate) remain relatively high, while production volumes decrease significantly each year. The reader should note that following this detailed presentation of the spill indicators in separate figures, all three spill indicators will be given in one figure in order to conserve space and make the report a little more concise.

Spill indicators by facility type were also quantified. All three spill indicators for pipelines for Beaufort Sea Sale 1 are shown in Figure 5.5. Figure 5.6 shows the spill indicators for platforms and Figure 5.7 shows the spill indicators for drilling of wells and producing wells. Numerous conclusions can be drawn from the comparison of these spill indicators. For example, it can be seen that the major contributors to spill frequency are platforms. The largest of the facility spill expectations, as represented by spill index, are the wells, simply because they have the potential to release the largest amounts of oil in blowouts.

Finally, as part of the assessment of each lease sale or development scenario, a Monte Carlo analysis was carried out for each year, with the distributed inputs described earlier. For Lease Sale 1, tabular results of the Monte Carlo simulation of 5,000 iterations for distributions in Arctic effects inputs only, is summarized in Table 5.1. This table gives the statistical characteristics of the calculated indicators for each of three spill size ranges, as well as a tabular summary of their cumulative distribution curves for a representative production year (2016). Figure 5.8 shows graphs of the calculated cumulative distribution functions. Basically, the vertical axis gives the probability in percent that the corresponding value on the horizontal axis will not be exceeded. Thus, for example, referring to the central graph, for spills < 1,000 bbl (small and medium), there is a 40% probability that a spill frequency will be no more than 0.2 per billion barrels produced.

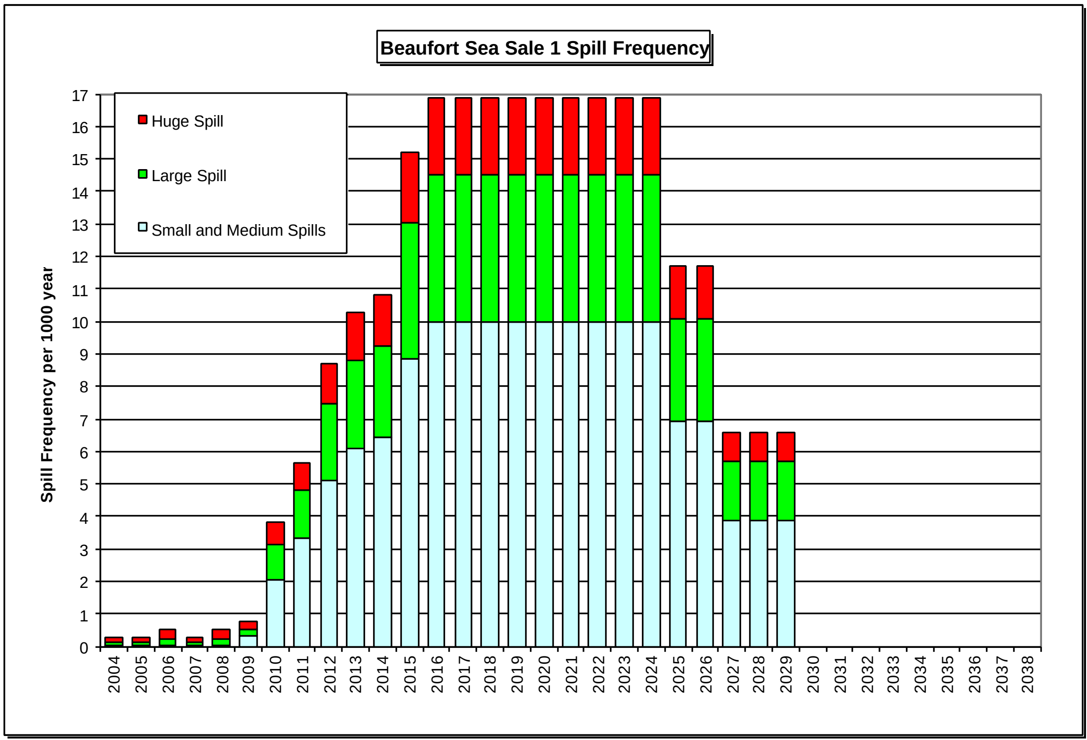


Figure 5.2
Beaufort Sea Sale 1 Spill Frequency

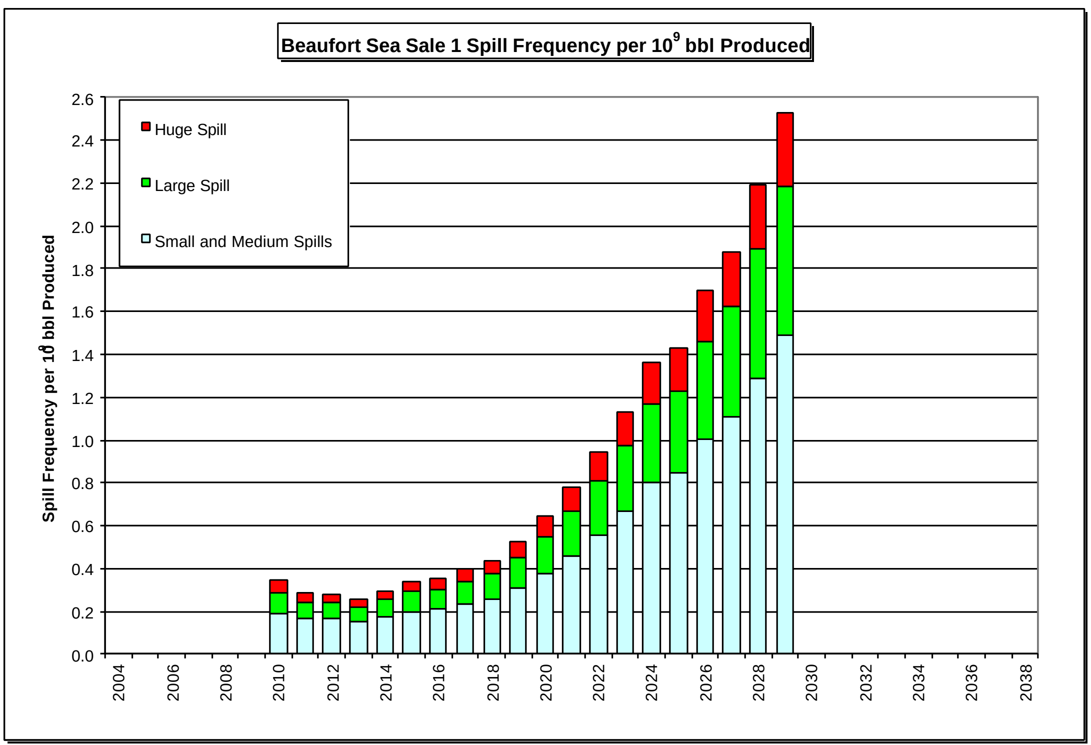


Figure 5.3
Beaufort Sea Sale 1 Spill Frequency per 10^9 Barrels Produced

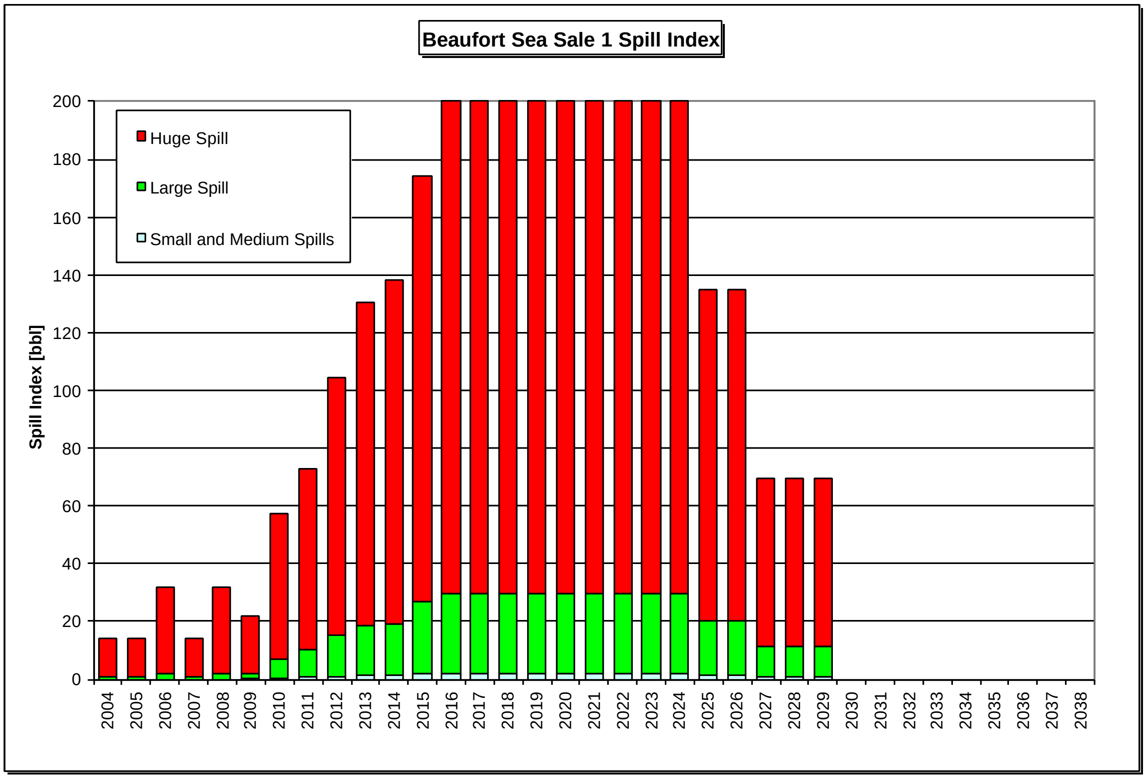


Figure 5.4
Beaufort Sea Sale 1 Spill Index

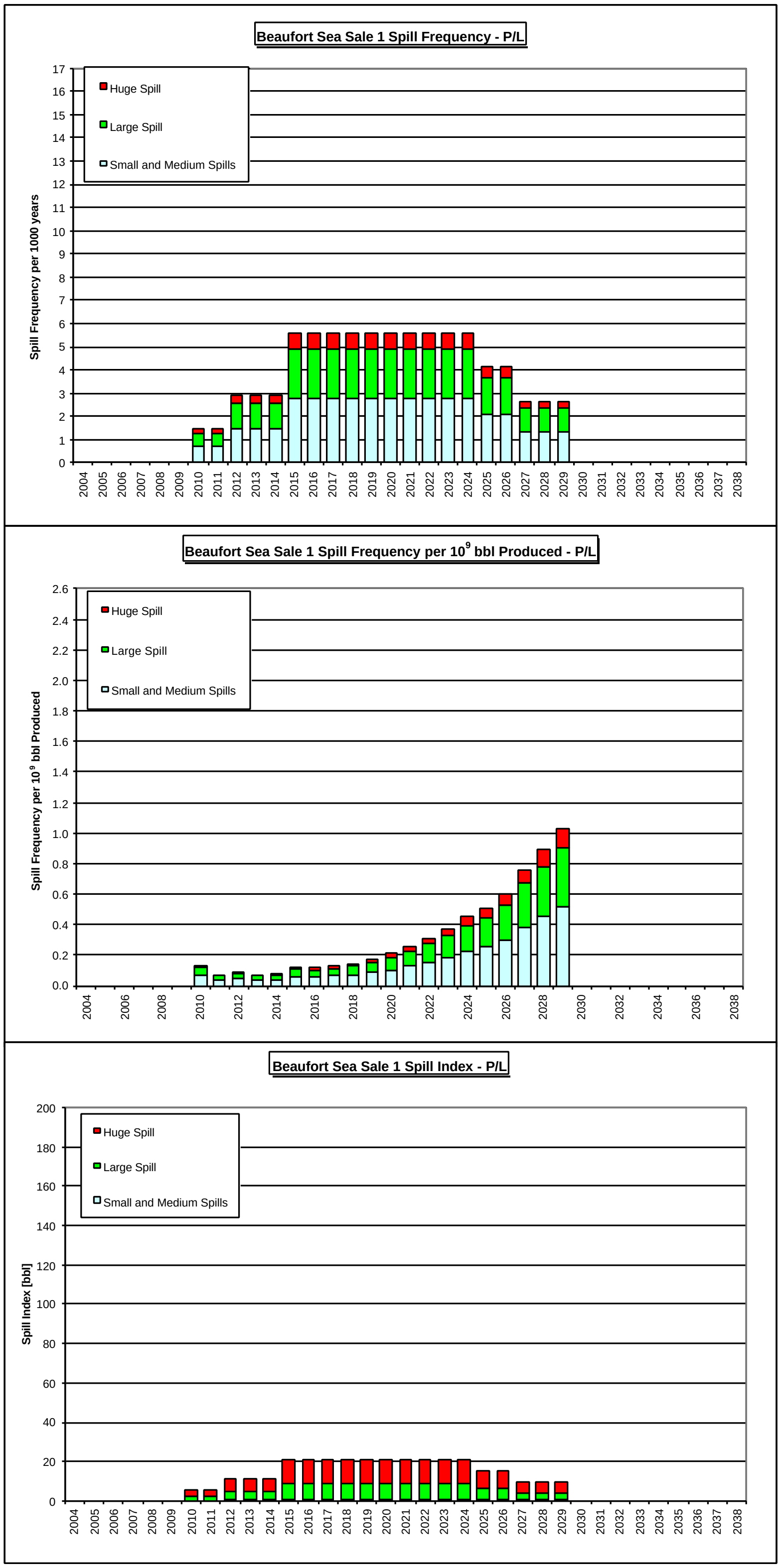


Figure 5.5
Beaufort Sea Sale 1 Indicators – Pipeline

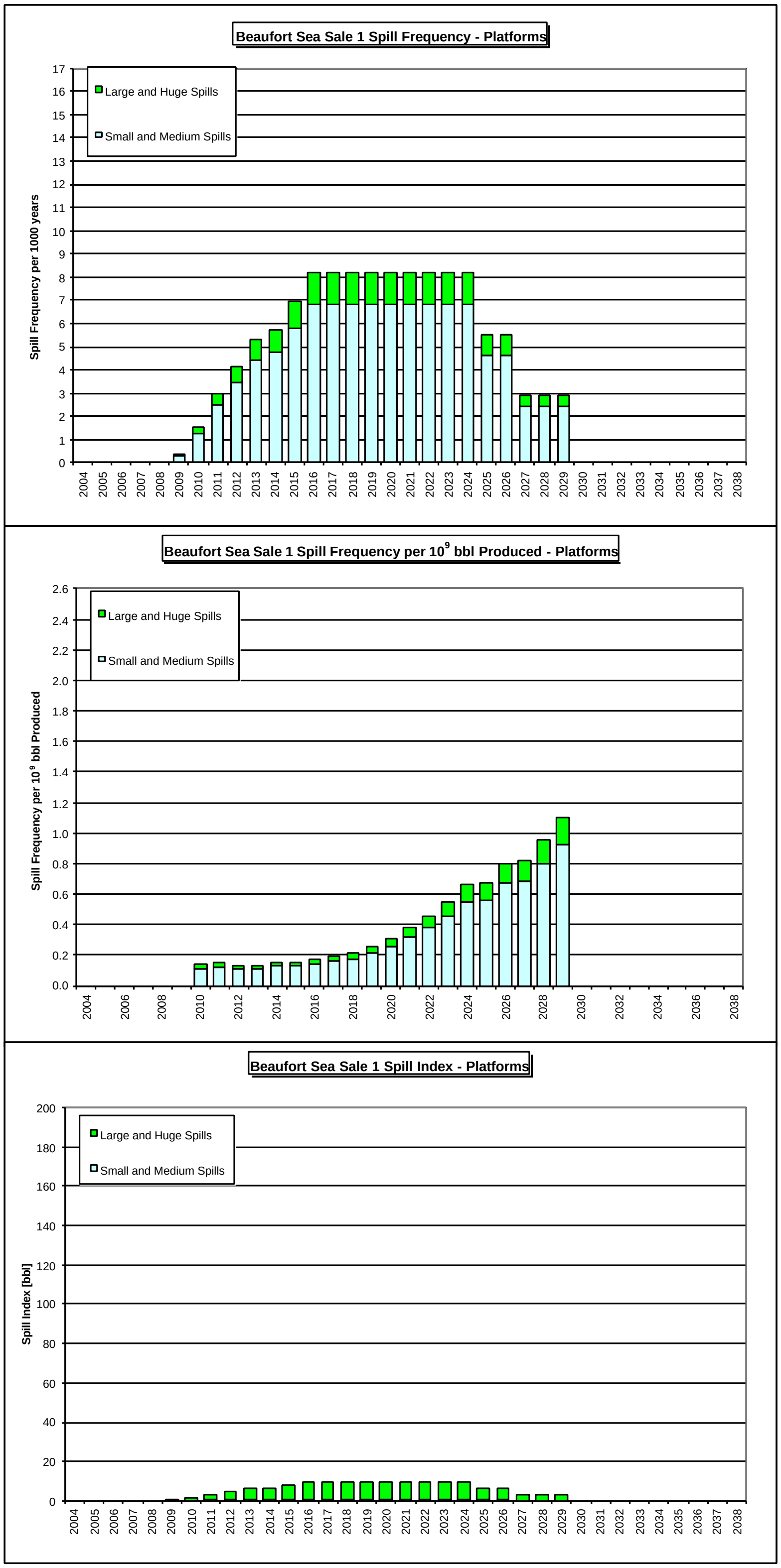


Figure 5.6
Beaufort Sea Sale 1 Indicators - Platforms

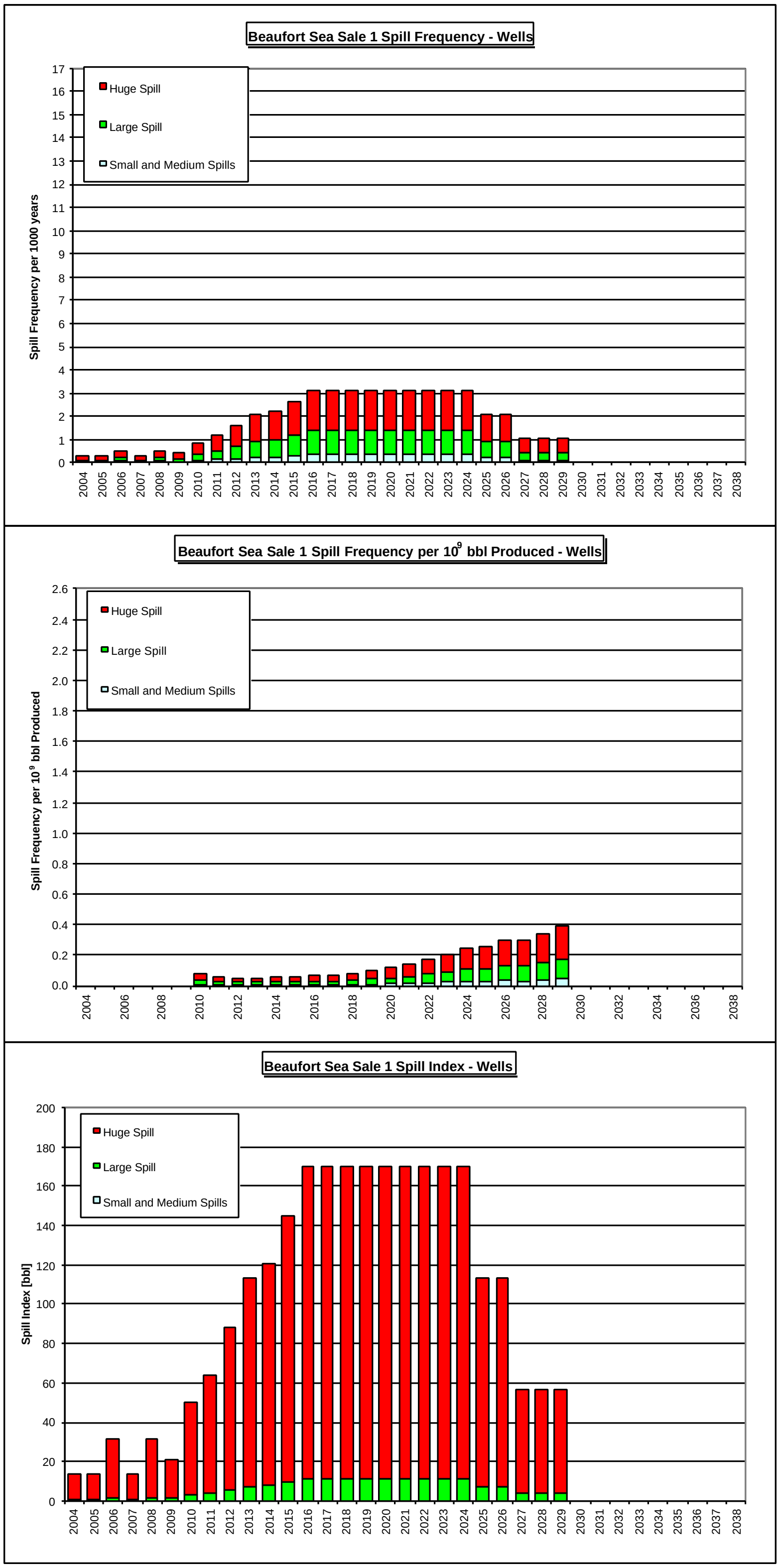
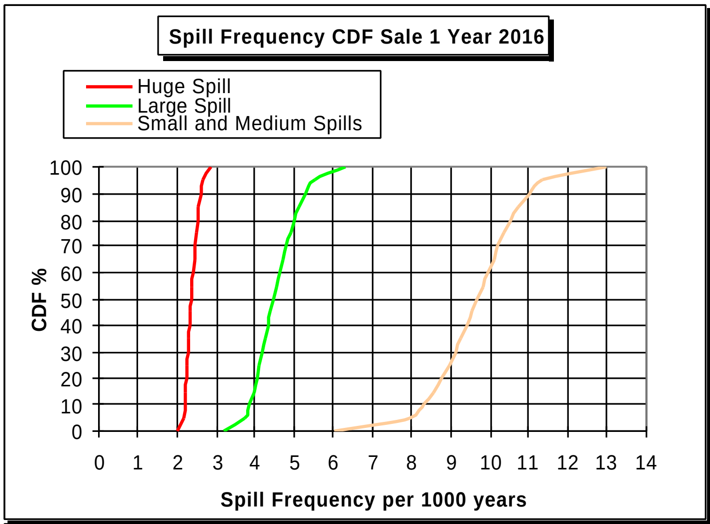
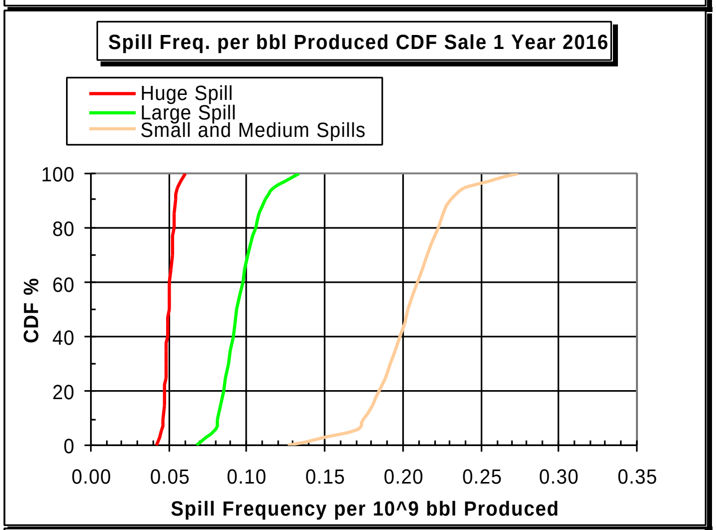


Figure 5.7
Beaufort Sea Sale 1 Indicators - Wells

Table 5.1
Beaufort Sea Sale 1 Year 2016 – Monte Carlo Results

SALE 1	Small and Medium Spills			Large Spills			Huge Spills		
Year 2016	Frequency Spills per 10^3years	Frequency Spills per 10^9 bbl Produced	Spill Index [bbl]	Frequency Spills per 10^3years	Frequency Spills per 10^9 bbl Produced	Spill Index [bbl]	Frequency Spills per 10^3years	Frequency Spills per 10^9 bbl Produced	Spill Index [bbl]
Mean =	9.67	0.20	2.02	4.53	0.10	27.58	2.39	0.05	170.39
Std Deviation =	1.03	0.02	0.18	0.54	0.01	2.20	0.15	0.00	2.61
Variance =	1.07	0.00	0.03	0.29	0.00	4.84	0.02	0.00	6.83
Skewness =	-0.04	-0.04	0.01	0.41	0.41	0.37	0.41	0.41	0.41
Kurtosis =	2.87	2.87	2.89	2.66	2.66	2.70	2.57	2.57	2.57
Mode =	8.63	0.18	1.83	3.97	0.09	29.13	2.33	0.05	167.05
Minimum =	6.02	0.127	1.35	3.20	0.067	21.72	2.00	0.042	163.64
5% Perc =	7.96	0.168	1.71	3.75	0.079	24.31	2.17	0.046	166.63
10% Perc =	8.34	0.176	1.78	3.88	0.082	24.90	2.21	0.046	167.23
15% Perc =	8.59	0.181	1.83	3.97	0.083	25.31	2.23	0.047	167.68
20% Perc =	8.79	0.185	1.86	4.05	0.085	25.62	2.25	0.047	168.05
25% Perc =	8.97	0.189	1.89	4.12	0.087	25.94	2.27	0.048	168.38
30% Perc =	9.13	0.192	1.92	4.19	0.088	26.22	2.29	0.048	168.72
35% Perc =	9.27	0.195	1.95	4.27	0.090	26.56	2.31	0.049	169.04
40% Perc =	9.42	0.198	1.97	4.33	0.091	26.83	2.33	0.049	169.38
45% Perc =	9.55	0.201	2.00	4.40	0.093	27.10	2.35	0.049	169.72
50% Perc =	9.67	0.204	2.02	4.46	0.094	27.38	2.37	0.050	170.05
55% Perc =	9.80	0.206	2.04	4.54	0.095	27.64	2.39	0.050	170.42
60% Perc =	9.95	0.209	2.07	4.61	0.097	27.94	2.41	0.051	170.81
65% Perc =	10.08	0.212	2.09	4.69	0.099	28.28	2.43	0.051	171.26
70% Perc =	10.22	0.215	2.11	4.79	0.101	28.65	2.46	0.052	171.73
75% Perc =	10.37	0.218	2.14	4.89	0.103	29.09	2.49	0.052	172.22
80% Perc =	10.54	0.222	2.17	5.00	0.105	29.49	2.52	0.053	172.78
85% Perc =	10.73	0.226	2.21	5.12	0.108	30.00	2.55	0.054	173.30
90% Perc =	11.01	0.232	2.26	5.28	0.111	30.67	2.60	0.055	174.12
95% Perc =	11.36	0.239	2.33	5.52	0.116	31.58	2.65	0.056	175.06
Maximum =	13.01	0.274	2.65	6.33	0.133	35.39	2.85	0.060	178.64





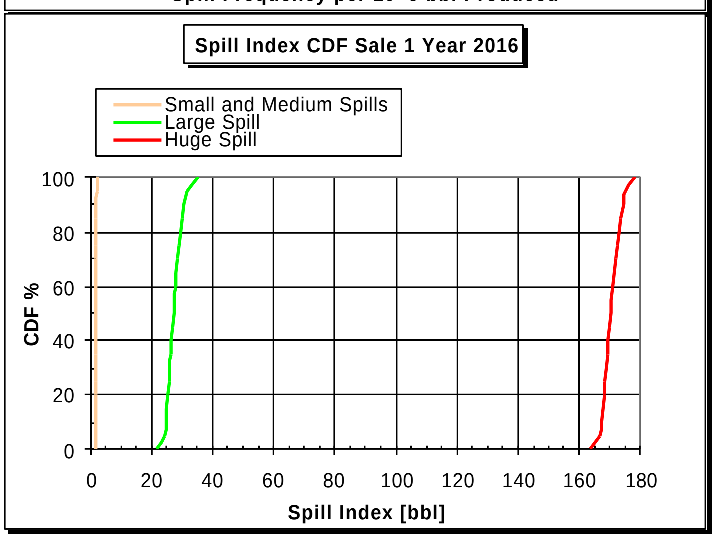


Figure 5.8
Beaufort Sea Sale 1 Indicator Distributions

In other words, there is a 40% chance that small and medium spills will occur at a rate of 0.2 per billion or less. Conversely, there is a 60% chance that the small and medim spill rate will be greater than 0.2 per billion. The distributions show relatively small variance; this is largely attributable to the fact that the historical data used as a basis for the calculations, were considered to be precise; only Arctic effect input distributions were used. The frequency spill indicator variability can be estimated from the upper (95%) and lower (5%) bound values. For example, for large spill frequency (from Table 5.1), the lower bound is 83% of the mean; the upper bound, 130% of the mean.

5.3.2 Beaufort Sea Lease Sale 2 Oil Spill Occurrence Indicators

Figure 5.9 summarizes the three oil spill occurrence indicators for Beaufort Sea Sale 2. The primary difference is one of scheduling with some differences in magnitude of the indicators, although they are not substantially different from those of Sale 1.

5.3.3 Beaufort Sea Lease Sale 3 Oil Spill Occurrence Indicators

Figure 5.10 summarizes all three of the Beaufort Sea Sale 3 oil spill occurrence indicators. Again, these are not substantially different from the Sale 1 and 2 indicators.

5.3.4 Beaufort Sea Sale All Oil Spill Occurrence Indicators

The oil spill occurrence indicators for all three Beaufort Sea Sale development scenarios are summarized in Figure 5.11. As one would expect, the absolute values of spill frequencies are significantly higher than any of the sales, essentially because they are the sum, through the Monte Carlo iteration process, of the three sales spill frequencies. Spills per barrel produced tend to be the same as those of the individual sales. Finally, the spill index, which is the product of the frequency and average spill size, as one would expect, is significantly higher for the composite scenario, roughly three times the average value for the three sales. Naturally, the spill by facility breakdowns, the Monte Carlo results, and all the details of the calculations for the composite scenario as well as each individual sale scenario are given in Appendix C.

5.3.5 Beaufort Sea Sale All Comparative Non-Arctic Indicator Assessment

To give an idea of the effect of the frequency variations introduced in Chapter 4, the composite (Sale All) Beaufort Sea scenario was also modeled utilizing unaltered historical frequencies. That is, no changes to incorporate the Arctic effects were introduced in the spill indicator calculations. Put yet another way, it was assumed that the facilities of the composite scenario would behave as if they were in the Gulf of Mexico environment rather than in the Arctic environment. Figures 5.12, 5.13, and 5.14 show the

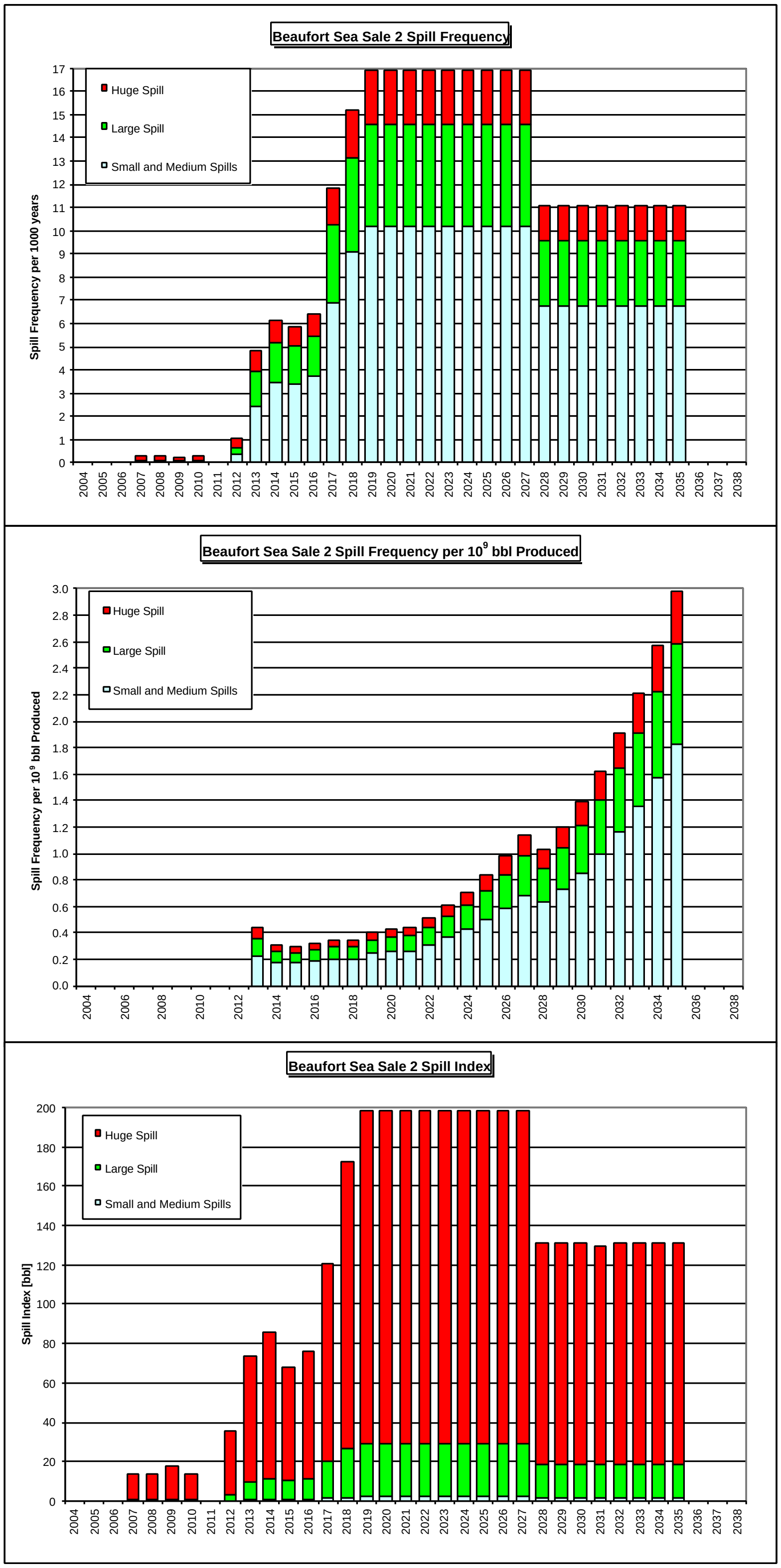


Figure 5.9
Beaufort Sea Sale 2 Indicators

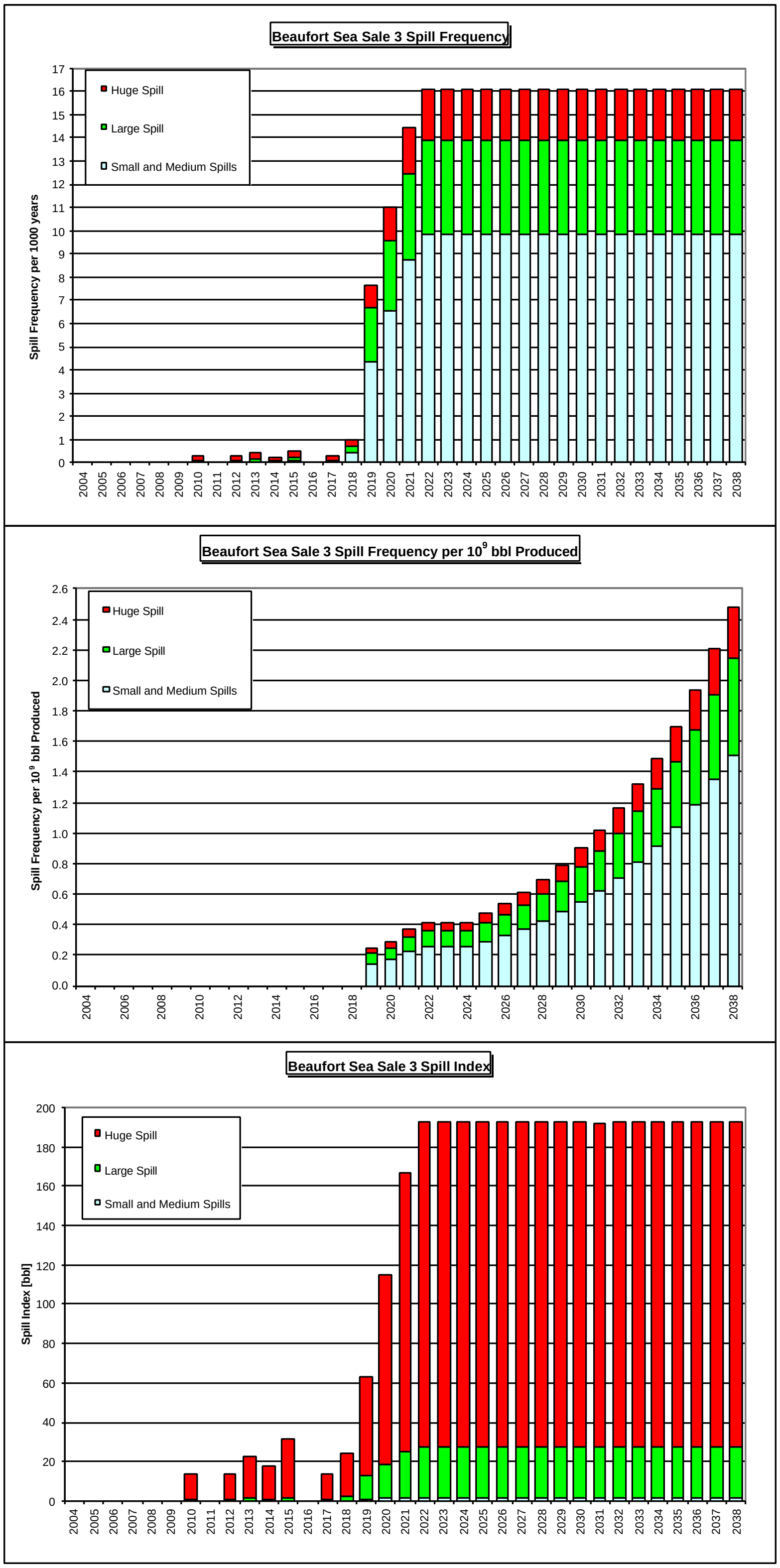


Figure 5.10
Beaufort Sea Sale 3 Indicators

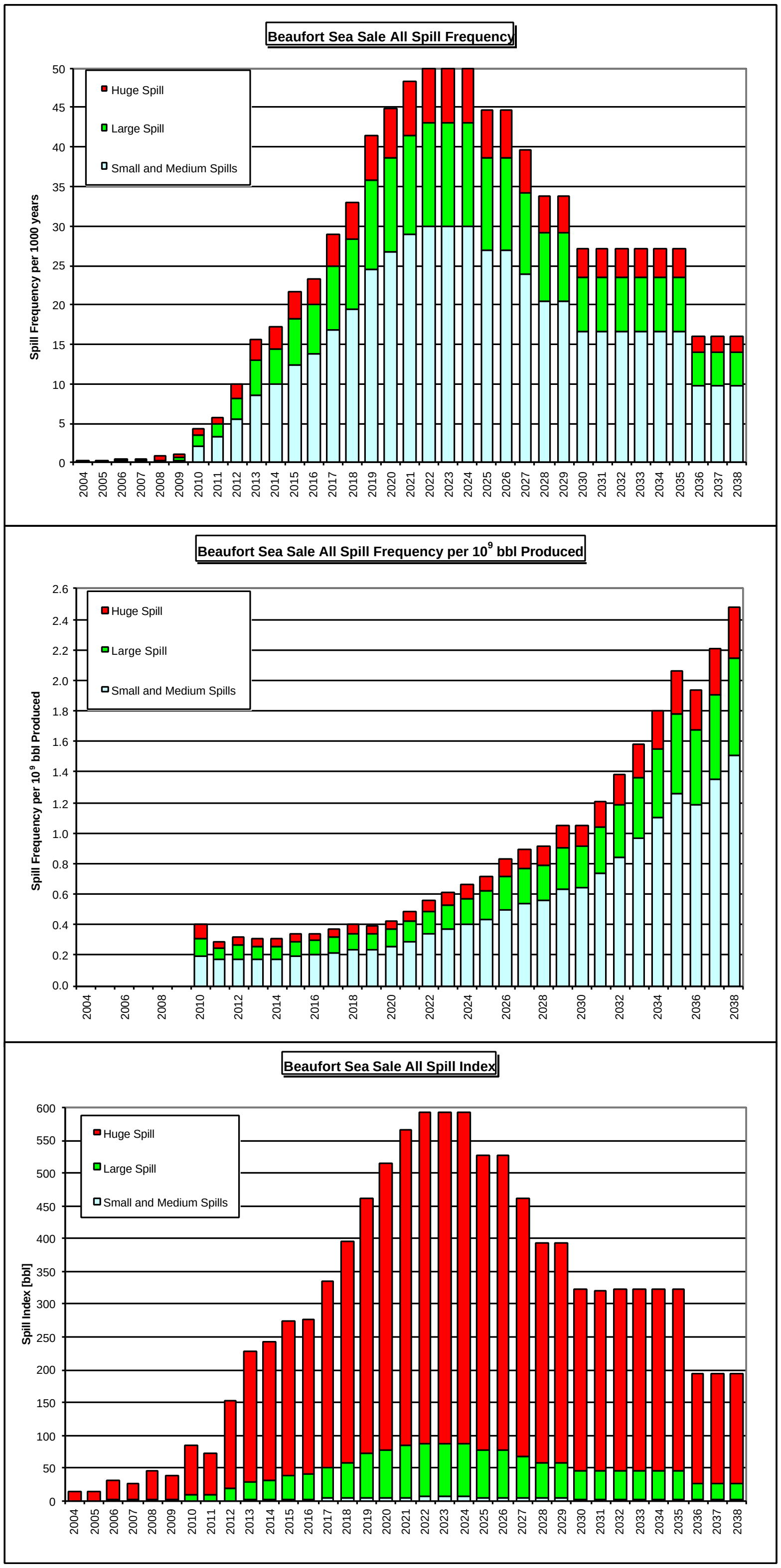


Figure 5.11
Beaufort Sea Sale All Indicators

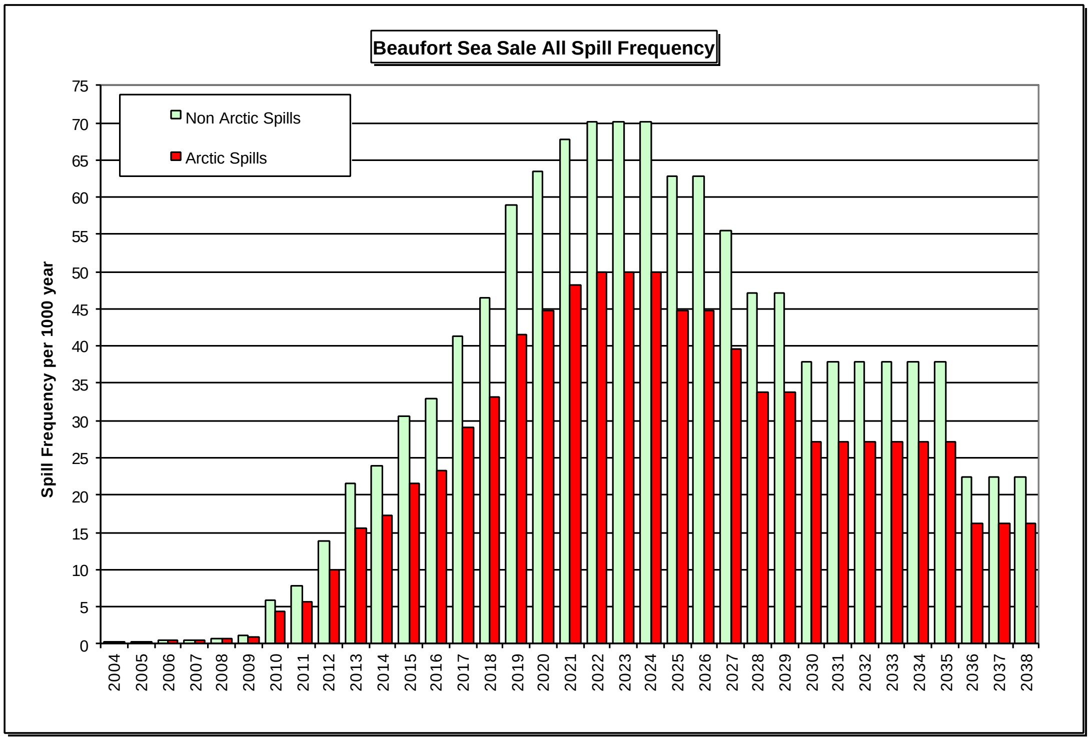


Figure 5.12
Beaufort Sea Sale All Spill Frequency – Arctic and Non-Arctic

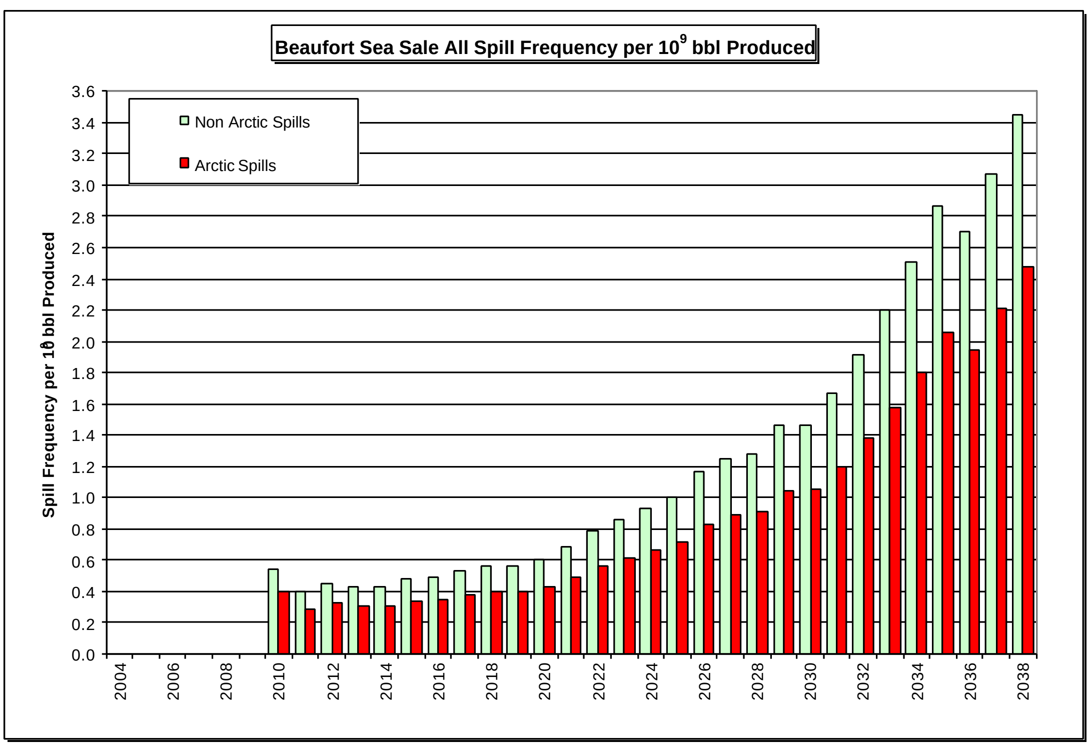


Figure 5.13
Beaufort Sea Sale All Spill Frequency per 10^9 Barrels Produced – Arctic and Non-Arctic

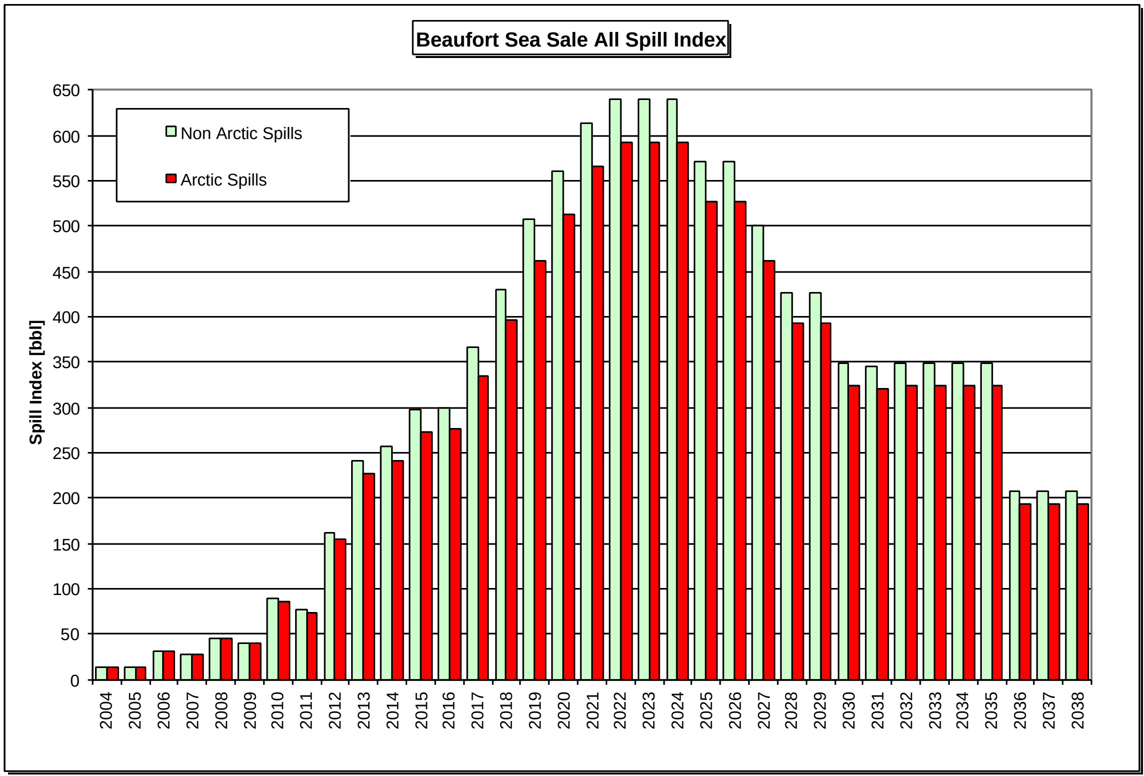


Figure 5.14
Beaufort Sea Sale All Spill Index – Arctic and Non-Arctic

total values calculated for each of the three spill indicators. The dark histogram bar on the right side corresponds to the Arctic spill indicator, while that, on the left, corresponds to the computation based on historical frequencies only. Spill frequency in an absolute sense is significantly reduced for the Arctic situation roughly by 30%. The spills per barrel produced are also significantly reduced, as can be seen in Figure 5.13. However, the spill index, because of the disproportionate effect of large spills, shows only a small reduction of less than 10%. What the comparison shows is that the Arctic development scenarios will have a lower oil spill occurrence than similar development scenarios in the GOM.

5.4 Summary of Chukchi Sea Oil Spill Occurrence Indicators

5.4.1 Chukchi Sea Base Case Oil Spill Occurrence Indicators

Chukchi Sea scenarios described in Chapter 3 span only 10 years. Figure 5.15 shows all of the Chukchi Sea Base Case midpoint oil spill occurrence indicators. The spill indicators tend to be higher than those for the Beaufort Sea individual lease sales, but are comparable to those of the composite Beaufort Sea case. Again, the details of the indicators are presented in Appendix C.

The variation shown by the cumulative distribution functions for each of the indicators is shown in Figure 5.16. The Chukchi Sea small and medium spill indicators exhibit a greater variance than their Beaufort Sea counterparts with value of lower bound (5%) and upper bound (95%) of 67% and 150% of the mean, respectively.

5.4.2 Chukchi Sea High Case Oil Spill Occurrence Indicators

Figure 5.17 shows the Chukchi Sea High Case midpoint oil spill occurrence indicators. Again, these indicators tend to be higher than those for the individual Beaufort Sea components, and in this case, even higher than those of the Beaufort Sea composite and the Chukchi Sea Base Case. This is clearly because the potential spill sources increase significantly with the increase in the extent of the facilities. Some affects of scale, however, can be noted in the reduction of the expected Chukchi Sea spill frequency per barrel produced as shown in the middle graph in Figure 5.17.

Finally, the Chukchi Sea High Case indicator cumulative distribution functions are illustrated in Figure 5.18. The same pattern of variance as for the Base Case is evident for the High Case CDFs.

5.4.3 Chukchi Sea High Case Comparative Non-Arctic Indicator Assessments

As was done for the Beaufort Sea (Section 5.3.5), a non-Arctic comparison was carried out for the Chukchi Sea. Figure 5.19 shows the comparative results of the calculation. Again, the non-Arctic scenario exhibits higher oil spill occurrences through higher values of all three oil spill indicators.

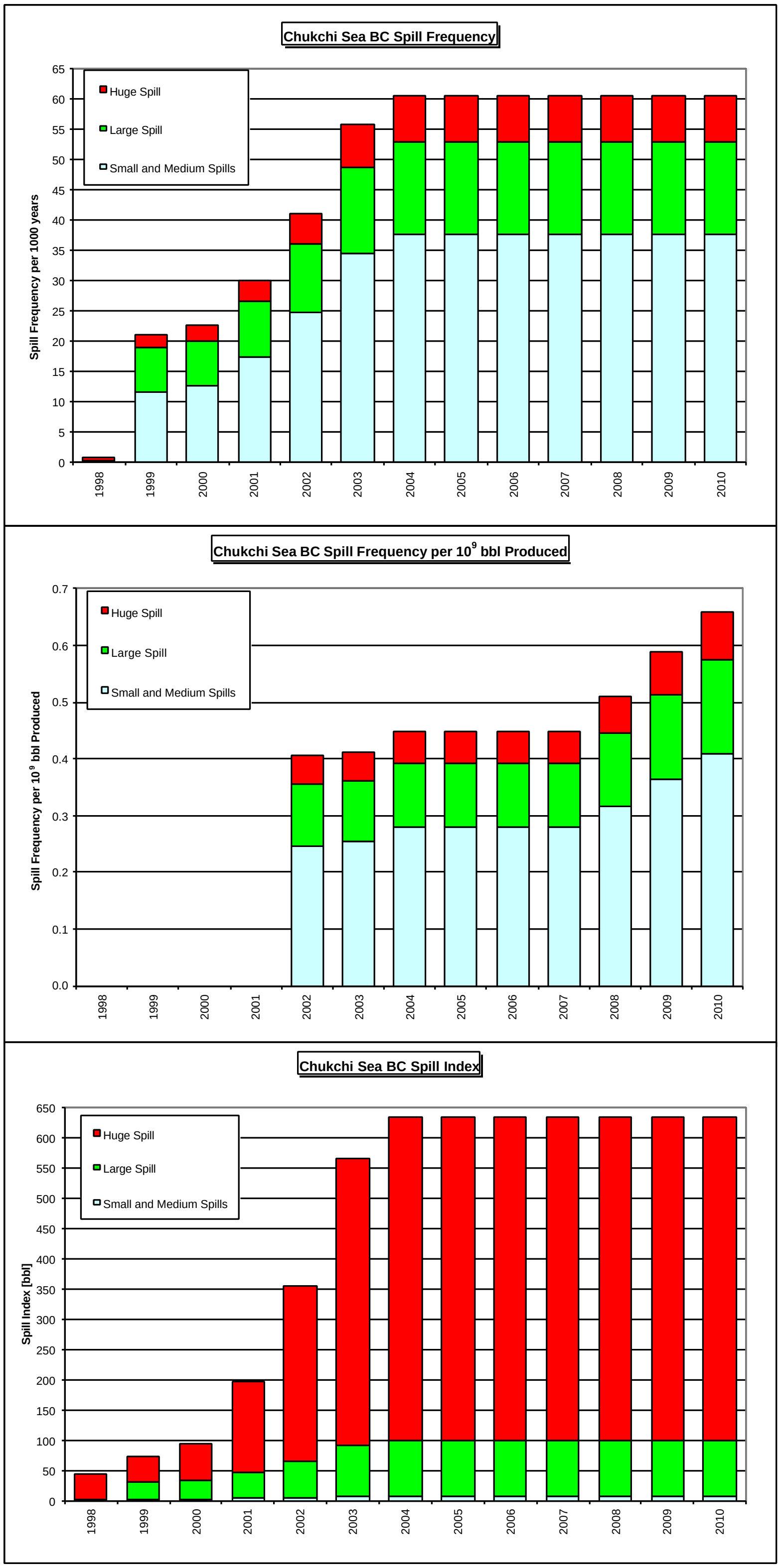


Figure 5.15
Chukchi Sea Base Case Indicators

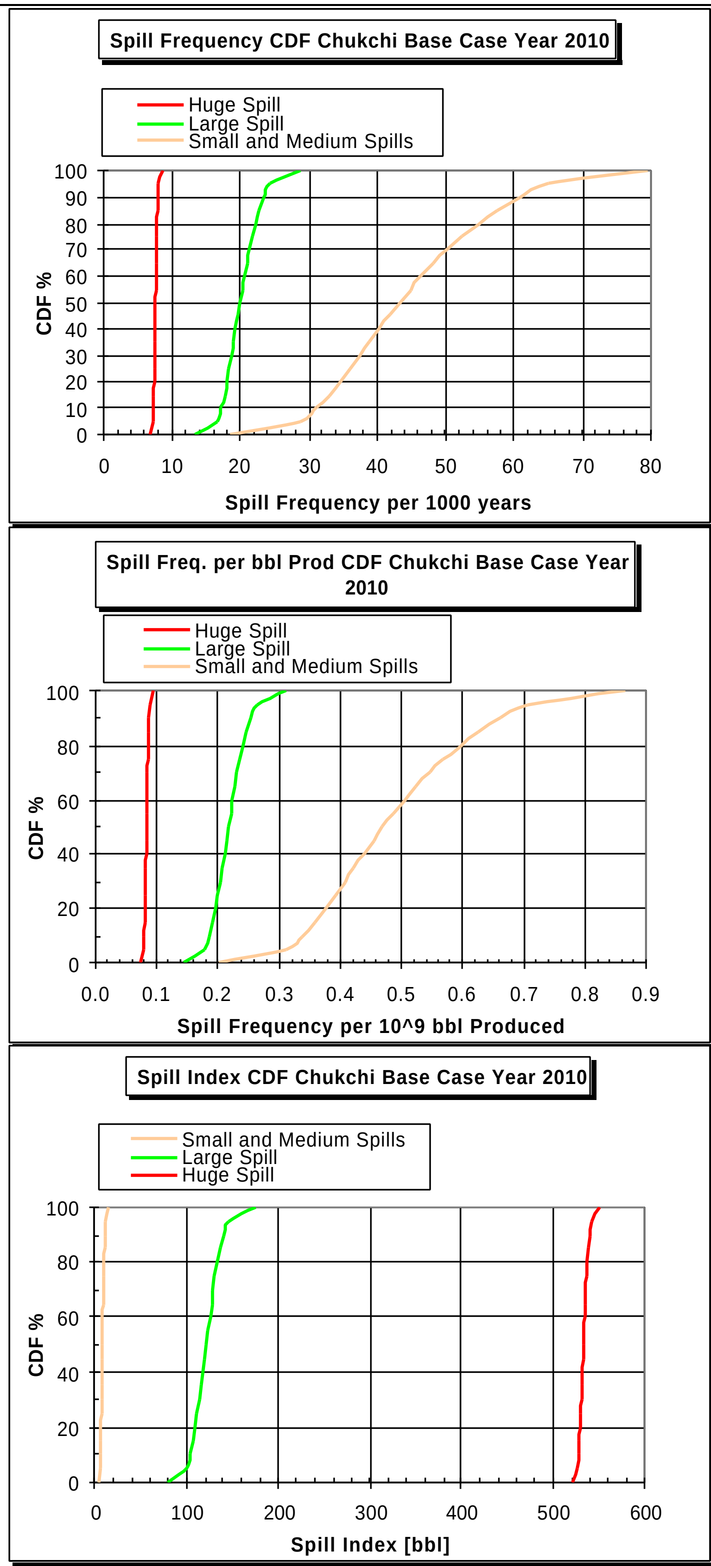


Figure 5.16
Chukchi Sea Base Case Indicator Distributions

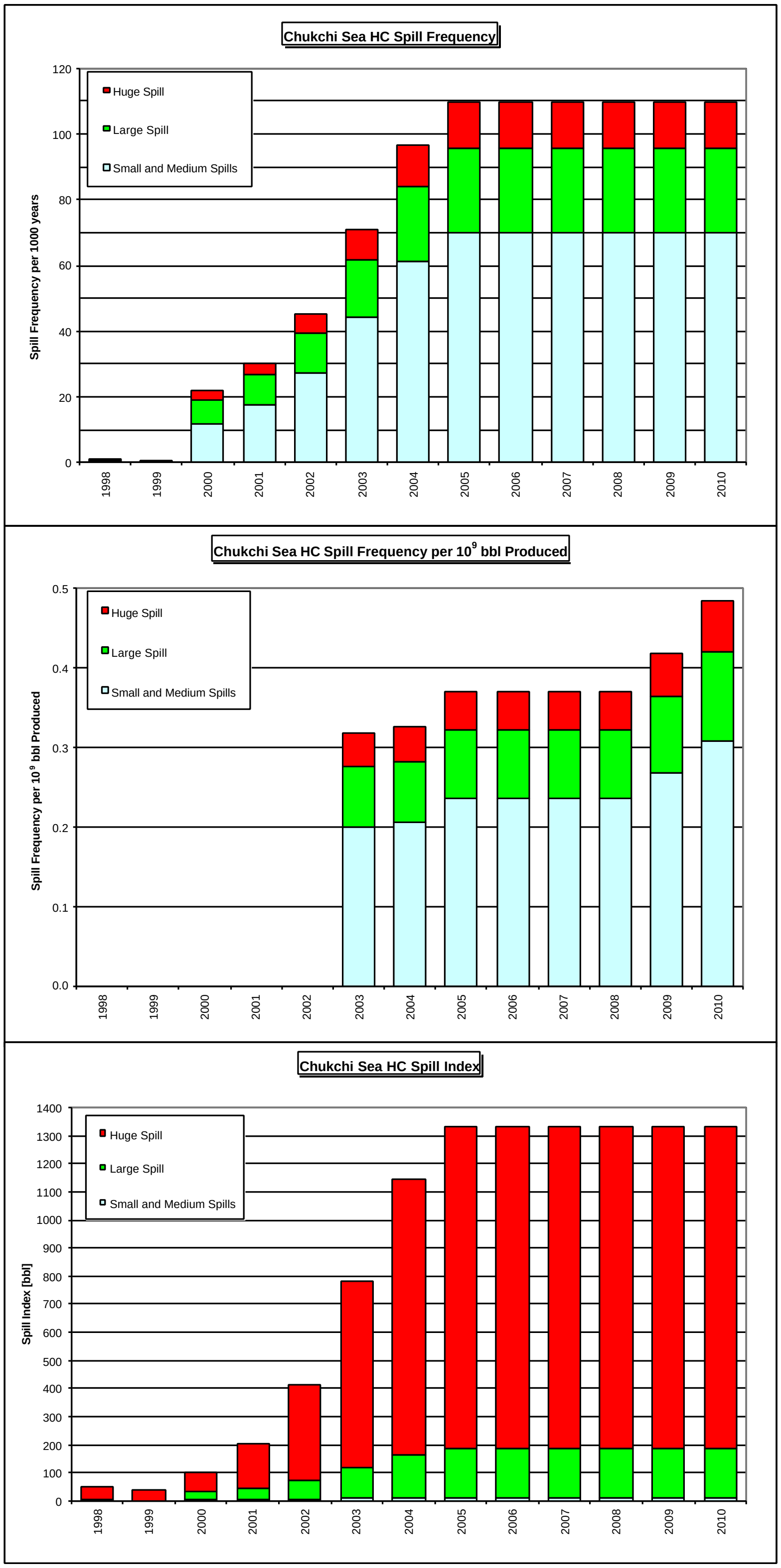


Figure 5.17
Chukchi Sea High Case Indicators

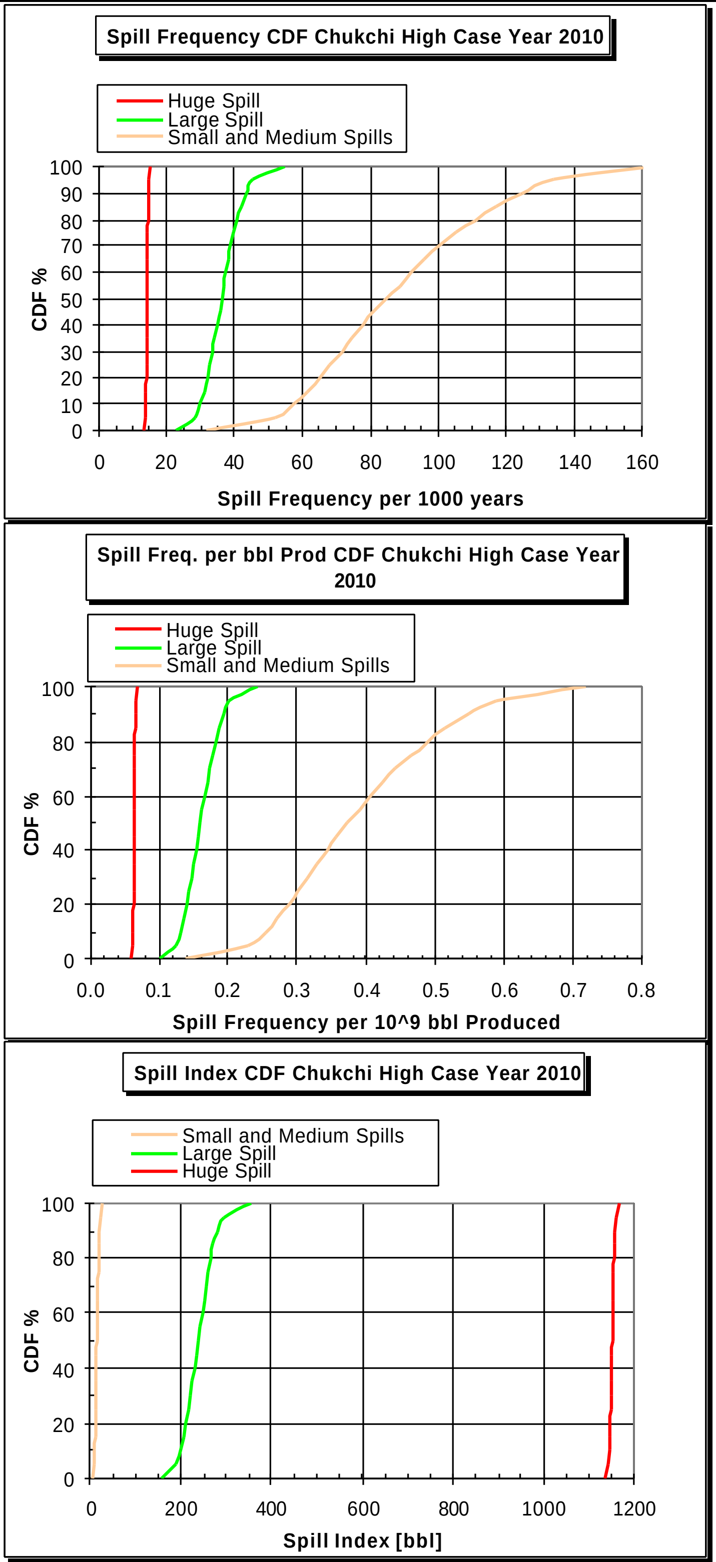


Figure 5.18
Chukchi Sea High Case Indicator Distributions

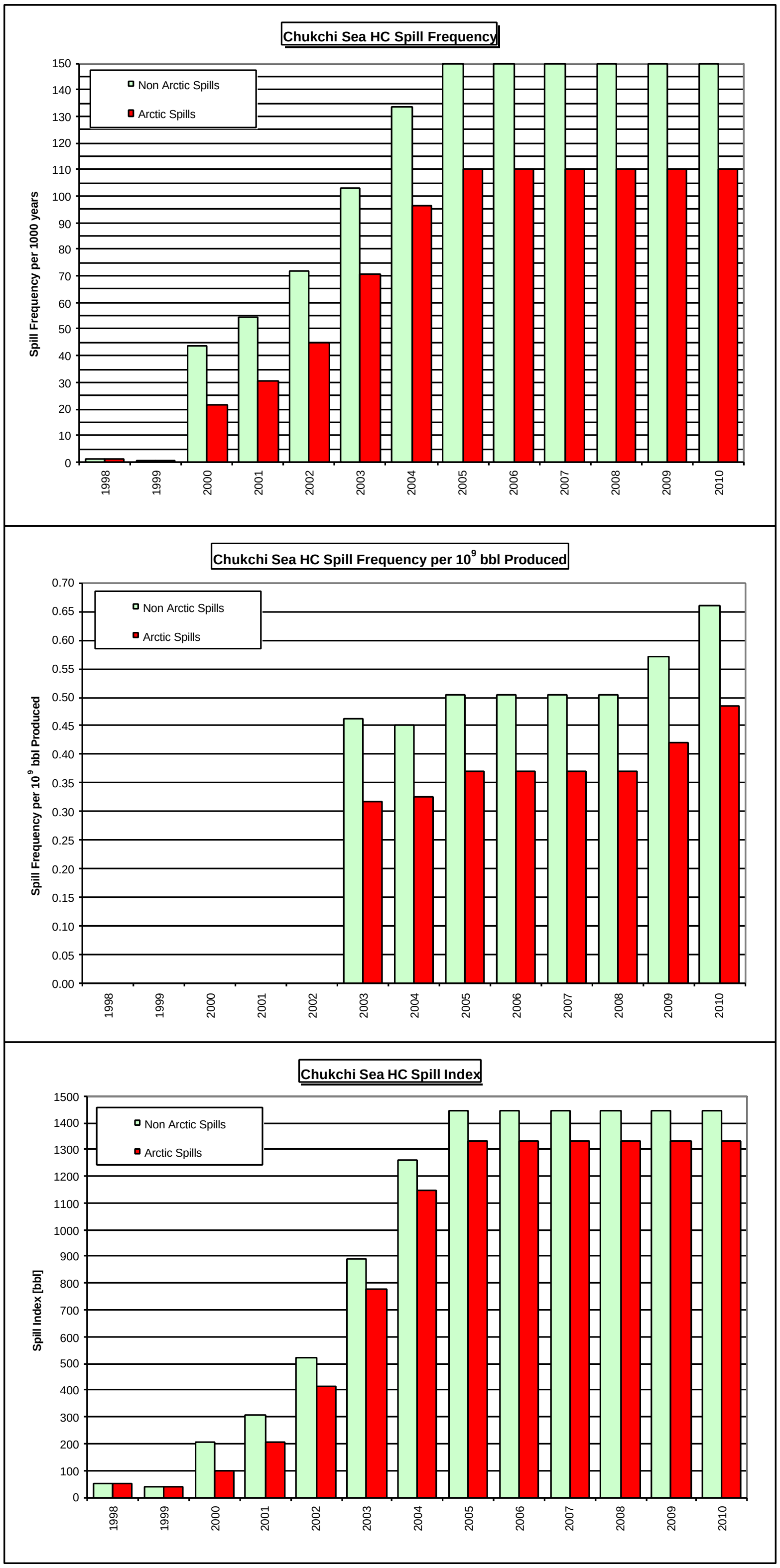


Figure 5.19

Comparative Chukchi Sea High Case Spill Indicators

5.5 Summary of Representative Oil Spill Occurrence Indicator Results

How do spill indicators for the different scenarios and for their non-Arctic counterparts vary by spill size location. Table 5.2 summarizes the spill indicator values for representative years. Except for the maximum spill frequency per barrel produced indicator, which occurs in the final year of the associated scenarios, representative years are chosen as the peak production years. The following can be observed from Table 5.2.

- Each spill indicator for Beaufort Sea Sale 1, 2, and 3 is similar in value. The indicators are higher for the composite "sale" scenario.
- Chukchi Sea spill indicators are all higher than Beaufort Sea indicators.
- Spill frequency per year and per barrel-year decreases significantly with increasing spill size for all scenarios.
- The spill index increases dramatically with spill size for all scenarios.
- All non-Arctic scenario spill indicators are greater than their Arctic counterparts. Non-Arctic spill frequencies are approximately 40% greater; spill indices are 8% greater for the non-Arctic scenarios.

How do the spill indicators vary by facility type for representative scenarios? The contributions of spill indicators by facility have also been summarized by representative scenario years. Table 5.3 gives the component contributions, in absolute value and percent, for each of the main facility types; namely, pipelines (P/L), platforms, and wells. The following may be noted from Table 5.3:

- For both the Beaufort and Chukchi scenarios, platforms contribute the most (50% and 61% respectively) to the two spill frequency indicators, but the least (5% and 6% respectively) to the spill index.
- Pipelines in the Beaufort scenarios are next in relative contribution to spill frequencies (31%) and intermediate in contribution to spill index (10%).
- The relative contributions of pipelines to spill frequencies in the Chukchi, however, are approximately the same (20%) as contributions of wells to spill frequencies in the Chukchi.
- Wells are by far (at 86% and 89% respectively) the highest contributors to spill index in the Beaufort and Chukchi Seas, while platforms and wells are responsible for 10% or less contribution to the spill index.
- It can be concluded that platforms are likely to have the most, but smaller spills, while wells will have the least number, but largest spills. Pipelines will be in between, with a tendency towards more spills than wells, but less or about the same number as platforms. Pipeline spill volumes will tend to be greater than (Beaufort) or similar in size (Chukchi) to platform spills.

Table 5.2
Summary of Spill Indicators for All Scenarios

SPILL INDICATORS	Spill Size	Beaufort Sea					Chukchi Sea		
		Year 2016	Year 2019	Year 2024	Year 2020	Year 2020	Year 2010	Year 2010	Year 2010
		Sale 1	Sale 2	Sale 3	Sale All	Sale All Non Arctic	Base Case	High Case	High C Non Arctic
Spill Frequency per 10^3 years	SM	9.97	10.17	9.84	29.98	43.90	37.66	70.18	95.17
	L	4.53	4.42	4.07	13.02	17.83	15.23	25.34	36.70
	H	2.39	2.34	2.21	6.93	8.31	7.68	14.38	17.85
	All	**16.88**	**16.93**	**16.12**	**49.93**	**70.04**	**60.58**	**109.91**	**149.72**
Spill Frequency per 10^9 bbl produced	SM	0.21	0.24	0.25	0.40	0.59	0.41	0.31	0.42
	L	0.10	0.11	0.11	0.17	0.24	0.17	0.11	0.16
	H	0.05	0.06	0.06	0.09	0.11	0.08	0.06	0.08
	All	**0.36**	**0.40**	**0.42**	**0.67**	**0.94**	**0.66**	**0.48**	**0.66**
Maximum Spill Frequency per 10^9 bbl produced (year varies)	All	**2.53**	**2.99**	**2.48**	**2.48**	**3.45**	**0.66**	**0.48**	**0.66**
Spill Index [bbl]	SM	2	2	2	6	9	8	13	19
	L	28	27	26	81	102	92	171	218
	H	170	169	165	505	529	534	1150	1211
	All	**200**	**199**	**193**	**592**	**640**	**633**	**1335**	**1448**

Table 5.3
Composition of Spill Indicators

SPILL INDICATORS	Beaufort Sea				Chukchi Sea			
	Sale All - Year 2024				High Case - Year 2010			
	P/L	Platforms	Wells	TOTAL	P/L	Platforms	Wells	TOTAL
Spill Frequency per 10^3 years	15.55	25.11	9.27	49.93	21.18	67.03	21.69	109.91
	31%	50%	19%	100%	19%	61%	20%	100%
Spill Frequency per 10^9 bbl produced	0.21	0.34	0.12	0.67	0.09	0.30	0.10	0.48
	31%	50%	19%	100%	19%	61%	20%	100%
Spill Index [bbl]	56	29	507	592	73	76	1186	1335
	10%	5%	86%	100%	5%	6%	89%	100%

Figure 5.20 shows the CDFs for the Beaufort Sea Sale All spill indicators. The variability of these indicators is fairly representative of the trends in variability for spill indicators for all sales and locations studied. Generally, the following can be observed from Figure 5.20:

- The variance of the frequency spill indicators decreases as spill size increases. In other words, small and medium spills illustrate the largest variability; huge spills show the least variability.
- The variability of the spill index shows the same trend, but with a much smaller variability for the spill indices for all spill sizes.

Generally, in Figure 5.20, the slope of each line is an indicator of its variance. Specifically, it was found that for all spills the upper and lower bound (95^{th} percentile and 5^{th} percentile, respectively) ranged from 20% to 30%, with the smaller variances corresponding to the Beaufort Sea scenarios and the large ones to the Chukchi Sea scenarios. Upper (95%) and lower (5%) bounds, however, varied as much as 20 to 50% and 20 to 35% of the mean. Since many of the variations in the Arctic inputs ranged in excess of plus or minus 80% of the mean value, the relatively small variances suggest that the total model is quite robust; large variances in inputs cause only small variances in outputs. However, this small variance relates only to the Arctic effects; variance in historical spill size and frequency was considered to be zero. Thus, the variances discussed here characterize the uncertainties associated with the Arctic effects incorporated through the fault tree methodology in this study.

5.6 Comparison of Monte Carlo and Expected Value Results

As has been indicated, because of the upward skewness of the Arctic input value distributions, mean values of these distributions are generally greater than their expected values or modes. Hence, Monte Carlo results give higher occurrence indicators than the expected value results.

Skewness of the Arctic effect distributions results from the constraints on the lower bound. Clearly, physical quantities such as gouge flux cannot take on a value of less than zero; however, their upper bound is virtually unrestricted. Thus, lower bounds are restricted to less than 100% of the expected value, while upper bounds are unrestricted and can be several hundred percent of the expected value. If normal distributions had been chosen for the Arctic effects, then the Monte Carlo mean values and the expected values would have been numerically identical.

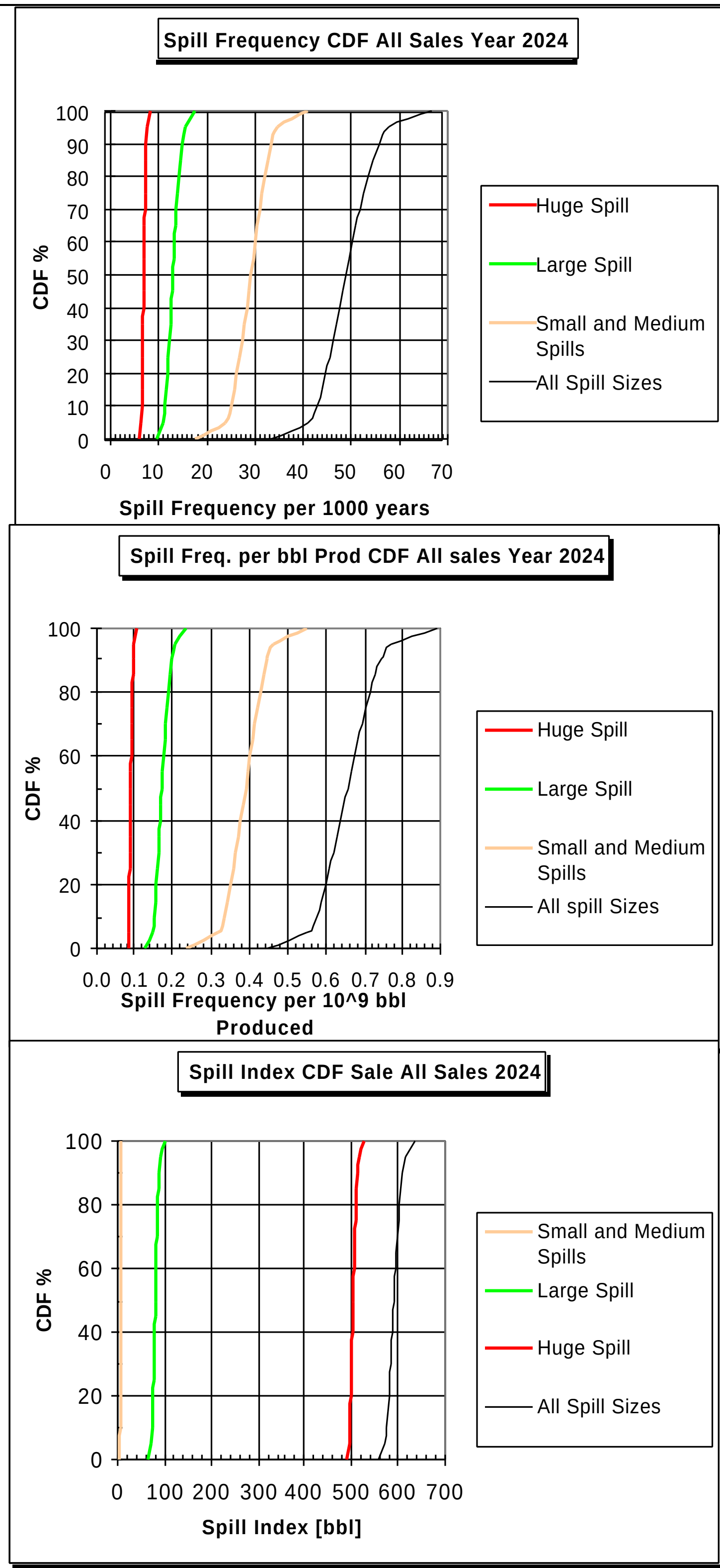


Figure 5.20
Typical Spill Occurrence Indicator Variance Graphs

Table 5.4 compares values of the spill occurrence indicators obtained by the two methods, and gives the difference as a percentage of the expected value result in each case. The percentage of the expected value result is taken so that if calculations are done using the expected value method, the simpler method, one has an idea of how much the expected value results should be increased to reach the levels of the Monte Carlo results. As can be seen from Table 5.4, except for wells for which no Arctic effects were included, the Monte Carlo values are greater by as much as 76%, and vary with facility type. The following observations can be made:

- Beaufort Sea pipeline Monte Carlo results for frequency calculations are in the order of 50% higher than the expected value calculations, and approximately 20% higher for the Chukchi Sea.
- Platform occurrence frequency indicators are in the order of 17% higher with Monte Carlo calculations for the Beaufort Sea, and roughly 28% higher for the Chukchi Sea.
- Wells, as indicated earlier, show no difference with calculation method, as no Arctic effects were introduced.
- On the average, total frequency indicators are roughly 20% higher calculated using the Monte Carlo method for both the Beaufort and Chukchi Seas.
- Pipeline spill indices are 76% and 32% higher for Beaufort and Chukchi Seas locations, respectively.
- Platform spill indices are 15% and 25% higher for Beaufort and Chukchi Seas locations, respectively.
- Because the average spill index under the total column is dominated by the well spill indices, which show no Arctic effects, their overall difference is quite low, in the order of 4%.

What the comparison demonstrates is that there is a significant difference between the Monte Carlo and expected value results. Generally, if total development scenario expected value results are to be used, they should be increased by at least 20% to account for the likely skewness in the input value distributions.

Table 5.4
Comparison of Monte Carlo and Expected Value Spill Indicators

SPILL INDICATORS	ITEM	Beaufort Sea				Chukchi Sea			
		Sale All - Year 2024				High Case - Year 2010			
		P/L	Platforms	Wells	TOTAL	P/L	Platforms	Wells	TOTAL
Spill Frequency per 10^3 years	Monte Carlo	15.55	25.11	9.27	49.93	21.18	67.03	21.69	109.91
	Expected Value	10.15	21.72	9.27	41.14	17.43	52.77	21.69	91.89
	Difference	53%	16%		21%	22%	27%		20%
Spill Frequency per 10^9 bbl produced	Monte Carlo	0.21	0.34	0.12	0.67	0.09	0.3	0.1	0.48
	Expected Value	0.14	0.29	0.12	0.55	0.08	0.23	0.10	0.41
	Difference	55%	17%		23%	17%	29%		17%
Spill Index [bbl]	Monte Carlo	56	29	507	592	73	76	1186	1335
	Expected Value	32	25	507	564	55	61	1186	1302
	Difference	76%	15%		5%	32%	25%	0%	3%

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

6.1.1 Conclusions on Spill Indicator Trends

The three spill occurrence indicators – annual frequency, annual frequency per barrel produced, and spill index – exhibit a wide range of values varying with location, scenario year, facility composition, and spill size. For the Beaufort Sea and Chukchi Sea locations, comparative non-Arctic scenarios were also postulated and analyzed.

6.1.1.1 Spill Occurrence Indicator Variations by Spill Size and Location

How do spill indicators for the different scenarios and for their non-Arctic counterparts vary by spill size and location? Table 6.1 summarizes the spill indicator values for representative years. Representative years are chosen as the peak production years. Figures 6.1 and 6.2 show the spill size composition associated with each scenario representative year chosen. The total values of each spill index are also given in a rectangle in the bottom right hand corner of each pie chart. The following can be observed from Figures 6.1 and 6.2 and Table 6.1.

- Each spill indicator for Beaufort Sea Sale 1, 2, and 3 is similar in value. The indicators are higher for the composite “Sale All” scenario (Table 6.1).
- Chukchi Sea spill indicators are all higher than Beaufort Sea indicators (Table 6.1).
- Spill frequency per year and per barrel produced decreases significantly with increasing spill size for all scenarios (Figures 6.1 and 6.2). The spill frequency and spill frequency per barrel proportions are the same for any given year. Their absolute value differs only because the latter is divided by the annual production volume.
- The spill index increases dramatically with spill size for all scenarios (Table 6.1 and Figures 6.1 and 6.2).
- All non-Arctic scenario spill indicators are greater than their Arctic counterparts. Non-Arctic spill frequencies are approximately 40% greater; spill indices, 8% greater for the non-Arctic scenarios (Table 6.1).

In addition, the unit Arctic oil spill frequencies for pipelines show a decrease with increasing water depth. That is, pipeline failures per km-yr are highest for shallow water and lowest for deep water. Thus, given the same size and length of pipeline in shallow and deep water, the spill indicators for deep water pipelines would be lower than those for shallow water pipelines. The opposite trend was observed to apply to platforms. No water depth effect was introduced for wells.

Table 6.1
Summary of Spill Indicators for All Scenarios

SPILL INDICATORS Spill Size bbl x 1000		Beaufort Sea					Chukchi Sea		
		Year 2016	Year 2019	Year 2024	Year 2020	Year 2020	Year 2010	Year 2010	Year 2010
		Sale 1	Sale 2	Sale 3	Sale All	Sale All Non Arctic	Base Case	High Case	High C Non Arctic
Spill Frequency per 10^3 years	SM	9.97	10.17	9.84	29.98	43.90	37.66	70.18	95.17
	L	4.53	4.42	4.07	13.02	17.83	15.23	25.34	36.70
	H	2.39	2.34	2.21	6.93	8.31	7.68	14.38	17.85
	All	**16.88**	**16.93**	**16.12**	**49.93**	**70.04**	**60.58**	**109.91**	**149.72**
Spill Frequency per 10^9 bbl produced	SM	0.21	0.24	0.25	0.40	0.59	0.41	0.31	0.42
	L	0.10	0.11	0.11	0.17	0.24	0.17	0.11	0.16
	H	0.05	0.06	0.06	0.09	0.11	0.08	0.06	0.08
	All	**0.36**	**0.40**	**0.42**	**0.67**	**0.94**	**0.66**	**0.48**	**0.66**
Spill Index [bbl] (Product of spill frequency and mean spill size)	SM	2	2	2	6	9	8	13	19
	L	28	27	26	81	102	92	171	218
	H	170	169	165	505	529	534	1150	1211
	All	**200**	**199**	**193**	**592**	**640**	**633**	**1335**	**1448**

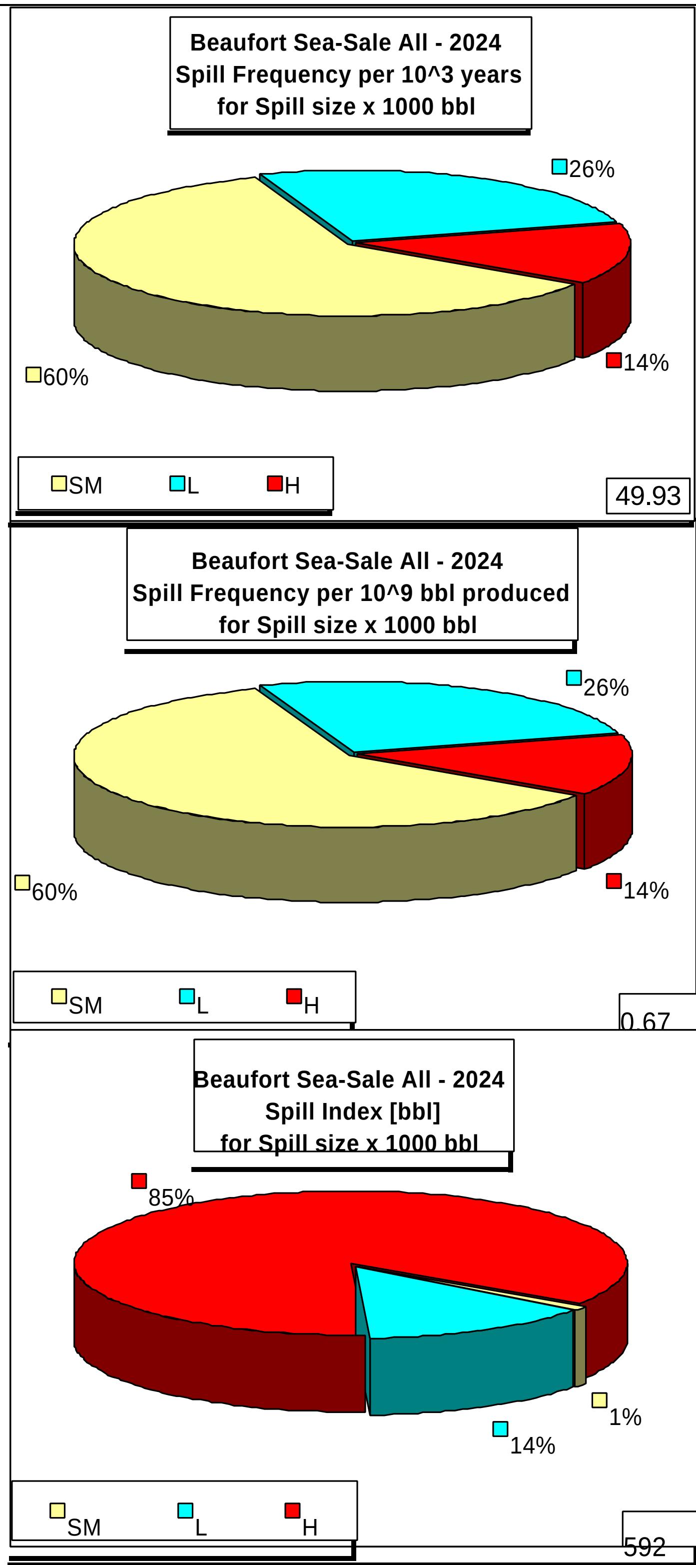


Figure 6.1
Beaufort Sea 'Sale All' Spill Indicators – Year 2024

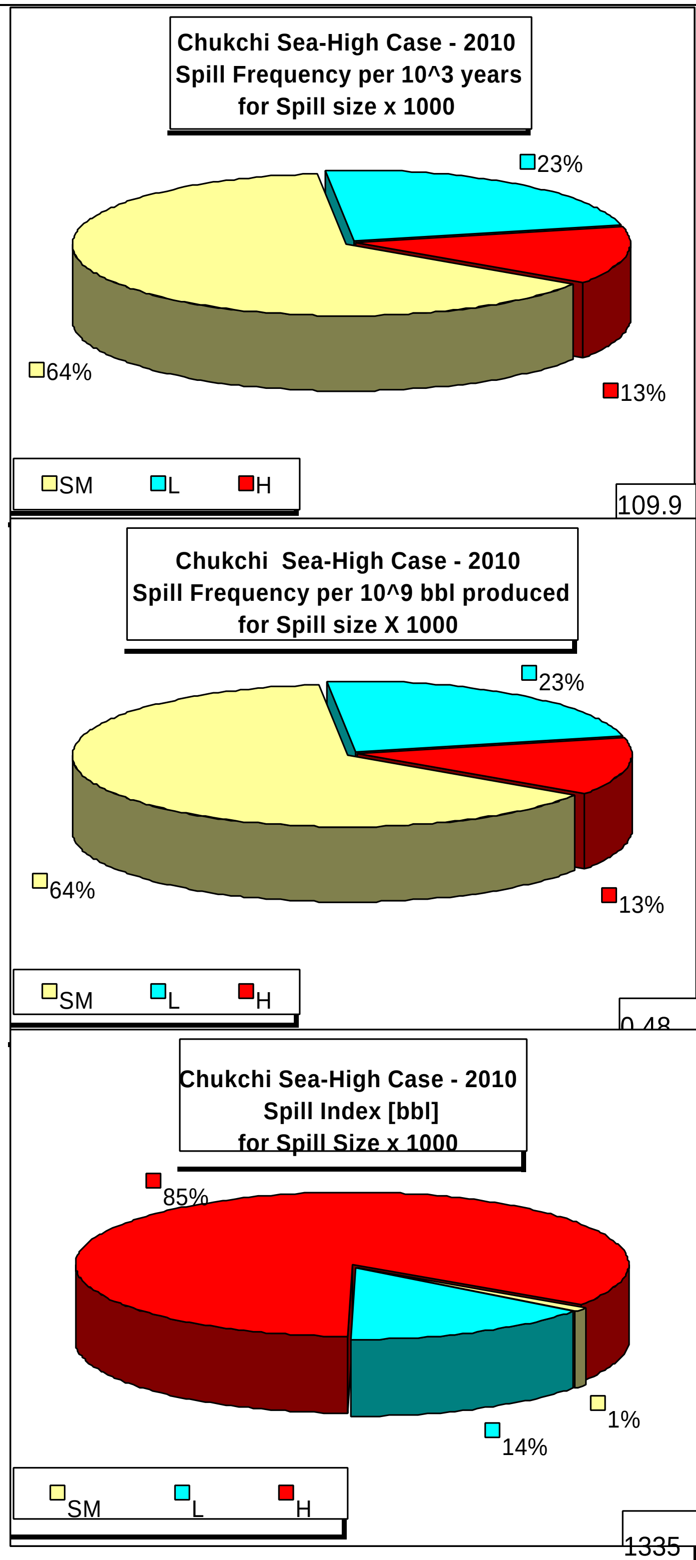


Figure 6.2
Chukchi Sea 'High Case' Spill Indicators – Year 2010

6.1.1.2 Facility Contributions to Spill Occurrence Indicators

How do the spill indicators vary by facility type for representative scenarios? The contributions of spill indicators by facility have also been summarized for representative scenario years. Figures 6.3 and 6.4 gives the relative component contributions, in absolute value and percent, for each of the main facility types; namely, pipelines (P/L), platforms, and wells. Platform spills do not include blowouts. Blowouts are the only spill events categorized under well spills. The following may be noted from these figures:

- For both the Beaufort and Chukchi scenarios, platforms contribute the most (50% and 61% respectively) to the two spill frequency indicators, but the least (5% and 6% respectively) to the spill index (Figure 6.3 and 6.4).
- Pipelines in the Beaufort scenarios are next in relative contribution to spill frequencies (31%) and intermediate in contribution to spill index (10%) (Figure 6.3).
- The relative contribution of pipelines to spill frequencies in the Chukchi, however, are approximately the same (19%) as contributions of wells (20%) (Figure 6.4).
- Wells are by far the highest contributors to spill index in the Beaufort and Chukchi Seas, at 85% and 89% respectively, while platforms and wells are each responsible for 10% or less contribution to the spill index (Figures 6.3 and 6.4).
- It can be concluded that platforms are likely to have the most, but smaller spills, while wells will have the least number, but largest spills. Pipelines will be in between, with a tendency towards more spills than wells, but less or about the same number as platforms. Pipeline spill volumes will tend to be greater than (in Beaufort) or similar in size (in Chukchi) to platform spills.

6.1.1.3 Projected Annual Variations of Spill Occurrence Indicators

How do spill indicators vary over the development life cycle? Figure 6.5 shows the composite Beaufort Sea scenario annual variation in spill indicators over the expected development lifetime. Generally, spill frequencies and the spill index can be seen to follow the facility build-up and phase-out, as they are directly proportional to facility quantities. Spill frequency per barrel produced, however, continues to rise beyond the peak production year. The lack of fall of spills per billion barrels produced in years after peak production is partially artificial. The development scenarios used by MMS in environmental analyses (and used in this report) assume pipelines, platforms, and wells are abandoned at a rate lower than the rate of decrease in production. This leads to the artifact that as production goes to zero, spills per barrel produced increase to infinity. The artifact disappears when spill rates are summed or normalized over the life of the fields.

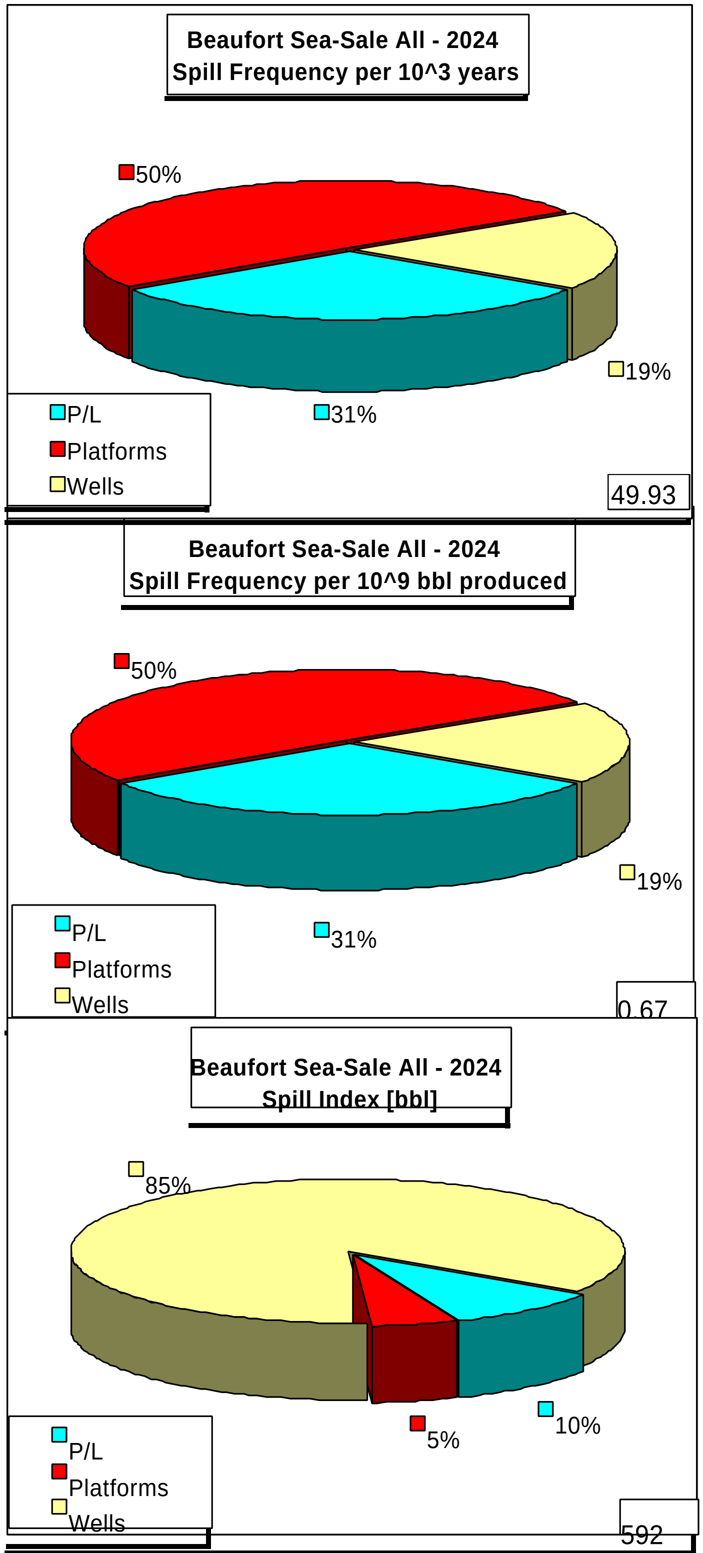


Figure 6.3
Beaufort Sea 'Sale All' Spill Indicators – Year 2024

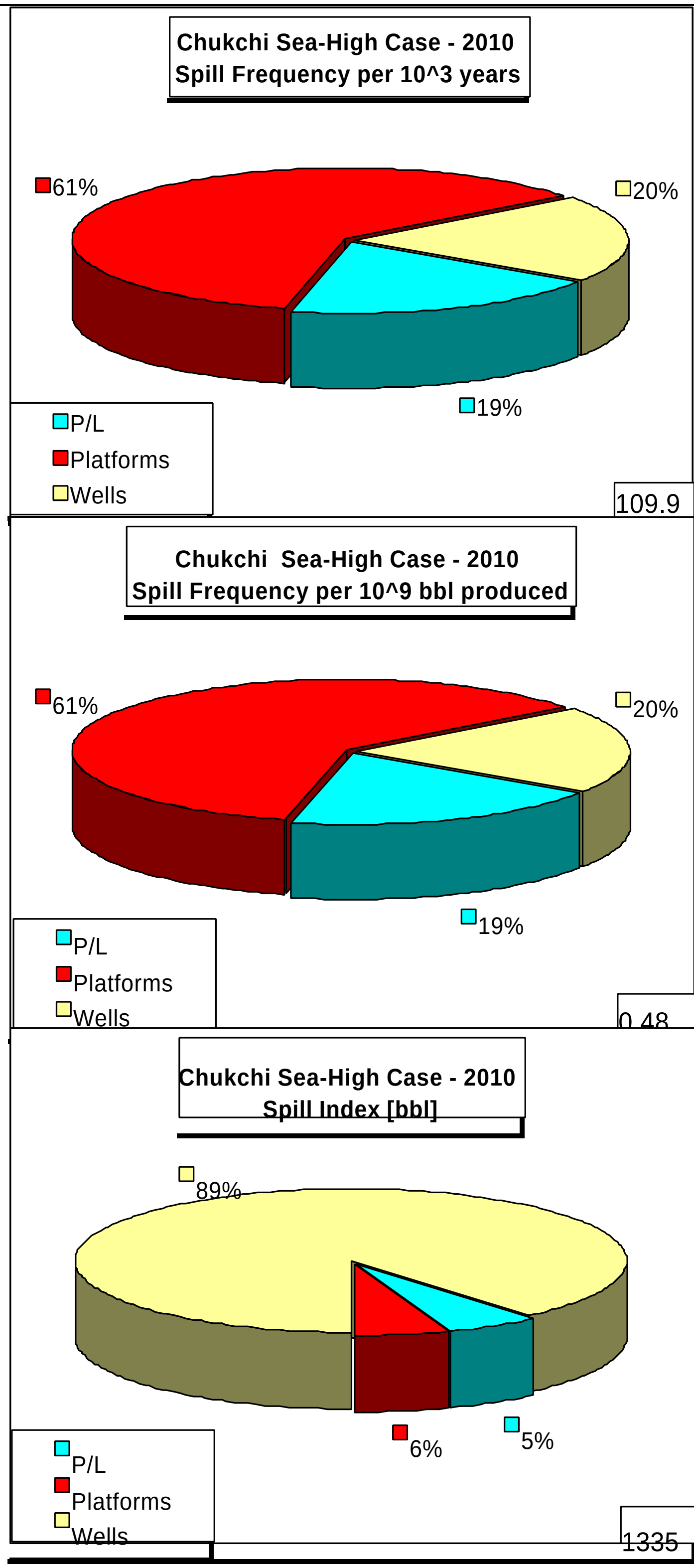


Figure 6.4
Chukchi Sea 'High Case' Spill Indicators – Year 2010

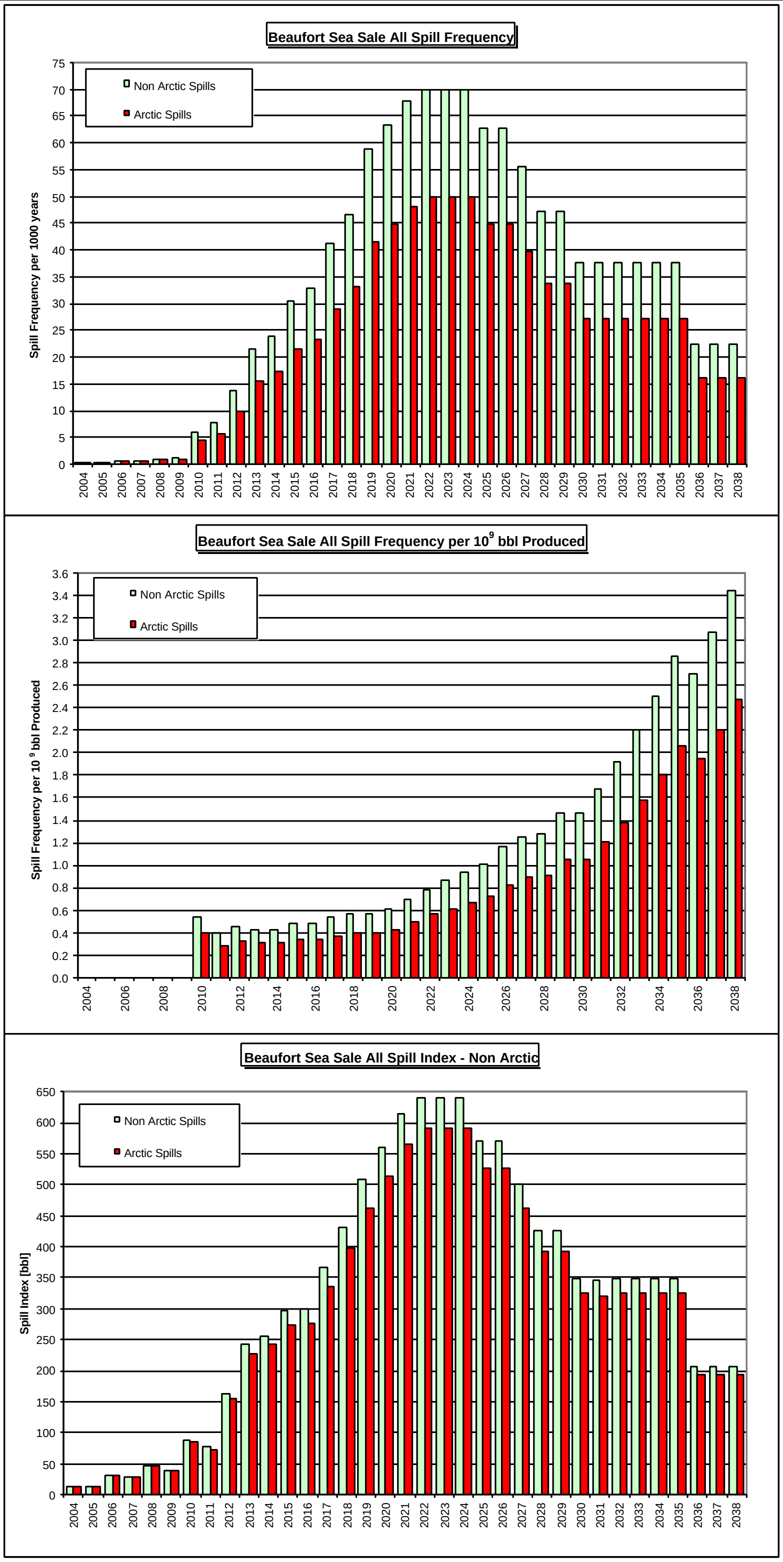


Figure 6.5
Beaufort Sea Composite Scenario Annual Variation in Arctic and Non-Arctic Spill Occurrence Indicators

6.1.1.4 Spill Indicator Statistical Variance

The variance introduced into the spill occurrence indicators by the incorporation of Arctic effects was numerically evaluated. Figure 6.6 shows typical distributions of the resulting indicators, in this case for the Beaufort Sea composite (All Sales) scenario. The slope of each line is an indicator of its variance. Specifically, it was found that for all spills the standard deviation ranged from 12% to 15% of the mean, while the upper and lower bound (95th percentile and 5th percentile, respectively) ranged from 20% to 30%, with the smaller variances corresponding to the Beaufort Sea scenarios and the large ones to the Chukchi Sea scenarios. Upper (95%) and lower (5%) bounds, however, varied as much as 20 to 50% and 20 to 35% of the mean. Since many of the variations in the Arctic inputs ranged in excess of plus or minus 80% of the mean value, the relatively small variance of the indicators suggest that the total model is quite robust; large variances in inputs cause only small variances in outputs. However, this small variance relates only to the Arctic effects; variance in historical spill size and frequency was considered to be zero. Thus, the variances discussed here characterize the uncertainties associated with the Arctic effects incorporated through the fault tree methodology in this study.

6.1.2 Conclusions on the Methodology and Its Applicability

An analytical tool for the prediction of oil spill occurrence indicators for systems without history has been developed based on the utilization of fault tree methodology. Although the results generated are voluminous, they are essentially transparent, simple, and easy to understand. The analytical tool developed is also quite transparent, very efficient in terms of computer time and input-output capability, and user friendly for users that are generally familiar with the process. In addition, the basic model is setup so that any input variables can be entered as distributions; the model presented in this study only uses distributed values of the Arctic effect inputs.

A wealth of information that can be utilized for the optimal planning and regulation of future developments is generated by the analytical tool. Key aspects of the analytical tool capability may be summarized as follows:

- Ability to generate expected and mean values as well as their variability in rigorous numerical statistical format.
- Use of verifiable input data based on MMS historical spill data and statistics.
- Ability to independently vary the impacts of different causes on the spill occurrences as well as add new causes such as some of those that may be expected for the Arctic or other new environments.
- Ability to generate spill occurrence indicator characteristics such as annual variations, facility contributions, spill size distributions, and spill causes.

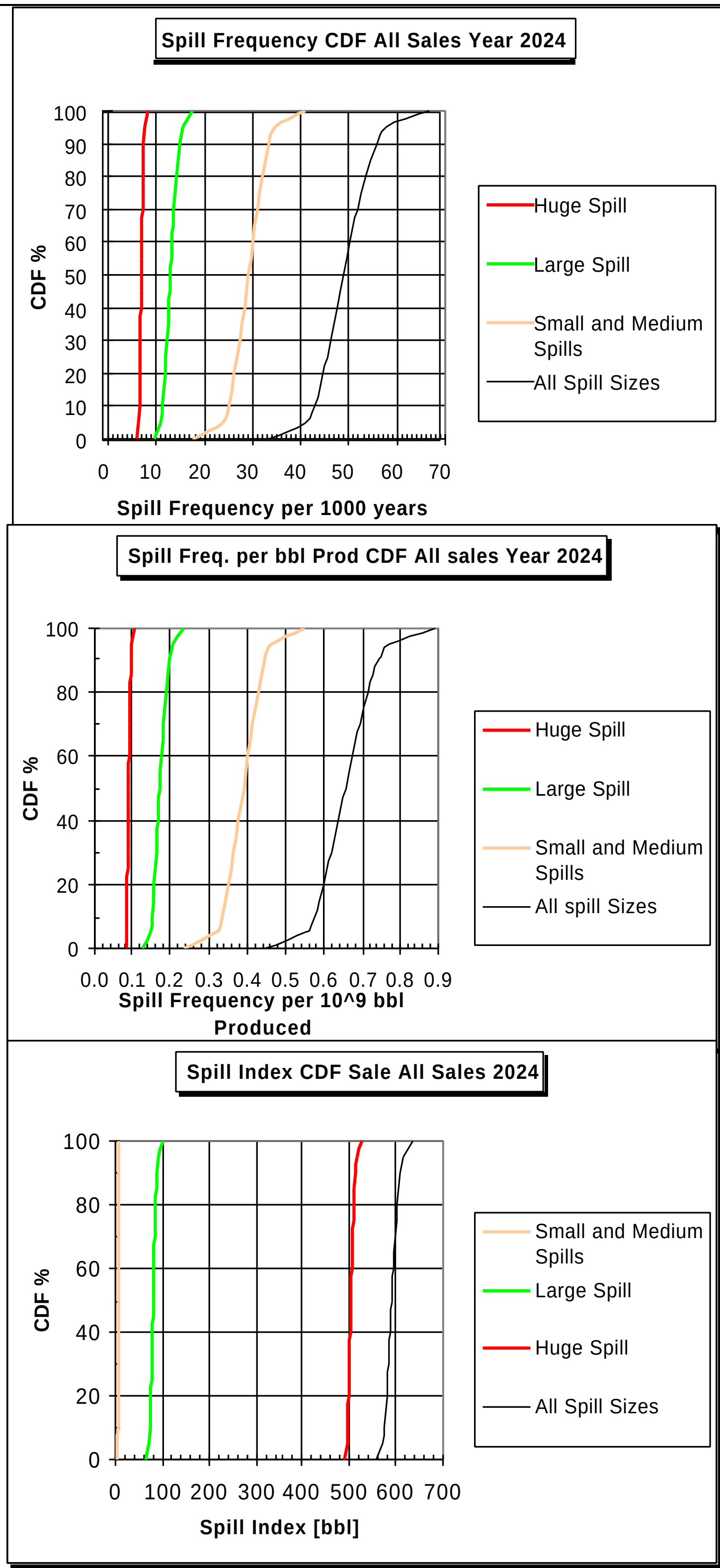


Figure 6.6
Typical Spill Occurrence Indicator Variance Graphs

- Ability to generate comparative spill occurrence indicators such as those of comparable scenarios in more temperate regions. The model developed provides a basis for estimating each Arctic effect's importance through sensitivity analysis as well as propagation of uncertainties.
- Capability to quantify uncertainties rigorously, together with their measures of variability.

6.2 Limitations of Methodology and Results

6.2.1 General Description of Limitations

During the work, a number of limitations in the input data, the scenarios, the application of the fault tree methodology, and finally the oil spill occurrence indicators themselves have been identified. These shortcomings are summarized in the following paragraphs.

6.2.2 Limitations of Input Data

Two categories of input data were used; namely the historical spill data and the Arctic effect data. Although a verifiable and optimal historical spill data set has been used, the following shortcomings may be noted:

- Gulf of Mexico (OCS) historical data bases were provided by MMS and used as a starting point for the fault tree analysis; however, some inconsistencies were identified in these databases as discussed in Appendix A, Section A.2.4.
- Only the historical spill frequency point value was utilized, since adequate data were not provided to create distributions of these frequencies.
- Several ranges of spill sizes were analyzed, but only the mean value of each spill size range was used to characterize representative spill size for each range. Spill size distribution data for each spill size range was available, but was not used in the interest of restricting the uncertainties to the Arctic effects.
- The assessment of the variability or statistical properties of the GOM historical data is a significant study in itself, which is expected to be carried out in the companion study being conducted in parallel with the present work
- The Arctic effects include modifications in causes associated with the historical data set as well as additions of spill causes unique to the Arctic environment. Quantification of existing causes for Arctic effects was done in a relative cursory way restricted to engineering judgement.
- A reproducible but relatively elementary analysis of gouging and scour effects was carried out.

- Upheaval buckling and thaw settlement effect assessments were included on the basis of an educated guess; no engineering analysis was carried out for the assessment of frequencies to be expected for these effects.
- No Arctic effects were estimated for the wells, which were considered to blowout with frequencies the same as those for the GOM.

6.2.3 Scenarios

The scenarios are those developed for use in the MMS Alaska OCS Region Environmental Impact Statements for Oil and Gas Lease Sales. As estimated they appear reasonable and were incorporated in the form provided. There are two possible shortcomings of the scenarios as follows:

- Distributed values for the key quantities were not provided, thus precluding their incorporation as distributions in the Monte Carlo analysis.
- The facility abandonment rate is significantly lower than the rate of decline in production.

6.2.4 Fault Tree Methodology

Generally, the fault tree methodology was limited primarily by the shortcomings in input data discussed above.

- The primary method for assessing uncertainties was restricted to the fault tree module, which incorporates the uncertainties or bounds assigned to the Arctic effects. The treatment of uncertainties could be expanded to incorporate distributions in volume of spills, and the original historical frequencies.
- The treatment of uncertainties was carried out utilizing a Monte Carlo process, which requires an add-in (called @Risk©) to the Excel spreadsheet within which the algorithms have been programmed. For some users, this might be slightly arcane; accordingly, it may be desirable to have two versions, the Monte Carlo version which gives more rigorous results and is used for results in the body of this report, and an expected value version, which may be utilized for rough estimates. Appendix C gives the detailed results and calculations for the Monte Carlo model; Appendix D gives those from the expected value model.
- The Monte Carlo results give higher oil spill occurrence indicators than the expected value results. This is due to the skewness of the Arctic effect distributed values, which are inputs to the Monte Carlo calculations.

6.2.5 Limitations of Indicators Generated

The following comments can be made on limitations associated with the indicators that have been generated.

- The indicators have inherited the deficiencies in the input and scenario data noted above. Indicators should be viewed primarily as trend indicators of the expected values and their distributions for Arctic developments.
- The indicator distribution shows relatively small variability – this is primarily because the only variability introduced is that of the Arctic effects.
- The model generating the indicators is fundamentally a linear model which ignores the effects of scale, of time variations such as the learning and wear-out curves (Bathtub curve), and production volume non-linear effects.
- The expected value (simpler) calculation results (given in Appendix D) should be used with caution since they underestimate the spill indicators. The underestimation ranges from 3 to 76%. Appendix D gives all the expected value calculations. The body of the report is based on the Monte Carlo results given in Appendix C.

6.3 Recommendations

6.3.1 Recommendations on Direct Application of Results from This Study

The results of this study can be applied directly in two principal ways; namely, on an annual per barrel produced basis, and on a total production volume basis.

On an annual basis, the peak production year oil spill frequency per barrel produced can be used to calculate corresponding annual spill frequencies for other annual production rate scenarios. This is done simply by multiplying the appropriate spill frequency per billion barrels produced from Table 6.1 by the subject annual production rate.

To apply the results on a total production volume basis, the following steps can be used:

- For the desired spill size range and facility component (or all facilities), add together the annual spill frequencies for each year of the production life.
- Divide the sum of the frequencies by the total production volume. This provides the number of spills per barrel produced for the entire development.
- For another development, multiply the above spills per barrel produced by the other development's total production volume.
- The resultant is the expected number of spills of the desired spill size range and for the desired facility component for the total production life of the other development.

6.3.2 General Recommendations

The following recommendations based on the work may be made:

- Utilize the oil spill occurrence indicator model to generate additional model validation information, including direct application to specific non-Arctic scenarios, such as GOM projects, which have an oil spill statistical history.
- Utilize the oil spill occurrence indicator model in a sensitivity mode to identify the importance of different Arctic effect variables introduced to provide a prioritized list of those items having the highest potential impact on Arctic oil spills.
- Use GOM historical data together with its measures of spill size variance and setup the Monte Carlo model to run with these measures of spill size variance.
- Generalize the model so that it can be run both in an expected value and a distributed value (Monte Carlo) form with the intent that expected value form can be utilized without the Monte Carlo add-in for preliminary estimates and sensitivity analyses, while for more comprehensive rigorous studies, the Monte Carlo version can be used. All calculations in this report are based on the Monte Carlo version.
- Finally, convert the current oil spill occurrence indicator model into a user friendly software package, which can be used for the assessment of oil spill occurrence indicators and their characteristics for any designated scenario. The software package should include the following:
  - Modular structure
  - User manual
  - Online help
  - Password protected parameters and algorithms
  - Extensive graphical outputs

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