OCS Study MMS 2008-035

FINAL TASK 4A.1 REPORT

VOLUME I

Alternative Oil Spill Occurrence Estimators and their Variability for the Beaufort Sea – Fault Tree Method

MMS Contract Number 1435-01-05-CT-39348

March 2008

By

Bercha International Inc.
Calgary, Alberta, Canada

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

OCS Study MMS 2008-035

FINAL TASK 4A.1 REPORT

VOLUME I

Alternative Oil Spill Occurrence Estimators and their Variability for the Beaufort Sea – Fault Tree Method

March 2008

Principal Investigator: Dr. Frank G. Bercha, P.Eng.

Bercha International Inc.
2926 Parkdale Boulevard N.W.
Calgary, Alberta, T2N 3S9, Canada
Email: berchaf@berchagroup.com

This study was funded by the U.S. Department of the Interior, Minerals Management Service (MMS), Alaska Outer Continental Shelf Region, Anchorage, under Contract No. 1435-01-05-CT-39348, as part of the MMS Alaska Environmental Studies Program.

ABSTRACT

Oil spill occurrence estimates were generated for high and low case estimated future oil and gas development scenarios (including exploration, production, and abandonment) in the Beaufort Sea Outer Continental Shelf (OCS) lease sale region. Because sufficient historical data on offshore oil spills for this region 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 including the variability of the data, were modified and augmented to represent expected Arctic offshore oil spillage frequencies. Three principal spill occurrence indicators, as follows, were quantified for each year of each scenario, as well as scenario life of field averages:

- Spill frequency
- 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 - 99 bbl
- Medium (M): 100 - 999 bbl
- Large (L): 1,000 - 9,999 bbl
- Huge (H): >= 10,000 bbl
- Significant (SG): >=1,000 bbl

Quantification was carried out for each future year for a high and low principal Beaufort Sea development scenario, with a range of development parameters, in duration up to 36 years. In addition, a comparative scenario for non-Arctic locations was 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 base and scenario data and 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.
- Life of field averages of spill occurrence estimators.
- The variability in the results due to uncertainties in the inputs was 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.

ACKNOWLEDGEMENTS

Grateful acknowledgement for funding and direction is made to MMS Alaska OCS Region. In particular, the following MMS personnel are acknowledged together with their roles:

- Dr. Dick Prentki, Contracting Officer's Technical Representative
- Dr. James Craig, Resource Evaluation Section
- Caryn Smith, Oil-Spill-Risk-Analysis Coordinator
- Cheryl Anderson, MMS Spill Database Coordinator
- Debra Bridge, Contracting Officer
- Dr. Warren Horowitz, Oceanographer

This work was carried out by Bercha International Inc. Key Bercha personnel on the project team were as follows:

- Dr. Frank G. Bercha, Project Manager and Principal Engineer
- Milan Cerovšek, Reliability Engineering Specialist
- Edmund A. Yasinko, Offshore Pipeline Specialist
- Wesley Abel, Offshore Engineering Specialist
- Susan Charlton, Editorial and Word Processing Manager

EXECUTIVE SUMMARY

A. Summary of Work Done

Oil spill occurrence estimators were generated for high and low production estimated future oil and gas development scenarios (including exploration, production, and abandonment) in the Beaufort Sea Outer Continental Shelf (OCS) lease sale region. 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, including their variability, were modified and augmented to represent expected Arctic offshore oil spillage frequencies for the Beaufort Sea region under study. Three principal spill occurrence indicators, as follows, were quantified for each year of each scenario, as well as scenario life of field averages:

- Spill frequency
- 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 - 99 bbl
- Medium (M): 100 - 999 bbl
- Large (L): 1,000 - 9,999 bbl
- Huge (H): >=10,000 bbl
- Signficant (SG): >=1,000 bbl

Fractional spill sizes were rounded up or down to the nearest whole number, with rounding up for any decimal ending in 5.

Quantification was carried out for each future year for estimated Beaufort Sea exploration and development scenarios, extending up to 30 years from 2010 to 2039. In addition, a comparative high production case scenario for non-Arctic locations was formulated and analyzed for oil spill occurrence. Generally, it was found that the non-Arctic spill indicators were likely to be higher than those for a similar scenario in the Arctic. The computations were carried out using a Monte Carlo process to permit the inclusion of estimated uncertainties in the input data. 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 input data 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 General Conclusions

Oil spill occurrence indicators were quantified for future offshore development scenarios in the Beaufort Sea in the area of MMS jurisdiction. The quantification included the consideration of the variability of historical and future scenario data, as well as that of Arctic effects in predicting oil spill occurrence indicators. Consideration of the variability of all input data yields both higher variability and a higher expected value of the spill occurrence indicators. The three types of spill occurrence indicators were: annual oil spill frequency, annual oil spill frequency per billion barrels produced, and annual spill index – and, additionally, the life of field averages for each of these three oil spill indicators were assessed.

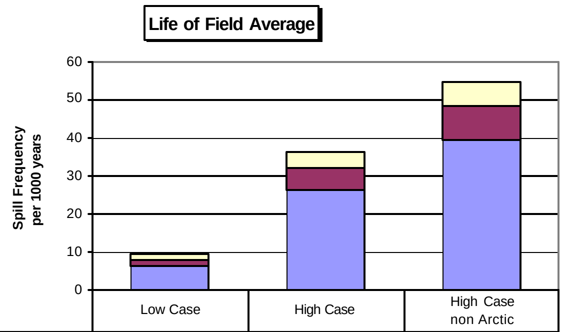
B.2 Oil Spill Occurrence Indicators by Spill Size

How do spill indicators for the Beaufort scenario and for its non-Arctic counterpart vary by spill size and location? Table 1 and Figures 1 and 2 summarize the Life of Field average spill indicator values by spill source and size for the Low and High Cases and Non-Arctic High Case scenarios. The following can be observed from Table 1.

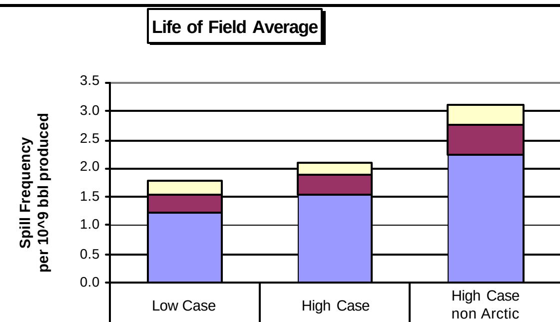
- Spill frequency per year and per barrel-year decreases significantly with increasing spill size for all scenarios.
- The spill index increases significantly with spill size for all scenarios.
- All non-Arctic scenario spill indicators are greater than their Arctic counterparts.

Table 1
Summary of Life of Field Average Spill Indicators by Spill Source and Size
(Appendix Table 5.1)

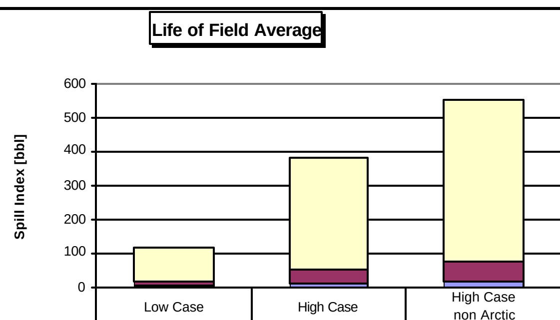
Spill Indicators LOF Average	Low Case			High Case			High Case Non-Arctic		
	Spill Frequency per 10^3 years	Spill Frequency per 10^9 bbl produced	Spill Index [bbl]	Spill Frequency per 10^3 years	Spill Frequency per 10^9 bbl produced	Spill Index [bbl]	Spill Frequency per 10^3 years	Spill Frequency per 10^9 bbl produced	Spill Index [bbl]
Small and Medium Spills 50-999 bbl	6.431	1.232	3	26.468	1.534	11	39.306	2.233	14
	69%	**69%**	**2%**	**73%**	**73%**	**3%**	**72%**	**72%**	**3%**
Large Spills 1000-9999 bbl	1.623	0.311	12	5.773	0.335	40	9.029	0.511	60
	17%	**17%**	**11%**	**16%**	**16%**	**12%**	**17%**	**16%**	**12%**
Huge Spills =>10000 bbl	1.256	0.241	93	4.222	0.245	293	6.312	0.361	417
	13%	**13%**	**87%**	**12%**	**12%**	**85%**	**12%**	**12%**	**85%**
Significant Spills =>1000 bbl	2.879	0.551	104	9.995	0.579	332	15.341	0.871	477
	31%	**31%**	**98%**	**27%**	**27%**	**97%**	**28%**	**28%**	**97%**
All Spills	9.310	1.783	107	36.463	2.113	343	54.647	3.104	492
	100%	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**
Pipeline Spills	4.414	0.845	12	18.402	1.066	44	31.209	1.746	76
	47%	**47%**	**11%**	**50%**	**50%**	**13%**	**57%**	**56%**	**15%**
Platform Spills	3.615	0.692	4	14.085	0.816	14	17.873	1.036	17
	39%	**39%**	**4%**	**39%**	**39%**	**4%**	**33%**	**33%**	**3%**
Well Spills	1.281	0.245	92	3.977	0.230	285	5.565	0.322	399
	14%	**14%**	**86%**	**11%**	**11%**	**83%**	**10%**	**10%**	**81%**
Platform and Well Spills	4.896	0.938	95	18.062	1.047	299	23.438	1.358	416
	53%	**53%**	**89%**	**50%**	**50%**	**87%**	**43%**	**44%**	**85%**
All Spills	9.310	1.783	107	36.463	2.113	343	54.647	3.104	492
	100%	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**



	Low Case	High Case	High Case non Arctic
Huge Spills =>10000 bbl	1.256	4.222	6.312
Large Spills 1000-9999 bbl	1.623	5.773	9.029
Small and Medium Spills 50-999 bbl	6.431	26.468	39.306

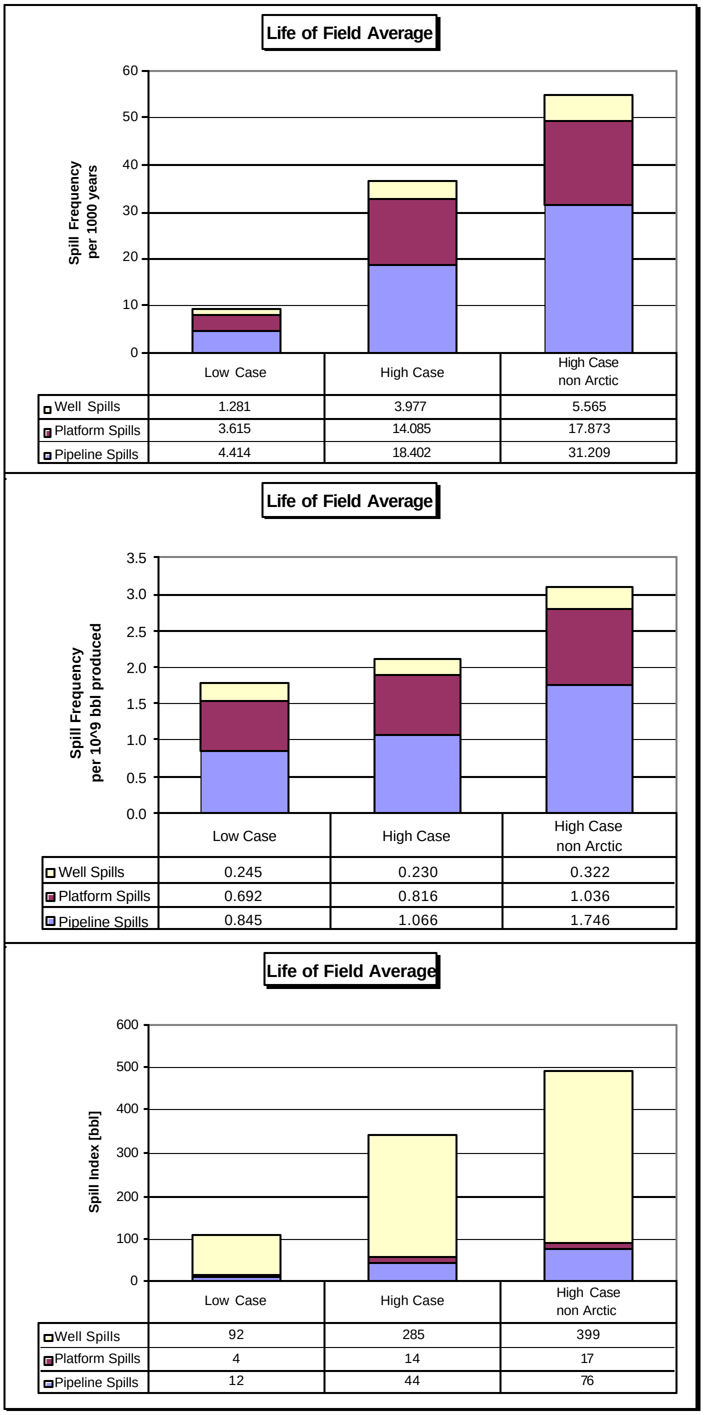


	Low Case	High Case	High Case non Arctic
Huge Spills =>10000 bbl	0.241	0.245	0.361
Large Spills 1000-9999 bbl	0.311	0.335	0.511
Small and Medium Spills 50-999 bb	1.232	1.534	2.233



	Low Case	High Case	High Case non Arctic
Huge Spills =>10000 bbl	104	332	477
Large Spills 1000-9999 bbl	12	40	60
Small and Medium Spills 50-999 bbl	3	11	14

Figure 1
Life of Field Spill Indicators – By Spill Size
Appendix Figure 5.1



	Low Case	High Case	High Case non Arctic
Well Spills	1.281	3.977	5.565
Platform Spills	3.615	14.085	17.873
Pipeline Spills	4.414	18.402	31.209

	Low Case	High Case	High Case non Arctic
Well Spills	0.245	0.230	0.322
Platform Spills	0.692	0.816	1.036
Pipeline Spills	0.845	1.066	1.746

	Low Case	High Case	High Case non Arctic
Well Spills	92	285	399
Platform Spills	4	14	17
Pipeline Spills	12	44	76

Figure 2
Life of Field Spill Indicators – By Source Composition
(Appendix Figure 5.2)

B.3 Oil Spill Occurrence Indicators by Spill Source

How do the spill indicators vary by facility type for representative scenarios? The contributions of spill indicators by facility have been summarized in Table 1 and also in Figure 2. Table 1 and Figure 2 give 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 these for the High Case:

- Pipelines contribute the most (50%) to the spill frequency indicators.
- Platforms are next in relative contribution to spill frequencies (39%) and least in contribution to spill index (4%).
- Wells are by far (at 83%) the highest contributors to spill index.
- It can be concluded that pipelines are likely to have the most, but smaller spills, while wells will have the least number, but largest spills.

Figures 3 and 4 show relative contributions by facility and spill size to the maximum production year 2030 and Life of Field average spill indicators, respectively. Although Life of Field average absolute values are significantly smaller than the maximum production year values, the proportional contributions by spill facility source and spill size are almost identical. In Figures 3 and 4, "TOTAL" designates the sum of the spill indicators for all spill sizes and facility types.

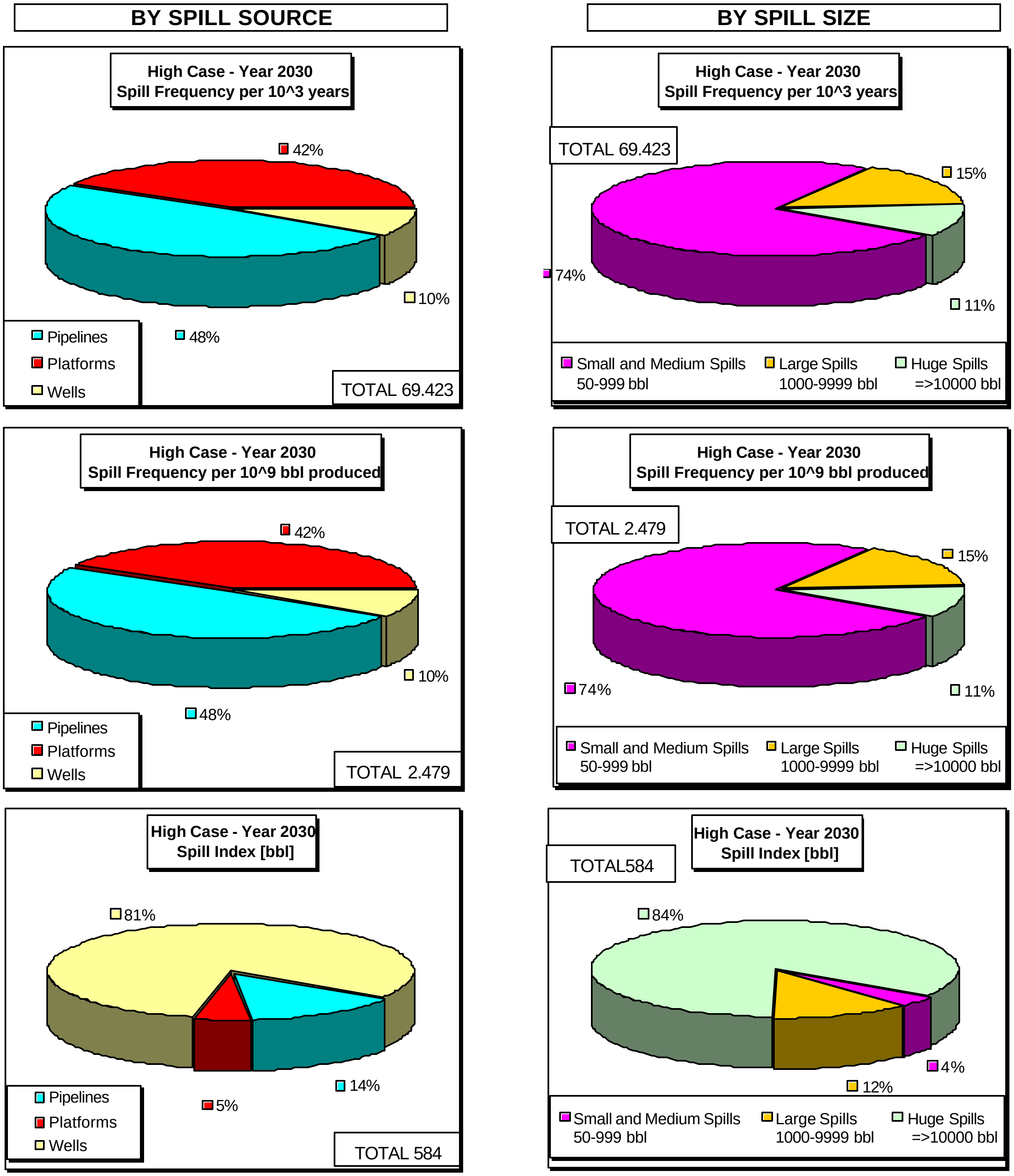


Figure 3

Beaufort Sea High Case – Year 2030 – Spill Indicator Composition by Source and Spill Size

(Appendix Figure 4.2.17)

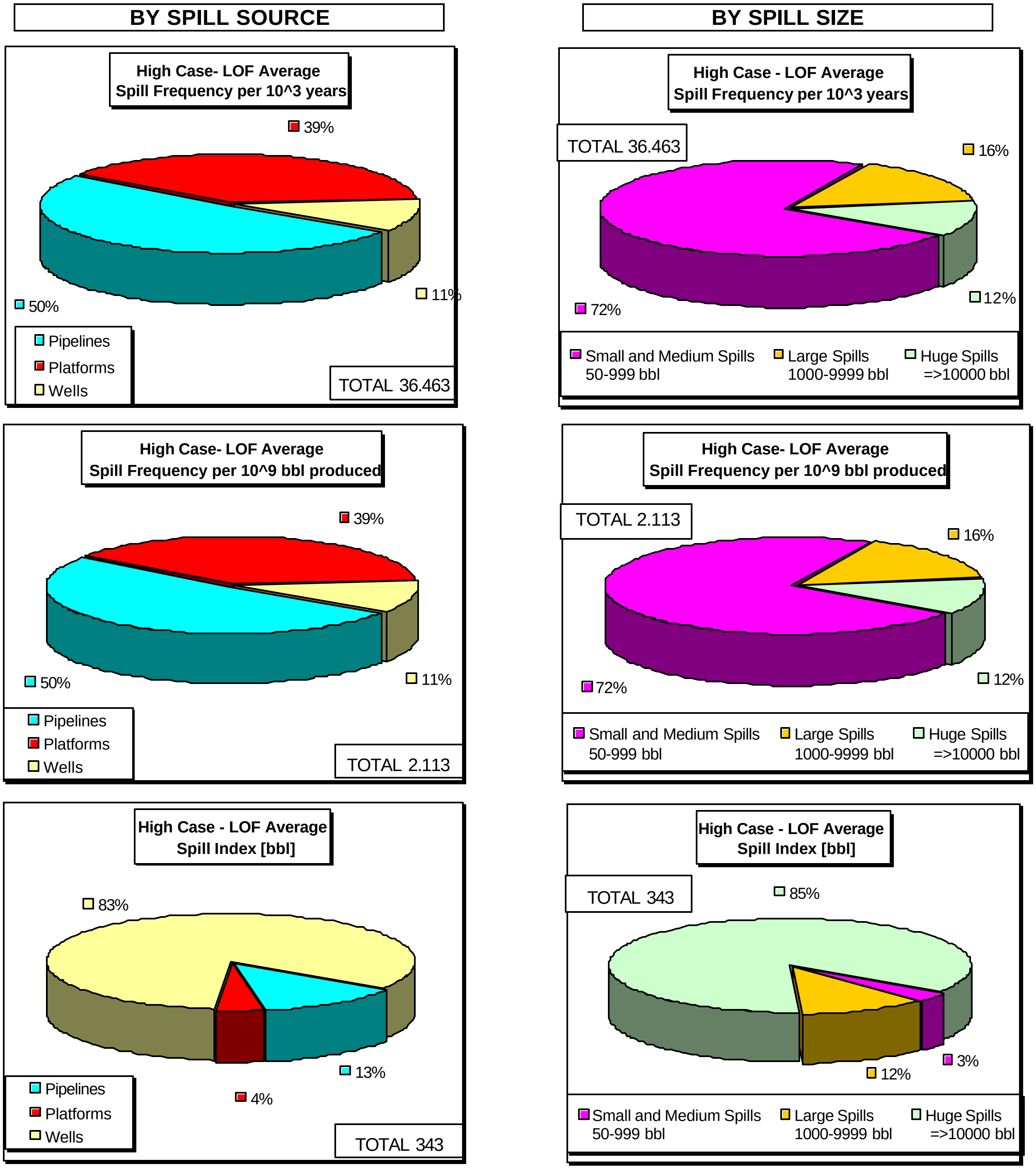


Figure 4
Beaufort Sea High Case– Life of Field Average Spill Indicator Composition by Source and Spill Size
(Appendix Figure 4.2.18)

B.4 Variability of Oil Spill Occurrence Indicators

Figures 5, 6, and 7 show the Cumulative Distribution Functions (CDF) for the Beaufort Sea Life of Field average spill indicators. The variability of these indicators is fairly representative of the trends in variability for spill indicators for the Low Case as well. Generally, the following can be observed from the figures:

- The variance of the frequency spill indicators (Figures 5 and 6) decreases as spill size increases for pipelines and platforms. In other words, small and medium spills illustrate the largest variability; huge spills show the least variability for pipelines and platforms.

- For wells, the frequency variability for different spill sizes does not change as much as that for platforms and pipelines.

- The variability of the spill index (Figure 7) shows an increasing variability with increasing spill size.

The Cumulative Distribution Functions contain extensive information on the statistical properties of the spill indicators. For example, from Figure 5 (bottom right-hand graph), it can be seen, for all significant spills, that the Life of Field average mean (50%) value of 10 (spills per 1,000 years) ranges between about 5 and 15 at the lower and 5% to 95% confidence intervals. A similar percentage variation is shown for the Life of Field average spill frequency per barrel produced in Figure 6. The spill index variability shown in Figure 7 is proportionally higher. For example, in Figure 7 (bottom right-hand corner graph), the mean value of the significant spills index of 325 per billion barrels produced ranges from 200 to 500 over the 5% to 95% confidence interval.

Figure 5
Beaufort Sea High Case Life of Field Average Spill Frequency
(Appendix Figure 4.2.14)

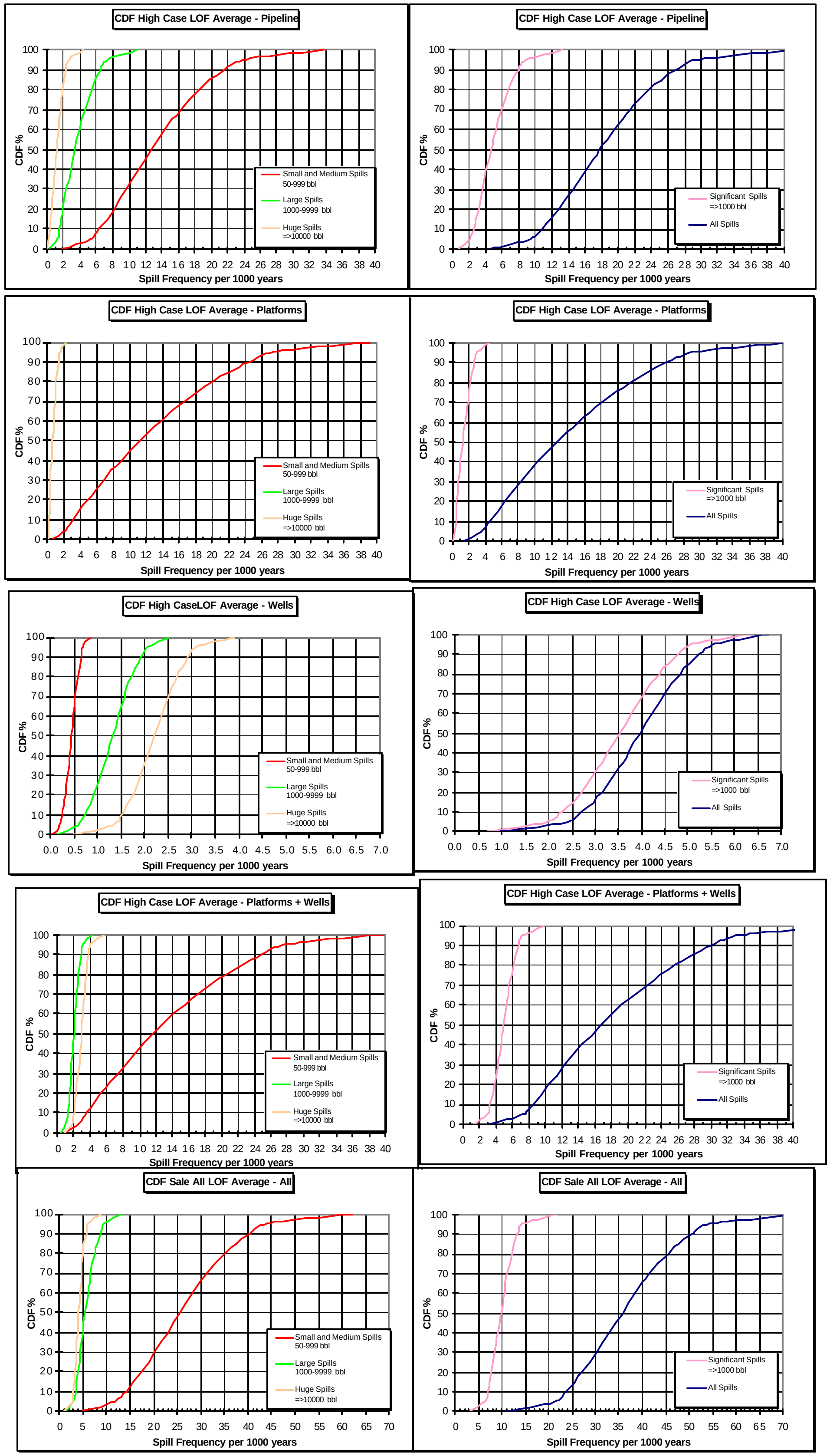


Figure 6
Beaufort Sea
High Case
Life of Field
Average Spills
per Barrel
Produced
(Appendix
Figure 4.2.15)

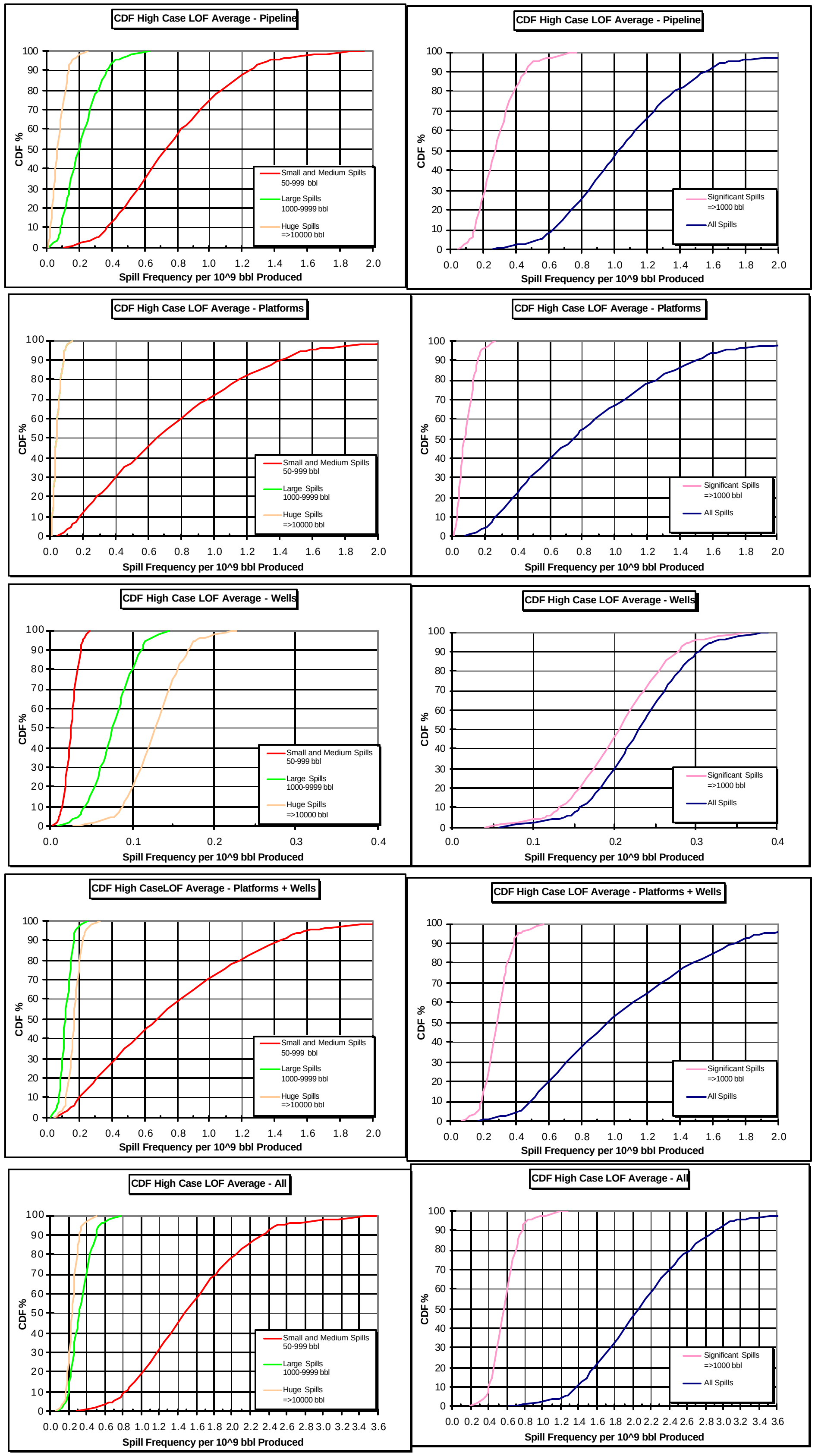
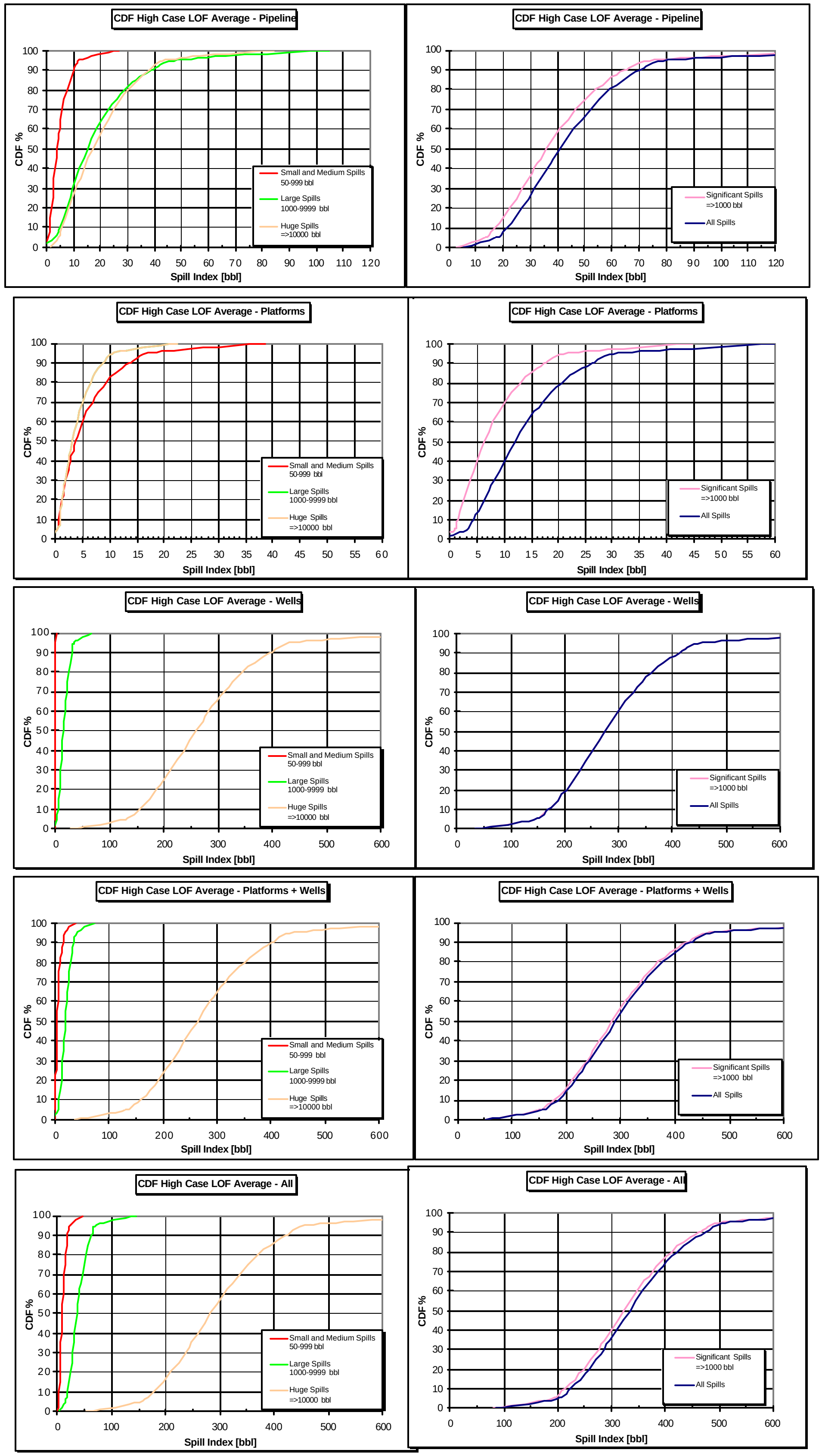


Figure 7
Beaufort Sea
High Case
Life of Field
Average Spill
Index (bbl) – CDF
(Appendix
Figure 4.2.16)



C. Conclusions on the Methodology and its Applicability

An analytical tool for the prediction of oil spill occurrence indicators for systems without history, such as future offshore oil production developments in the Beaufort Sea, 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. In addition, the predictive model is setup so that any input variables can be entered as distributions.

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 or other 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 life of field (Life of Field) averages.
- 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.

D. Limitations of the Methodology and Results

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.

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 for pipelines and facilities, and were used as a starting point for the fault tree analysis. Although these data are adequate, a broader population base would be expected to give more robust statistics. Unfortunately, data from a broader population base, such as the North Sea, do not contain the level of detail provided in the GOM data.
- 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 systematic manner dependent on engineering judgment.
- A reproducible but relatively elementary analysis of gouging and scour effects was carried out.
- Upheaval buckling 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, as they are highly variable for different locations and pipeline characteristics.

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. The only shortcoming appears to be that the facility abandonment rate is significantly lower than the rate of decline in production.

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

- The indicators have inherited the deficiencies of the input and scenario data noted above.
- 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), global warming, and production volume non-linear effects.

E. Recommendations

The following recommendations based on the work may be made:

- Continue to utilize the Monte Carlo spill occurrence indicator model for new scenarios to support MMS needs, as it is currently the best predictive spill occurrence model available.
- Utilize this 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.
- Generalize the model so that it can be run both in an adjusted 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.

TABLE OF CONTENTS

VOLUME I

CHAPTER **PAGE**

LIST OF APPENDICES

(VOLUME II – APPENDICES)

APPENDIX

LIST OF TABLES

TABLE **PAGE**

LIST OF FIGURES

FIGURE **PAGE**

GLOSSARY OF TERMS AND ACRONYMS

Bbbl	**B**illion Barrels
CDF	**C**umulative **D**istribution **F**unction
Consequence	The direct effect of an accidental event.
GOM	**G**ulf **o**f **M**exico
Hazard	A condition with a potential to create risks such as accidental leakage of natural gas from a pressurized vessel.
KBpd	Thousand Barrels per day
LOF	**L**ife of **F**ield
MMbbl	Million Barrels
MMS	**M**inerals **M**anagement **S**ervice, Department of the Interior
Monte Carlo	A numerical method for evaluating algebraic combinations of statistical distributions.
OCS	**O**uter **C**ontinental **S**helf
QRA	**Q**uantitative **R**isk **A**ssessment
Risk	A compound measure of the probability and magnitude of adverse effect.
RLS	Release
SINTEF	The Foundation of Scientific and Industrial Research at the Norwegian Institute of Technology
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 - 99 bbl Medium (M): 100 - 999 bbl Large (L): 1,000 - 9,999 bbl Huge (H): >=10,000 bbl Significant (SG): >=1,000 bbl

CHAPTER 1

INTRODUCTION

1.1 General Introduction

The MMS Alaska Outer Continental Shelf (OCS) Region uses oil spill occurrence estimates for National Environmental Policy Act assessments for all parts of their area of jurisdiction, ranging from near shore through shallow water, to deeper water. Although land to 3 nautical miles is not within MMS jurisdiction, it is included in the MMS environmental impact analysis; hence it is also included in the study area here. In 2002 and early 2006, studies were carried out by Bercha International Inc. [11, 12] * to assess and quantify oil spill occurrence indicators for the Beaufort and Chukchi Seas. In this study, methodologies based on fault tree analysis were developed for the assessment of oil spill rates associated with exploration and production facilities and operations in in the Beaufort Sea.

The prediction of the reliability (or failure) of systems without history can be approached through a variety of mathematical techniques, with one of the most preferable and accepted being fault trees [7, 10, 23, 26, 45, 51, 65], and their combination with numerical distribution methods such as Monte Carlo simulation [9, 45]. In the previous study [12, 13], 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 Sea in the Alaska OCS, and used to generate predictions of oil spill occurrence indicators.

As there is a paucity of offshore Arctic oil spill occurrences, associated data worldwide and from the Gulf of Mexico (GOM) were used as a starting point to develop a simulation model of oil spill occurrence probabilities. The model for non-Arctic occurrence probabilities was then modified to include Arctic effects and their variabilities. In the preceding Beaufort Sea study [12], variability in the non-Arctic input data was considered; but variability of the future development scenario physical facility parameters, such as miles of sub-sea pipeline, was not considered. However, these scenario variabilities have been included in the recent Chukchi Sea Study [13], and are included herein. Thus, in the present study, both the historical data variability and that of the future development scenario characteristics is included in calculation of oil spill occurrence probabilities.

1.2 Study Objectives

The objectives of this study are as follows:

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

- Assimilate and analyze world-wide and US OCS oil spill statistics and evaluate their applicability to lease tracts which could be offered in the upcoming Beaufort Sea sales.
- Develop the fault tree method for estimating oil spill occurrences from Beaufort Sea developments associated with spills of different size categories.
- Using the fault tree approach, develop alternative oil spill indicators and assess their variability, including effect of variability of both the historical data and the future development scenario parameters.
- Provide statistical support to MMS in evaluation of statistical issues in estimation of oil spill rates.
- One of the specific objectives of this study was to add the variability of the non-Arctic factors.

1.3 Study Area Definition

The geographical study area is the offshore continental shelf in the U.S. Beaufort Sea, 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 from the present to Year 2039.

1.4 General Background

The final reports – dated August 2002 [11], January 2006 [12], and October 2006 [13] – described the methodology and results of the fault tree method for the evaluation of oil spill occurrence estimators for the Beaufort and Chukchi Seas. The focus of the first report [11] was on the initial development of a fault tree method to model both non-Arctic GOM spill causes as well as Arctic causes and effects that would be encountered in the Beaufort and Chukchi Seas OCS Regions. The variability of the parameters associated with Arctic effects was developed in order to provide an estimate of the variance in the spill occurrence predictions resulting directly from variances in the Arctic effects. In addition, in 2006 [12], variance in the Gulf of Mexico (GOM) historical data was incorporated. In the most recent report [13], the variability of the future development scenario parameters is also considered. In the present study, all variances are considered in a manner analogous to that of the October 2006 [13] study. These variances were numerically incorporated through the use of Monte Carlo simulation for the fault tree model numerical predictions.

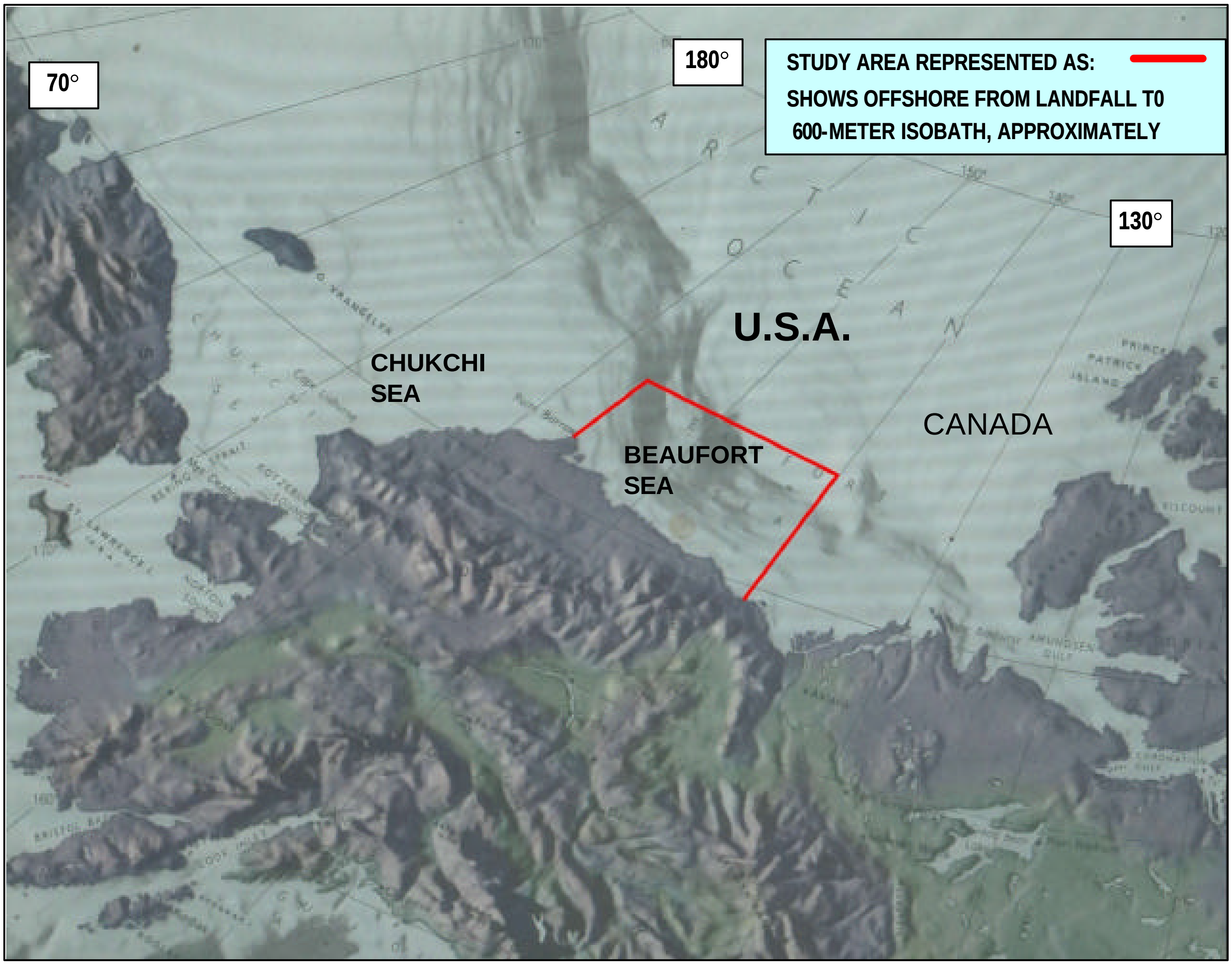


Figure 1.1
Study Area Map

1.5 Technical Approaches

Uncertainties in the results of oil spill occurrence predictions generated in this study can be attributed to uncertainties in input data, scenario characterization, and the occurrence model. In the original 2002 study [11], uncertainties in input data were quantified for the Arctic effects only. Uncertainties in the scenario were included through the choice of scenarios representing the expected and maximum development levels. In the 2006 study [13], uncertainties in the non-Arctic input data were also included. Thus the principal source of uncertainty in the occurrence results was that caused by uncertainties in the Arctic and non-Arctic input parameters themselves.

The non-Arctic input parameters fall under two principal categories as follows:

- Spill frequencies
- Spill volumes

These spill frequencies and volumes as used in the study were derived from the following principal sources:

- Pipeline spills – GOM data
- Platform spills – GOM data
- Well (drilling and production) blowout spills – Worldwide data

The specific sources of the data are described in detail in Chapter 2 of this report.

In the October 2006 [13] and the current study, in addition to the above data uncertainties, those of the following main facility parameters were also considered:

- Number of wells drilled
- Number of platforms and sub-sea production wells
- Sub-sea pipeline length
    - For pipelines less than nominal 10” diameter
    - For pipelines greater than or equal to 10” nominal diameter.

The inclusion of all of these types of variability – Arctic effects, non-Arctic data, and facility parameters – is intended to provide a realistic estimate of the spill occurrence indicators and their resultant variability.

1.6 Scope of Work

Task 1: *Data Assimilation*

a) Update of GOM pipeline and platform spill data [14].

b) Identification of alternative data sources including the Foundation of Scientific and Industrial Research at the Norwegian Institute of Technology (SINTEF), United Kingdom Health & Safety Executive (HSE), and others.

c) Assimilation and analysis of additional blowout data (SINTEF).

d) Beaufort Sea scenario development from MMS information.

Task 2: *Development of Non-Arctic Total Annual Spill Frequency and Volume Probability Distributions*

a) Development of non-Arctic total annual spill frequency and volume distribution for pipelines.

b) Development of non-Arctic total annual spill frequency and volume distribution for platforms.

c) Development of non-Arctic total annual spill frequency and volume distribution for well drilling and production wells.

Task 3: *Development of Arctic Spill Frequency Causal Event and Total Probability Distributions*

a) Development of Arctic spill frequency causal event probability distributions associated with pipeline spills.

b) Development of Arctic spill frequency causal event probability distributions associated with platform spills.

c) Development of Arctic spill frequency causal event probability distributions associated with well drilling and production well blowouts.

Task 4: *Generation of Oil Spill Occurrence Estimator Probability Distributions*

a) Variability in future development scenario parameters.

b) Model runs for variable Beaufort Sea high and low scenarios.

c) Model runs for comparative non-Arctic scenario.

Task 5: *Reporting*

a) Preliminary results following completion of Tasks 1, 2, 3, and 4.

b) Draft Final Report and Final Report.

1.7 Work Organization

The present study consisted of statistical and engineering investigations, followed by numerical simulation. Although the assimilation of historical and future scenario data is of key 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 different variable development scenarios resulted in a relatively complex mix of computations, generally illustrated in the flow chart in Figure 1.2.

The flow chart in Figure 1.2, 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. Moving from left to right; initially historical data were obtained for each of three principal facility categories, pipelines, platforms, and wells. 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, huge, and significant spills, defined as follows:

- Small (S) - 50 to 99 bbl
- Medium (M) - 100 to 999 bbl
- Large (L) - 1,000 to 9,999 bbl
- Huge (H) - >= 10,000 bbl
- Significant (SG) - >= 1,000 bbl

Significant spills, which are spills of 1,000 bbl or more (Large and Huge) are also identified. Fractional spill sizes were rounded up or down to the nearest whole number, with rounding up for any decimal ending in 5. For example, a spill of 99.5 bbl is taken as 100 bbl; 99.42 is taken as 99 bbl.

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

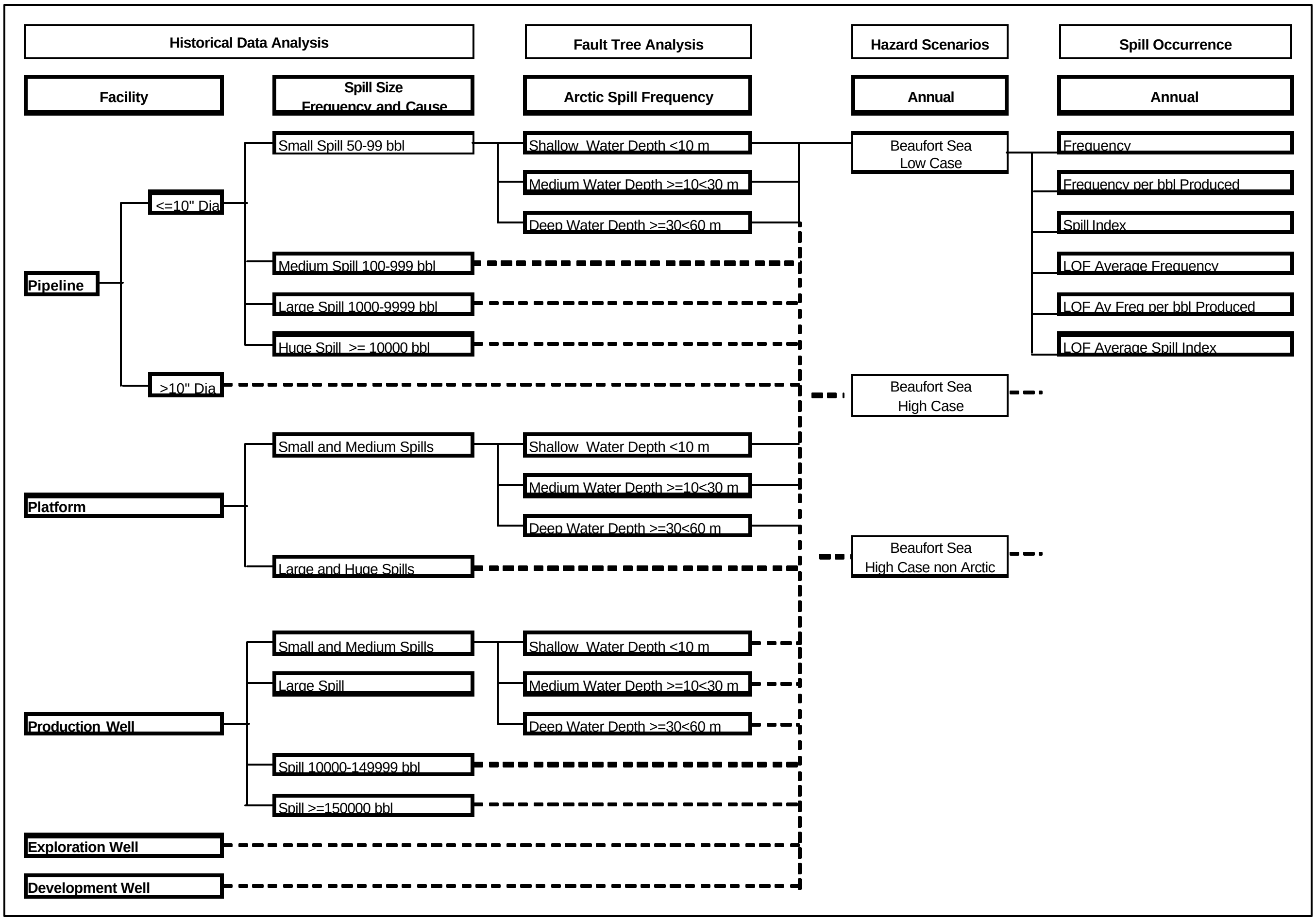


Figure 1.2
Calculation Flow Chart

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

- Shallow - < 10 meters
- Medium - 10 to 29 meters
- Deep - 30 to 60 meters

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

Two principal future development scenarios were defined for the Beaufort Sea, as well as a compatible non-Arctic (hypothetical) scenario. Each scenario was described for each year in its development history, from the year 2010 to the year 2039 (High) and 2034 (Low). The hypothetical non-Arctic scenario was developed for comparative purposes on the assumption that it was located with the same facility distribution 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.

Finally, for each of the scenarios considered, four 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)
- Life of Field Indices

1.8 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 summarizes the historical data assimilation and analysis detailed in [14], Chapter 3 defines the future development scenario used, Chapter 4 discusses 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 1 summarizes the historical data assimilated and analyzed. Appendix 2 gives details of the fault tree analysis. Appendix 3 gives details on the future development scenario utilized as a basis for the study. Appendix 4 gives a printout of all the calculation steps, including results, utilized in the development of the Arctic oil spill occurrence indicators using the Monte Carlo approach. Appendix 5 gives general conclusions and results.

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 utilized:

(a) GOM OCS Pipeline Spills (1972-2006)
(b) GOM OCS Platform Spills (1972-2006)
(c) Oil Blowouts, Worldwide (1955-1995)

The GOM categories of data are discussed in detail in the GOM update report [14], while the blowout data are given in this chapter as before [13]. The contents of the balance of this chapter are restricted to the presentation of only those data sets utilized in the present study.

2.2 Pipeline Spills

The pipeline spill statistics generated in this update are basic spill statistics. First, the number of spills by size occurring for each causal category is given. Next, spill causes by two principal spill size categories are given, and transformed to spill frequencies per kilometer-year by dividing the number of kilometer-years exposure. And finally, the spill frequency distribution for spills of different size categories, by pipe diameter is determined. Table 2.1 summarizes the spill occurrences by size for each of the principal causes. These causes are those that are reported in the MMS database*. Both the exact spill size in barrels and the spill size distribution by each of the spill size categories are given in Table 2.1.

Table 2.2 gives the pipeline hydrocarbon spill statistics by cause. These statistics are given as the probability of occurrence per kilometer-year of operating pipeline. Thus, for example, approximately 12.78 spills per 100,000 km-yrs in the small and medium size category are projected. Of these, it is expected that approximately 1.1 per 100,000 km-yrs can be attributed to pipe corrosion.

* MMS Website, www.mms.gov/incidents/spills

Table 2.1
Analysis of GOM OCS Pipeline Spill Data for Causal Distribution and Spill Size
(App. Table 1.1)

CAUSE CLASSIFICATION	# OF SPILLS	SPILL SIZE (BBL)																	NUMBER OF SPILLS					
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	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	**18**																		**2**	**6**	**7**	**3**	**8**	**10**
Anchor Impact	12	19833	65	50	300	900	323	15576	2000	800	1211	2240	600						2	5	3	2	**7**	**5**
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	**20**																		**6**	**11**	**3**		**17**	**3**
Mud Slide	3	250	80	8212															1	1	1		**2**	**1**
Storm/ Hurricane	17	3500	671	126	200	260	250	1720	95	123	960	50	50	100	75	862	66	108	5	10	2		**15**	**2**
ARCTIC																								
Ice Gouging																								
Strudel Scour																								
Upheaval Buckling																								
Thaw Settlement																								
Other																								
UNKNOWN	**2**	119	190																	**2**			**2**	
TOTALS	**50**																		**12**	**23**	**12**	**3**	**35**	**15**

Table 2.2
Distribution and Frequency of Historical Spills – Pipeline
(App. Table 1.2)

CAUSE CLASSIFICATION	Small and Medium Spills 50-999 bbl				Large and Huge Spills >=1000 bbl			
	HISTORICAL DISTRI-BUTION %	NUMBER OF SPILLS	EXPOSURE [km-years]	FREQUENCY spill per 10^5 km-year	HISTORICAL DISTRI-BUTION %	NUMBER OF SPILLS	EXPOSURE [km-years]	FREQUENCY spill per 10^5 km-year
CORROSION	**8.57**	**3**		**1.0955**	**6.67**	**1**		**0.3652**
External	2.86	1		0.3652				
Internal	5.71	2		0.7303	6.67	1		0.3652
THIRD PARTY IMPACT	**22.86**	**8**		**2.9213**	**66.67**	**10**		**3.6517**
Anchor Impact	20.00	7		2.5562	33.33	5		1.8258
Jackup Rig or Spud Barge					6.67	1		0.3652
Trawl/Fishing Net	2.86	1		0.0365	26.67	4		1.4607
OPERATION IMPACT	**8.57**	**3**		**1.0955**	**6.67**	**1**		**0.3652**
Rig Anchoring	2.86	1		0.3652				
Work Boat Anchoring	5.71	2		0.7303	6.67	1		0.3652
MECHANICAL	**5.71**	**2**		**0.7303**				
Connection Failure	2.86	1	**273847**	0.3652			**273847**	
Material Failure	2.86	1		0.3652				
NATURAL HAZARD	**48.57**	**17**		**6.2078**	**20.00**	**3**		**1.0955**
Mud Slide	5.71	2		0.7303	6.67	1		0.3652
Storm/ Hurricane	42.86	15		5.4775	13.33	2		0.7303
ARCTIC								
Ice Gouging								
Strudel Scour								
Upheaval Buckling								
Thaw Settlement								
Other								
UNKNOWN	**5.71**	**2**		**0.7303**				
TOTALS	**100.00**	**35**		**12.7809**	**100.00**	**15**		**5.4775**

Finally, Table 2.3 summarizes the pipeline hydrocarbon spill statistics by spill size and pipe diameter; while Table 2.4 gives the derived values for the present study. For example, if there were 30 data points, the upper 90% (or high value) was the third highest, while the lower 90% (or low value) was selected as the third lowest, which was invariably zero, as numerous years had no spills. Next, the third highest value was divided by the historical value to get the high factor. Finally, the high factor was used to obtain the high value by multiplying the applicable historical frequency by this high factor. The mode was then calculated from the triangular distribution relationship [13], as follows:

$$\textit{Mode} = 3 \times \textit{Historical} - \textit{High} - \textit{Low} \qquad \textbf{(2.1)}$$

2.3 Platform Spills

The primary platform spill statistical information required is the spill frequency distribution by different causes and spill sizes, and the spill rate per well year. Table 2.5 summarizes the spill size distribution among the principal reported causes. As can be seen, the major cause attributable to almost 50% of the spills – at 35 out of 74 spills – is equipment failure. However, although hurricanes have only caused a relatively small number of spills, their total spill volumes are the largest, giving the largest spill volume total. The largest single spill, however, is the tank failure which caused a spill of nearly 10,000 barrels. From a review of the platform spill data [14], it can be seen that platform spills are limited to those caused from process, storage, or transfer equipment losses of containment, so that they do not include blowouts, which are dealt with subsequently here in Section 2.4.

The spill rate data, given per production well-year, is shown in Table 2.6, again, by causal distribution as well as two broad spill size categories of small and medium spills and large and huge spills. Here, it becomes immediately evident that the largest spill potential in terms of volume is attributable to hurricanes, which are responsible for roughly 43% of the large and huge spills.

Finally, Table 2.7 gives the input data derived from Table 2.6.

Table 2.3
GOM OCS Pipeline Spills Statistics Summary (1972-2006)
(App. Table 1.3)

GOM OCS Pipeline Spills, Categorized 1972-2006			Spill Statistics Number of Spills	Exposure km-years	Frequency spills per 10^5 km-years
By Pipe Diameter		<= 10"	30	187,984	15.9588
		> 10"	20	85,863	23.2929
By Spill Size		Small <100 bbl	12	273,847	4.3820
		Medium 100 - 999 bbl	23	273,847	8.3989
		Large 1000 - 9999 bbl	12	273,847	4.3820
		Huge >=10000 bbl	3	273,847	1.0955
By Diameter, By Spill Size	<=10"	Small <100 bbl	8	187,984	4.2557
		Medium 100 - 999 bbl	14	187,984	7.4474
		Large 1000 - 9999 bbl	7	187,984	3.7237
		Huge >=10000 bbl	1	187,984	0.5320
	> 10"	Small <100 bbl	4	85,863	4.6586
		Medium 100 - 999 bbl	9	85,863	10.4818
		Large 1000 - 9999 bbl	5	85,863	5.8232
		Huge >=10000 bbl	2	85,863	2.3293

Table 2.4
Pipeline Historical Spill Frequency Variability
(App. Table 1.4 Modified)

GOM OCS Pipeline Spills, Categorized 1972-2006		Low Factor	High Factor	Frequency spill per 10^5 km-years Historical	Low	Mode	High
By Diameter, By Spill Size							
<=10"	Small	0	2.81	4.2557	0	0.8086	11.9585
	Medium	0	2.81	7.4474	0	1.4150	20.9273
	Large	0	2.81	3.7237	0	0.7075	10.4637
	Huge	0	2.81	0.5320	0	0.1011	1.4948
>10"	Small	0	2.81	4.6586	0	0.8851	13.0906
	Medium	0	2.81	10.4818	0	1.9915	29.4539
	Large	0	2.81	5.8232	0	1.1064	16.3633
	Huge	0	2.81	2.3293	0	0.4426	6.5453

Table 2.5
Analysis of GOM OCS Platform Spill Data for Causal Distribution and Spill Size (1972-2006)
(App. Table 1.5)

CAUSE CLASSIFICATION	NUMBER OF SPILLS	SPILL SIZE BBL														NUMBER OF SPILLS					
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	S	M	L	H	SM	LH
EQUIPMENT FAILURE	35															**17**	**18**			**35**	
Process Equipment	14	130	50	104	60	95	107	50	643	60	50	400	75	125	127	7	7			**14**	
Transfer Hose	12	321	118	50	400	228	214	540	125	77	200	77	58			4	8			**12**	
Incorrect Operation	9	300	70	83	58	60	50	280	436	60						6	3			**9**	
HUMAN ERROR	12	239	95	120	286	100	64	600	170	200	262	429	60			**3**	**9**			**12**	
TANK FAILURE	3	9935	150	50												**1**	**1**	**1**		**2**	**1**
SHIP COLLISION	6	166	100	1500	320	95	119									**1**	**4**	**1**		**5**	**1**
WEATHER	10	7000	165	258	80	1456	66	89	105	100	105					**3**	**5**	**2**		**8**	**2**
HURRICANE	6	75	200	1536	954	3093	6897									**1**	**2**	**3**		**3**	**3**
OTHER	2	64	100													**1**	**1**			**2**	
TOTALS	**74**															**27**	**40**	**7**		**67**	**7**

Table 2.6
Causal and Spill Size Distribution of GOM OCS Platform Spills (1972-2006)
(App. Table 1.6)

CAUSE CLASSIFICATION	Small and Medium Spills 50-999 bbl				Large and Huge Spills >=1000 bbl			
	HIST. DISTRI-BUTION %	NUMBER OF SPILLS	EXPOSURE [well-years]	FREQUENCY spill per 10^4 well-year	HIST. DISTRI-BUTION %	NUMBER OF SPILLS	EXPOSURE [well-years]	FREQUENCY spill per 10^4 well-year
EQUIPMENT FAILURE	**52.24**	**35**		**1.6434**				
Process Equipment	20.90	14		0.6574				
Transfer Hose	17.91	12		0.5635				
Incorrect Operation	13.43	9		0.4226				
HUMAN ERROR	**17.91**	**12**		**0.5635**				
TANK FAILURE	**2.99**	**2**	**212971**	**0.0939**	**14.29**	**1**	**212971**	**0.0470**
SHIP COLLISION	**7.46**	**5**		**0.2348**	**14.29**	**1**		**0.0470**
WEATHER	**11.94**	**8**		**0.3756**	**28.57**	**2**		**0.0939**
HURRICANE	**4.48**	**3**		**0.1409**	**42.86**	**3**		**0.1409**
OTHER	**2.99**	**2**		**0.0939**				
TOTALS	**100.00**	**67**		**3.1460**	**100.00**	**7**		**0.3287**

Table 2.7
Platform Historical Spill Frequency Variability
(App. Table 1.7 Modified)

Spill Size	Frequency Unit	Low Factor	High Factor	Historical	Low	Mode	High
Small and Medium Spills (50-999 bbl)	**Spill per 10^4 well-year**	0	3	3.1460	0.0000	0.0000	9.4379
Large and Huge Spills (>= 1000 bbl)	**Spill per 10^4 well-year**	0	3	0.3287	0.0000	0.0000	0.9860

2.4 Oil Well Blowout Data

The development scenarios considered under this study include both the drilling of exploratory and development wells, and the production wells producing oil. To identify a basis for the non-Arctic historical oil well blowout statistics, a number of sources were reviewed including the Northstar and Liberty oil development project reports [52], a study by ScanPower giving the cumulative distribution function for oil blowout releases [59], as well as the book by Per Holand entitled “Offshore Blowouts”, which gives risk analysis data from the SINTEF worldwide offshore blowout database [25]. The most comprehensive historical information was found in the latter reference [25], which not only gives the results of database analyses for the North Sea and the Gulf of Mexico, but also provides confidence intervals calculated from these databases. Table 2.8 gives a summary of the historical data analysis by Per Holland [25] for production wells and the drilling of exploratory and development wells. The combination of these statistics together with the cumulative distribution function for oil blowout release volumes given in [59], generated in support of the Northstar project, permits the blowout spill volume frequency distribution as summarized in Table 2.9. Finally, combining the population parameters of oil well blowouts from Table 2.8 with the size distribution factors – which can be derived from Table 2.9 – one arrives at the historical oil spill blowout distribution characteristics by spill size and well type, summarized in Table 2.10.

Table 2.8
Summary of North Sea and Gulf of Mexico Blowout Rates
(Holand, 1997)

Well Type	Unit	Low 90% CI	Average	High 90% CI
Production Well	Spills per 10^4 well-year	0.86	1.91	2.95
Exploration Well Drilling	Spills per 10^4 wells	11.00	25.05	51.00
Development Well Drilling	Spills per 10^4 wells	4.00	9.15	16.10

Table 2.9
Well Blowout Historical Spill Size Distribution
(ScanPower, 2001) *(App. Table 1.8)*

EVENT	FREQUENCY UNIT	Small and Medium Spills 50-999 bbl	Large Spills 1000-9999 bbl	Small, Medium, and Large Spills 50-9999 bbl	Spills 10000-149999 bbl	Spills >=150000 bbl	All spills
		HISTORICAL FREQUENCY					
PRODUCTION WELL	**spills per 10^4 well-year**	0.15	1.03	1.18	0.44	0.29	1.91
EXPLORATION WELL DRILLING	**spills per 10^4 wells**	1.97	13.75	15.72	5.91	3.42	25.05
DEVELOPMENT WELL DRILLING	**spills per 10^4 wells**	0.65	4.57	5.22	1.96	1.96	9.15

Table 2.10
Well Blowout Historical Spill Probability and Size Variability
(App. Table 1.9)

EVENT	FREQUENCY UNIT	Low Factor	High Factor	Frequencies			
				Historical	Low	Mode	High
				Small and Medium Spills 50-999 bbl			
PRODUCTION WELL	spill per 10^4 well-year	0.448	1.545	0.147	0.066	0.148	0.227
EXPLORATION WELL DRILLING	spill per 10^4 wells	0.439	2.036	1.966	0.863	1.032	4.002
DEVELOPMENT WELL DRILLING	spill per 10^4 wells	0.437	1.760	0.654	0.286	0.526	1.151
				Large Spills 1000-9999 bbl			
PRODUCTION WELL	spill per 10^4 well-year	0.448	1.545	1.028	0.460	1.037	1.588
EXPLORATION WELL DRILLING	spill per 10^4 wells	0.439	2.036	13.754	6.039	7.220	28.001
DEVELOPMENT WELL DRILLING	spill per 10^4 wells	0.437	1.760	4.570	1.998	3.671	8.041
				Small, Medium and Large Spills 50-9999 bbl			
PRODUCTION WELL	spill per 10^4 well-year	0.448	1.545	1.175	0.526	1.185	1.815
EXPLORATION WELL DRILLING	spill per 10^4 wells	0.439	2.036	15.719	6.903	8.252	32.003
DEVELOPMENT WELL DRILLING	spill per 10^4 wells	0.437	1.760	5.224	2.284	4.197	9.192
				Spill 10000-149999 bbl			
PRODUCTION WELL	spill per 10^4 well-year	0.448	1.545	0.441	0.197	0.444	0.681
EXPLORATION WELL DRILLING	spill per 10^4 wells	0.439	2.036	5.909	2.595	3.102	12.031
DEVELOPMENT WELL DRILLING	spill per 10^4 wells	0.437	1.760	1.963	0.858	1.577	3.454
				Spill >=150000 bbl			
PRODUCTION WELL	spill per 10^4 well-year	0.448	1.545	0.294	0.132	0.296	0.454
EXPLORATION WELL DRILLING	spill per 10^4 wells	0.439	2.036	3.421	1.502	1.796	6.965
DEVELOPMENT WELL DRILLING	spill per 10^4 wells	0.437	1.760	1.963	0.858	1.577	3.454

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.

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:

$$N = e^{-kx} H_S \ ? \ F \ ? \ T \ ? \ L_P \ ? \ \sin ? \qquad \textbf{(2.2)}$$

Where:

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

For the Northstar project, according to [30], the mean scour depth is 0.2 m giving a ***k*** factor of 5.0. In addition, a good estimate of scour flux for shallow water is 2 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 0.83, gives a frequency of 5.26 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 detecting 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 2.11.

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 2.11. For medium water depth (10 to 29 m), an analogous process was carried out with a reduced gouge flux of 1.5 gouges/km-yr. For deep water (>= 30 m) no gouging is expected.

2.5.3 Strudel Scour

When water collects on top of the landfast ice, 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 2.11 can be derived. Strudel scours are not expected in water depths greater than 10 m.

Table 2.11
Summary of Pipeline Unique Arctic Effect Inputs
(App. Table 2.2 Modified)

Cause Classification	Spill Size	Water Depth								
		Shallow			Medium			Deep		
		Frequency Increment per 10^5 km-year								
		Min	Mode	Max	Min	Mode	Max	Min	Mode	Max
Ice Gouging	S	0.0087	0.1054	1.2841	0.0108	0.1318	1.6051			
	M	0.0087	0.1054	1.2841	0.0108	0.1318	1.6051			
	L	0.0216	0.2635	3.2103	0.0270	0.3294	4.0128			
	H	0.0043	0.0527	0.6421	0.0054	0.0659	0.8026			
Strudel Scour	S	0.0110	0.0235	0.1381						
	M	0.0110	0.0235	0.1381						
	L	0.0276	0.0587	0.3452						
	H	0.0055	0.0117	0.0690						
Upheaval Buckling	S	0.00221	0.00469	0.02761	0.00221	0.00469	0.02761	0.00221	0.00469	0.02761
	M	0.00221	0.00469	0.02761	0.00221	0.00469	0.02761	0.00221	0.00469	0.02761
	L	0.00552	0.01174	0.06904	0.00552	0.01174	0.06904	0.00552	0.01174	0.06904
	H	0.00110	0.00235	0.01381	0.00110	0.00235	0.01381	0.00110	0.00235	0.01381
Thaw Settlement	S	0.00110	0.00235	0.01381	0.00110	0.00235	0.01381	0.00110	0.00235	0.01381
	M	0.00110	0.00235	0.01381	0.00110	0.00235	0.01381	0.00110	0.00235	0.01381
	L	0.00276	0.00587	0.03452	0.00276	0.00587	0.03452	0.00276	0.00587	0.03452
	H	0.00055	0.00117	0.00690	0.00055	0.00117	0.00690	0.00055	0.00117	0.00690
Other Arctic	S	0.00230	0.01359	0.14636	0.00141	0.01388	0.16466	0.00033	0.00070	0.00414
	M	0.00230	0.01359	0.14636	0.00141	0.01388	0.16466	0.00033	0.00070	0.00414
	L	0.00575	0.03398	0.36590	0.00353	0.03470	0.41164	0.00083	0.00176	0.01036
	H	0.00115	0.00680	0.07318	0.00071	0.00694	0.08233	0.00017	0.00035	0.00207

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 an upheaval buckling occurs 20% as often as strudel scour, the distribution shown in Table 2.11 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.

2.5.6 Platform Arctic Unique Effects

Potential causes of platform spills (other than blowouts, which are included under wells) that are uniquely associated with the Arctic are ice forces and low temperature effects. Although the possibility that ice forces will cause spills varies greatly from facility to facility, some broad assumptions have been made in regards to the likelihood of spills being caused by ice force effects. Specifically, it was assumed that the platforms are designed for a 10,000 year return period with a reliability level of 96%, in accordance with the Draft ISO WG8 Arctic Structures Reliability Section 7.2.2.3 [28]. That is, 4% of the time, the 10,000 year return period ice force can cause a spill. Further, it was assumed that 85% of spills so caused are small and medium, with large and huge spills associated with the other 15%. In regards to facility low temperature, a percentage of historical facility releases was taken. Specifically, it was assumed that the facility low temperature effects will cause medium spills at a rate of 6% of that of total historical small and medium spills, and large and huge spills at a rate of 3% of that associated with large and huge historical spills. Finally, other Arctic unique causes were assumed to constitute another 10% of the sum of the above spill rates in each of the spill categories. Table 2.12 summarizes the resultant Arctic unique effect frequencies derived for platforms on a per-well year basis.

2.6 Historical Spill Size Distribution

Table 2.13 gives the historical spill size distributions obtained from the available historical data. Here, the mode was taken as the historical average spill size in each spill size category, while the high and low values were taken to be the upper and lower bounds of each spill size category. The Huge spill high values were chosen on the basis of the upper 90% confidence interval spill volumes in the databases.

Table 2.12
Summary of Platform Unique Arctic Effect Inputs
(App. Table 2.7 Modified)

CAUSE	SPILL SIZE	Water Depth: Shallow	Water Depth: Medium	Water Depth: Deep	REASON
		Frequency Increment per 10^4 well-year			
		Expected	Expected	Expected	
		Mode	*Mode*	*Mode*	
Ice Force	SM	0.1447	0.2170	0.3256	Assumed 10,000 year return period ice force causes spill 4% of occurrences (96% reliability). 85% of the spills are SM.
		0.0340	*0.0510*	*0.0765*	
	LH	0.0255	0.0383	0.0575	
		0.0060	*0.0090*	*0.0135*	
Facility Low Temperature	SM	0.0986	0.0986	0.0986	Assumed fraction of Historical Equipment Failure release frequency with 6% for SM and 1% for LH spill sizes.
		0.0986	*0.0986*	*0.0986*	
	LH	0.0164	0.0164	0.0164	
		0.0164	*0.0164*	*0.0164*	
Other Arctic	SM	0.0242	0.0315	0.0423	10% of sum of above.
		0.0133	*0.0150*	*0.0175*	
	LH	0.0042	0.0055	0.0074	
		0.0022	*0.0025*	*0.0030*	

Table 2.13
Summary of Historical Spill Size Distribution Parameters

	Spill Size:	Small Spills (50-99 bbl)				Medium Spills (100-999 bbl)				Large Spills (1000-9999 bbl)				Huge Spills (=>10000 bbl)			
PIPELINE SPILL VOLUMES	Spill Expectation	Low	Mode	High	Expected	Low	Mode	High	Expected	Low	Mode	High	Expected	Low	Mode	High	Expected
	Pipeline (Diameter <10") Spill	50	58	99	71	100	226	999	485	1000	4436	9999	5279	10000	14423	20000	14880
	Pipeline (Diameter > 10") Spill	50	58	99	71	100	387	999	516	1000	3932	9999	5176	10000	17705	20000	15552
PLATFORM SPILL VOLUMES	Spill Size:	Small and Medium Spills (50-999 bbl)				Large and Huge Spills (=>1000 bbl)											
	Spill Expectation	Low	Mode	High	Expected	Low	Mode	High	Expected								
	Platform Spill	50	158	999	452	1000	6130	10000	5631								
WELL SPILL VOLUMES	Spill Size:	Small and Medium Spills (50-999 bbl)				Large Spills (1000-9999 bbl)				Spills (10000-149999 bbl)				Spills (=>150000 bbl)			
	Spill Expectation	Low	Mode	High	Expected	Low	Mode	High	Expected	Low	Mode	High	Expected	Low	Mode	High	Expected
	Well Spill	50	500	999	519	1000	4500	9999	5292	10000	20000	150000	68349	150000	200000	250000	200000

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 Beaufort Sea offshore oil and gas development scenarios need to include the following characteristics for each year of the development scenario:

- Water depth range 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 are used:

- Shallow - < 10 meters
- Medium - 10 to 29 meters
- Deep - 30 to 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.

Table 3.1
Classification of Development Scenarios

PRINCIPAL ACTIVITY	WATER DEPTH (m)			
	SHALLOW (< 10)	**MEDIUM (10 to 29)**	**DEEP (30 to 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

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. Two Beaufort Sea scenarios were considered; namely, the Low and High Cases. Table 3.2 summarizes the key quantity parameters of each possible Beaufort scenario. The facility quantities are hypothetical, and not based on any operator's plan. No facilities are predicted in the very deep region. Facilities onshore were not considered in the analysis, but were included in Table 3.2 for completeness.

Tables 3.3 and 3.4 summarize the complete development scenario including the temporal development to the year forecast to cease production. Table 3.3 summarizes the High scenario and Table 3.4 Low scenario. Both start activity in 2010, while the Low Case is assumed to cease in 2033 and the High Case to cease in 2038.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 were estimated and distributed as shown in Tables 3.3 and 3.4:

- Exploration wells drilled – annual
- Delineation wells drilled – annual
- Production platforms – only one platform was assumed in the low case, and three in the high case
- Production/service wells – annual increment and cumulative number
- Pipeline lengths for < 10", and >=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 is available through the historical 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. An important aspect of the information in Table 3.3, however, is the distribution of the facilities by water depth, as there is a significant variation in pipeline Arctic hazards by water depth.

The low (Table 3.4) and high (Table 3.3) quantities were used in the balance of the calculations for the low and high case, respectively.

Table 3.2
Summary of Exploration and Development Scenario, Beaufort Sea OCS

Scenario Element	Range		Comments
	Low	High	
Maximum oil production (Bbbl/year)	16	55	Development from first 5-year plan sale only
Natural gas production	0	0	Delayed for North Slope gas line; initially reinjected
Exploration wells	4	9	2-5 wells are dry holes or sub-commercial shows
Delineation wells	4	13	Confirm and define the commercial discovery
Production platforms	1	3	Several platforms with processing facility; support several subsea satellite templates
Platform production wells	18	60	
Subsea wells	0	12	-
Offshore sales pipeline (mi)	15	90	Possible distance to landfall
Onshore sales pipeline (mi)	50	50	n/a
Landfall	1	1	n/a
Support shorebase	1	1	n/a
New processing facility	1	1	n/a
New waste facility	1	1	Co-located with shorebase (n/a)
Years of activity	20-30	20-30	Period from lease sale to end of oil production

Table 3.3
Beaufort Sea High Case Development Scenario (2010-2039)
(App. Table 3.3)

Year	Water Depth	Exploration Wells	Delineation Wells	Expl. / Del. Rigs	Production: Platforms Incr.	Production: Platforms Cum.	Production: Platform Wells Incr.	Production: Platform Wells Cum.	Production: Subsea Wells Incr.	Production: Subsea Wells Cum.	Production: Rigs	In-Use Pipeline Length (miles): Sum <= 10" Incr.	Sum <= 10" Cum.	Sum > 10" Incr.	Sum > 10" Cum.	Sum All Incr.	Sum All Cum.	Production (MMbbl).
2010	Shallow	1		1														
	Medium																	
	Deep																	
	Total	**1**		**1**														
2011	Shallow	1	2	1														
	Medium																	
	Deep																	
	Total	**1**	**2**	**1**														
2012	Shallow		2	1														
	Medium																	
	Deep	1		1														
	Total	**1**	**2**	**2**														
2013	Shallow	1		1														
	Medium																	
	Deep	1	2	1														
	Total	**2**	**2**	**2**														
2014	Shallow	1		1														
	Medium																	
	Deep		3	1														
	Total	**1**	**3**	**2**														
2015	Shallow																	
	Medium	1	2	1														
	Deep																	
	Total	**1**	**2**	**1**														
2016	Shallow																	
	Medium	1	2	2														
	Deep																	
	Total	**1**	**2**	**2**														
2017	Shallow													10	10	10	10	
	Medium	1		1														
	Deep																	
	Total	**1**		**1**										**10**	**10**	10	10	
2018	Shallow													5	15	5	15	
	Medium																	
	Deep																	
	Total													**5**	**15**	5	15	
2019	Shallow				1	1	6	6			1				15		15	8.8
	Medium																	
	Deep																	
	Total				**1**	**1**	**6**	**6**			**1**				**15**		15	**8.8**
2020	Shallow					1	6	12			1				15		15	16.3
	Medium																	
	Deep													10	10	10	10	
	Total					**1**	**6**	**12**			**1**			**10**	**25**	10	25	**16.3**
2021	Shallow					1	6	18			1				15		15	16.3
	Medium																	
	Deep													10	20	10	20	
	Total					**1**	**6**	**18**			**1**			**10**	**35**	10	35	**16.3**

Table 3.3 ~ *Continued* ~
Beaufort Sea High Case Development Scenario (2010-2039)

Year	Water Depth	Exploration Wells	Delineation Wells	Expl. / Del. Rigs	Production: Platforms		Production: Platform Wells		Production: Subsea Wells		Production: Rigs	In-Use Pipeline Length (miles): Sum <= 10"		Sum > 10"		Sum All		Production (MMbbl)
					Incr.	Cum.	Incr.	Cum.	Incr.	Cum.		Incr.	Cum.	Incr.	Cum.	Incr.	Cum.	
2022	Shallow					1		18							15		15	16.3
	Medium																	
	Deep				1	1	6	6			1			15	35	15	35	13.5
	Total				**1**	**2**	**6**	**24**			**1**			**15**	**50**	15	50	**29.8**
2023	Shallow					1		18							15		15	13.4
	Medium																	
	Deep					1	6	12	4	4	1	5	5		35	5	40	16.9
	Total					**2**	**6**	**30**	**4**	**4**	**1**	**5**	**5**		**50**	5	55	**30.3**
2024	Shallow					1		18							15		15	11.1
	Medium				1	1	6	6			1			10	10	10	10	8.8
	Deep					1	6	18	4	8	1	5	10		35	5	45	22.5
	Total				**1**	**3**	**12**	**42**	**4**	**8**	**2**	**5**	**10**	**10**	**60**	15	70	**42.4**
2025	Shallow					1		18							15		15	9.1
	Medium					1	6	12			1			15	25	15	25	16.3
	Deep					1	6	24	4	12	1	5	15		35	5	50	30.0
	Total					**3**	**12**	**54**	**4**	**12**	**2**	**5**	**15**	**15**	**75**	20	90	**55.4**
2026	Shallow					1		18							15		15	7.5
	Medium					1	6	18			1				25		25	16.3
	Deep					1		24		12			15		35		50	30.0
	Total					**3**	**6**	**60**		**12**	**1**		**15**		**75**		90	**53.8**
2027	Shallow					1		18							15		15	6.2
	Medium					1		18							25		25	16.3
	Deep					1		24		12			15		35		50	30.0
	Total					**3**		**60**		**12**			**15**		**75**		90	**52.5**
2028	Shallow					1		18							15		15	5.1
	Medium					1		18							25		25	13.4
	Deep					1		24		12			15		35		50	24.0
	Total					**3**		**60**		**12**			**15**		**75**		90	**42.5**
2029	Shallow					1		18							15		15	4.2
	Medium					1		18							25		25	11.1
	Deep					1		24		12			15		35		50	19.2
	Total					**3**		**60**		**12**			**15**		**75**		90	**34.5**
2030	Shallow					1		18							15		15	3.5
	Medium					1		18							25		25	9.1
	Deep					1		24		12			15		35		50	15.4
	Total					**3**		**60**		**12**			**15**		**75**		90	**28.0**
2031	Shallow					1		18							15		15	2.9
	Medium					1		18							25		25	7.5
	Deep					1		24		12			15		35		50	12.3
	Total					**3**		**60**		**12**			**15**		**75**		90	**22.7**
2032	Shallow					1		18							15		15	2.5
	Medium					1		18							25		25	6.2
	Deep					1		24		12			15		35		50	9.8
	Total					**3**		**60**		**12**			**15**		**75**		90	**18.5**
2033	Shallow					1		18							15		15	2.1
	Medium					1		18							25		25	5.1
	Deep					1		24		12			15		35		50	7.9
	Total					**3**		**60**		**12**			**15**		**75**		90	**15.1**

Table 3.3 ~ *Continued* ~
Beaufort Sea High Case Development Scenario (2010-2039)

Year	Water Depth	Exploration Wells	Delineation Wells	Expl. / Del. Rigs	Production: Platforms		Platform Wells		Subsea Wells		Rigs	In-Use Pipeline Length (miles): Sum <= 10"		Sum > 10"		Sum All		Production (MMbbl)
					Incr.	Cum.	Incr.	Cum.	Incr.	Cum.		Incr.	Cum.	Incr.	Cum.	Incr.	Cum.	
2034	Shallow				-1		-18							-15		-15		
	Medium					1		18							25		25	4.2
	Deep					1		24		12			15		35		50	6.3
	Total				**-1**	**2**	**-18**	**42**		**12**			**15**	**-15**	**60**	-15	75	**10.5**
2035	Shallow																	
	Medium					1		18							25		25	3.5
	Deep					1		24		12			15		35		50	5.0
	Total					**2**		**42**		**12**			**15**		**60**		75	**8.5**
2036	Shallow																	
	Medium					1		18							25		25	2.9
	Deep					1		24		12			15		35		50	4.0
	Total					**2**		**42**		**12**			**15**		**60**		75	**6.9**
2037	Shallow																	
	Medium					1		18							25		25	2.6
	Deep					1		24		12			15		35		50	3.0
	Total					**2**		**42**		**12**			**15**		**60**		75	**5.6**
2038	Shallow																	
	Medium					1		18							25		25	2.1
	Deep				-1		-24		-12			-15		-35		-50		
	Total				**-1**	**1**	**-24**	**18**	**-12**			**-15**		**-35**	**25**	-50	25	**2.1**
2039	Shallow																	
	Medium				-1		-18							-25		-25		
	Deep																	
	Total				**-1**		**-18**							**-25**		-25		

Table 3.4
Beaufort Sea Low Case Development Scenario (2010-2034)
(App. Table 3.1)

Year	Water Depth	Exploration Wells	Delineation Wells	Expl. / Del. Rigs	Production: Platforms Incr.	Production: Platforms Cum.	Production: Platform Wells Incr.	Production: Platform Wells Cum.	Production: Subsea Wells Incr.	Production: Subsea Wells Cum.	Production: Rigs	In-Use Pipeline Length (miles): Sum <= 10" Incr.	Sum <= 10" Cum.	Sum > 10" Incr.	Sum > 10" Cum.	Sum All Incr.	Sum All Cum.	Production (Bbbl)
2010	Shallow	1		1														
	Medium																	
	Deep																	
	Total	**1**		**1**														
2011	Shallow	1	2	1														
	Medium																	
	Deep																	
	Total	**1**	**2**	**1**														
2012	Shallow		2	1														
	Medium																	
	Deep																	
	Total		**2**	**1**														
2013	Shallow	1		1														
	Medium																	
	Deep																	
	Total	**1**		**1**														
2014	Shallow	1		1														
	Medium																	
	Deep																	
	Total	**1**		**1**														
2015	Shallow																	
	Medium																	
	Deep																	
	Total																	
2016	Shallow																	
	Medium																	
	Deep																	
	Total																	
2017	Shallow													10	10	10	10	
	Medium																	
	Deep																	
	Total													**10**	**10**	10	10	
2018	Shallow													5	15	5	15	
	Medium																	
	Deep																	
	Total													**5**	**15**	5	15	
2019	Shallow				1	1	6	6			1				15		15	8.8
	Medium																	
	Deep																	
	Total				**1**	**1**	**6**	**6**			**1**				**15**		15	**8.8**
2020	Shallow					1	6	12			1				15		15	16.3
	Medium																	
	Deep																	
	Total					**1**	**6**	**12**			**1**				**15**		15	**16.3**
2021	Shallow					1	6	18			1				15		15	16.3
	Medium																	
	Deep																	
	Total					**1**	**6**	**18**			**1**				**15**		15	**16.3**

Table 3.4 ~ *Continued* ~
Beaufort Sea Low Case Development Scenario (2010-2034)

Year	Water Depth	Exploration Wells	Delineation Wells	Expl. / Del. Rigs	Production: Platforms		Production: Platform Wells		Production: Subsea Wells		Production: Rigs	In-Use Pipeline Length (miles): Sum <= 10"		Sum > 10"		Sum All		Production (Bbbl)
					Incr.	Cum.	Incr.	Cum.	Incr.	Cum.		Incr.	Cum.	Incr.	Cum.	Incr.	Cum.	
2022	Shallow					1		18							15		15	16.3
	Medium																	
	Deep																	
	Total					**1**		**18**							**15**		15	**16.3**
2023	Shallow					1		18							15		15	13.4
	Medium																	
	Deep																	
	Total					**1**		**18**							**15**		15	**13.4**
2024	Shallow					1		18							15		15	11.1
	Medium																	
	Deep																	
	Total					**1**		**18**							**15**		15	**11.1**
2025	Shallow					1		18							15		15	9.1
	Medium																	
	Deep																	
	Total					**1**		**18**							**15**		15	**9.1**
2026	Shallow					1		18							15		15	7.5
	Medium																	
	Deep																	
	Total					**1**		**18**							**15**		15	**7.5**
2027	Shallow					1		18							15		15	6.2
	Medium																	
	Deep																	
	Total					**1**		**18**							**15**		15	**6.2**
2028	Shallow					1		18							15		15	5.1
	Medium																	
	Deep																	
	Total					**1**		**18**							**15**		15	**5.1**
2029	Shallow					1		18							15		15	4.2
	Medium																	
	Deep																	
	Total					**1**		**18**							**15**		15	**4.2**
2030	Shallow					1		18							15		15	3.5
	Medium																	
	Deep																	
	Total					**1**		**18**							**15**		15	**3.5**
2031	Shallow					1		18							15		15	2.9
	Medium																	
	Deep																	
	Total					**1**		**18**							**15**		15	**2.9**
2032	Shallow					1		18							15		15	2.5
	Medium																	
	Deep																	
	Total					**1**		**18**							**15**		15	**2.5**
2033	Shallow					1		18							15		15	2.1
	Medium																	
	Deep																	
	Total					**1**		**18**							**15**		15	**2.1**
2034	Shallow				-1		-18							-15		-15		
	Medium																	
	Deep																	
	Total				**-1**		**-18**							**-15**		-15		

CHAPTER 4

FAULT TREE ANALYSIS FOR ARCTIC OIL SPILL FREQUENCIES

4.1 General Description of Fault Tree Analysis

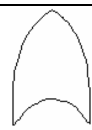
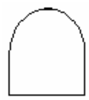
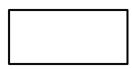
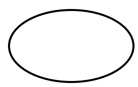
Fault trees are a method for modeling the occurrence of failures. They are used when an adequate history to provide failure statistics is not available. Developed initially by Rasmussen for the US Nuclear Regulatory Commission in the early 1970s [65, 51], fault trees have become a popular risk analytic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

4.2 Fault Tree Methodology

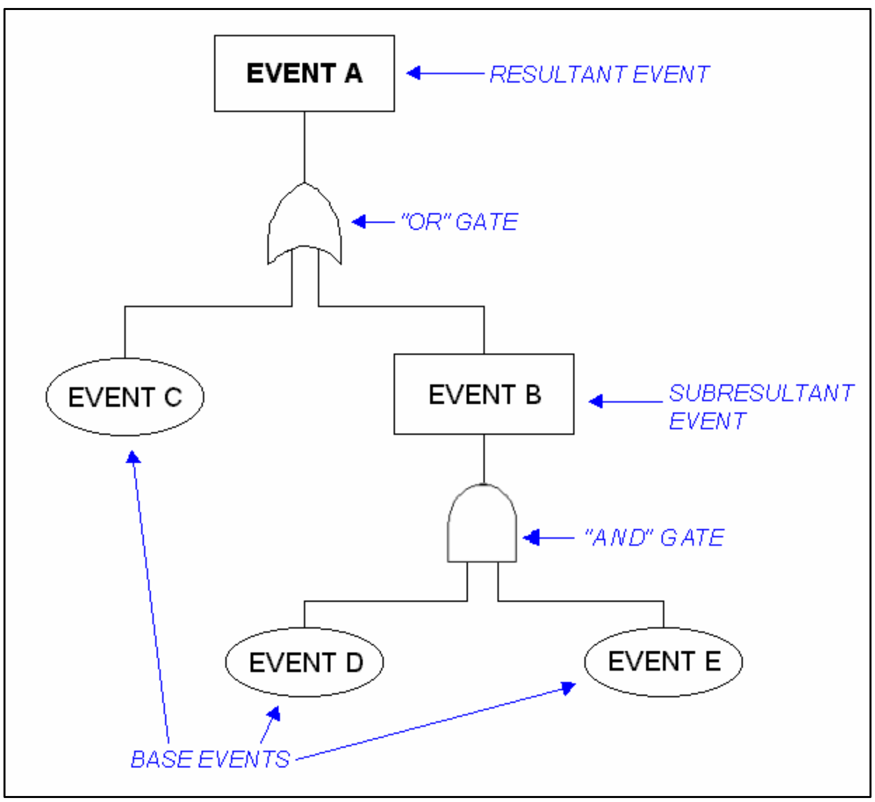
4.2.1 Fault Tree Analysis Basics

The basic symbols used in the graphic depiction of simple (as used here) fault tree networks are illustrated in Figure 4.1(a). 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 4.1(b). 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, 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

(a) Basic Fault Tree Symbols



(b) Basic Fault Tree Structure

Figure 4.1
Fault Tree Basics

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:

$$P = \prod_{n}^{i=1} P_i \qquad (4.1a)$$

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

$$P_x = P_1(P_2)(P_3) \qquad (4.1b)$$

For OR Gate:

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

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

$$P_y = 1 - \prod_{n}(1 - P_1)(1 - P_2)(1 - P_3)$$
$$P_y = P_1 + P_2 + P_3;\ \ for\ P_i \leq 0.1 \qquad (4.2b)$$

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 [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 4.2 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, such as that shown in Table 2.3. 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.

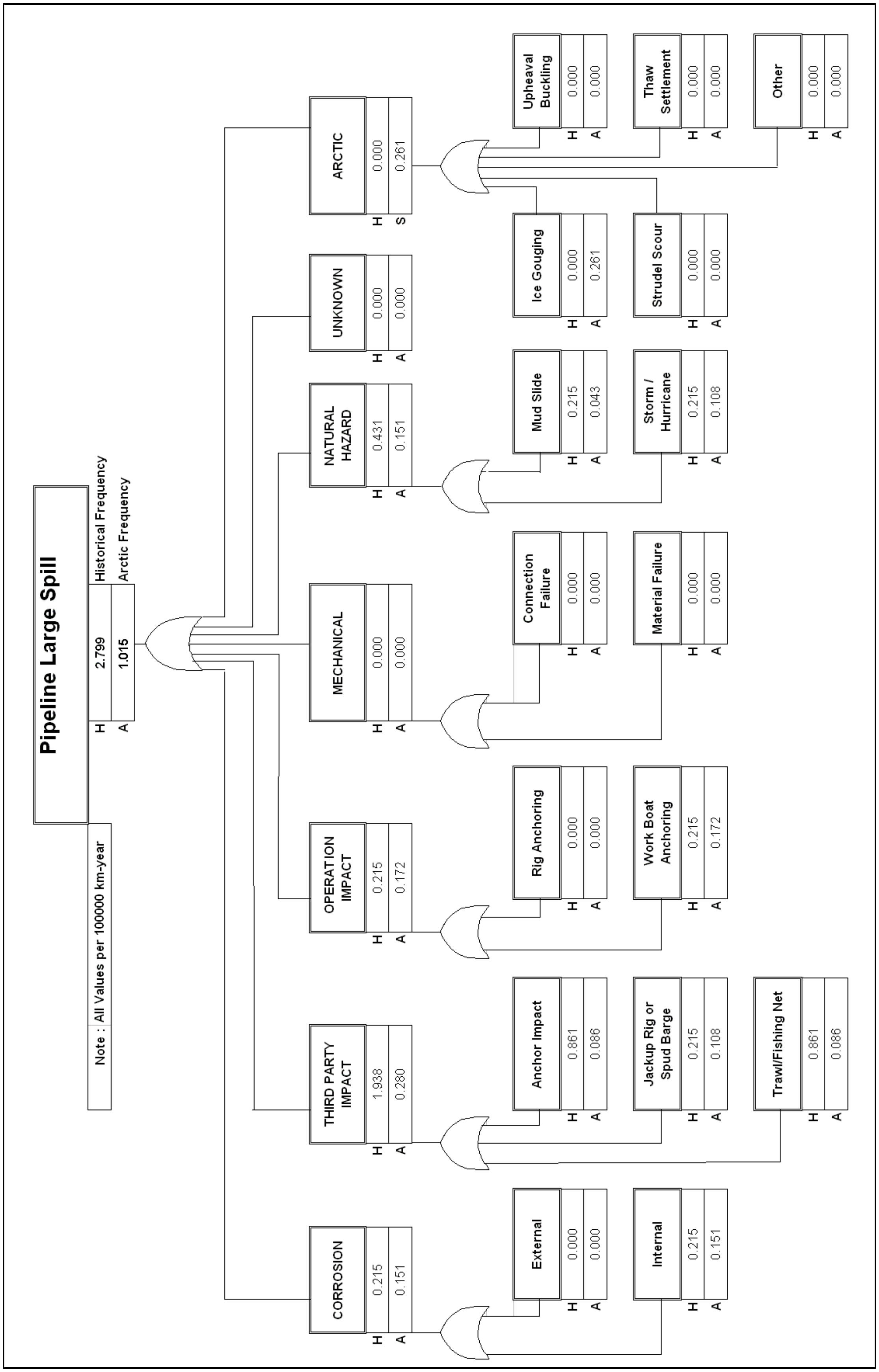


Figure 4.2
Example of Fault Tree to Transform Historical (GOM) to Arctic Spill Frequencies[1]

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

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. Both frequencies are for illustrative purposes only.

4.2.3 Monte Carlo Simulation

A type of numerical simulation, called Monte Carlo simulation [9] can be used to obtain the outcome of a set of interactions for equations in which the independent variables are described by distributions of any arbitrary form. The Monte Carlo simulation is a systematic method for selecting values from each of the independent variable distributions and computing all valid combinations of these values to obtain the distribution of the dependent variable. Naturally, this is done utilizing a computer, so that thousands of combinations can be rapidly computed and assembled to give the output distribution.

Consider the example of the following equation:

$$\boldsymbol{X = X_1 + X_2} \qquad \textbf{(4.3)}$$

Where X is the dependent variable (such as the resultant spill frequency) and X_1 and X_2 are base event probabilities joined through an "and" gate. Suppose now that X_1 and X_2 are some arbitrary distributions that can be described by a collection of values x_1 and x_2. What we do in the Monte Carlo process, figuratively, is to put the collection of the X_1 values into one hat, the X_1 hat, and the same for the X_2 values – into an X_2 hat. We then randomly draw one value from each of the hats and compute the resultant value of the dependent variable, X, using equation 4.3. This is done several thousand times. Thus, a resultant or dependent variable distribution, X, is estimated from the computations of all valid combinations of the independent variables (X_1 and X_2).

Generally, the resultant can be viewed as a cumulative distribution function as illustrated in Figure 4.3. Such a cumulative distribution function (CDF) is also a measure of the accuracy or, conversely, the variance of the distribution. As can be seen from this figure, if the distribution is a vertical line, no matter where one draws on the vertical axis, the same value of the variable will result – that is, the variable is a constant. At the other extreme, if the variable is completely random then the distribution will be represented as a diagonal straight line between the minimum and maximum value. Intermediate qualitative descriptions of the randomness of the variable follow from inspection of the CDF in Figure 4.3.

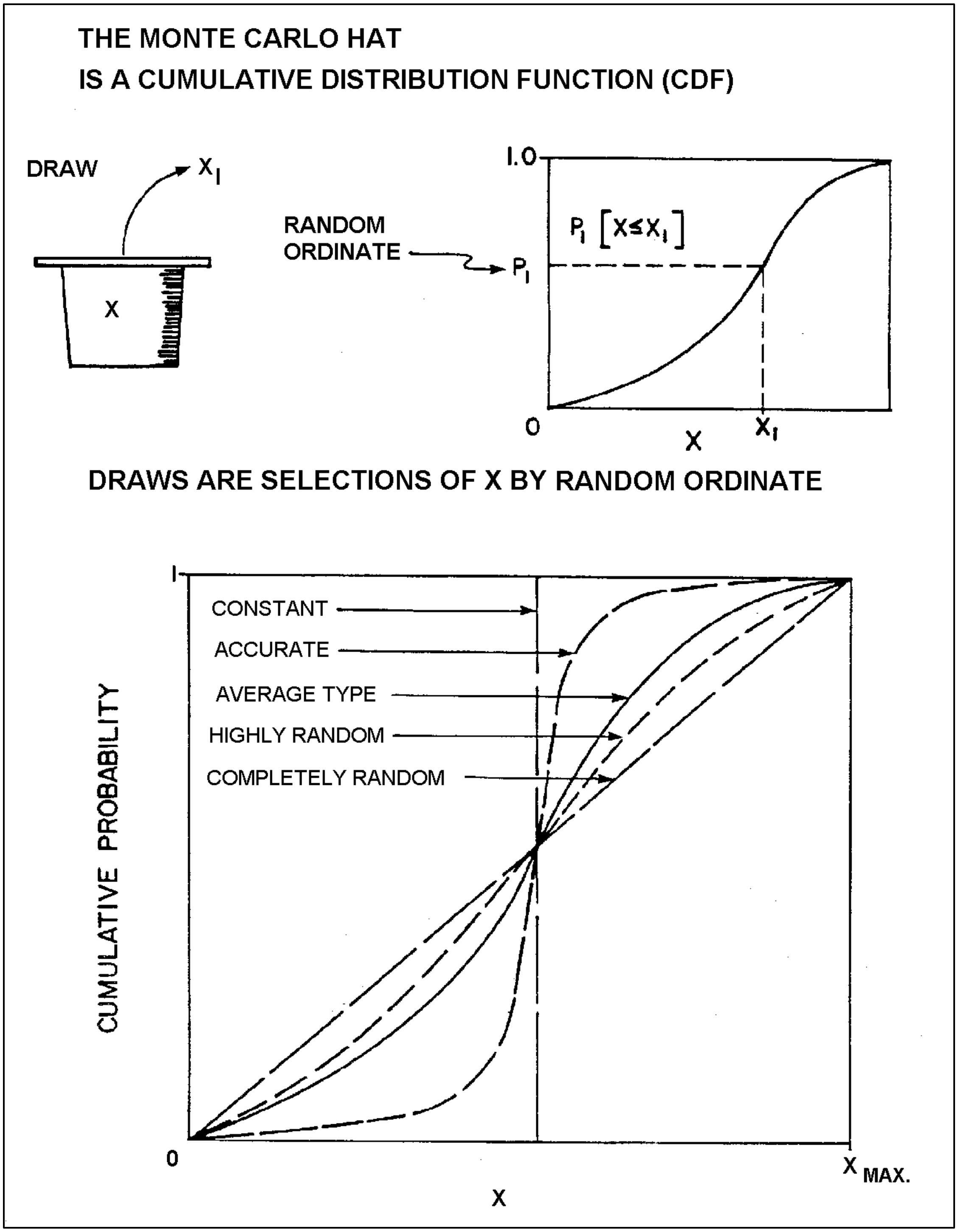


Figure 4.3
Monte Carlo Technique Schematic

There are two other important concepts related to the CDF enter into Monte Carlo modeling: auto-correlation and cross-correlation. Suppose the variables X_1 can vary only within a specified interval over the simulation time increment. Then, after the first random draw, the next draw would be restricted within certain limits of the initial draw simply as a result of the physical restrictions of the problem. Such a restriction is represented as an auto-correlation coefficient. Now, suppose that not only are the X_1 restricted, but also the X_2. Suppose further, however, that given a certain X_1, a restriction were placed on the range of X_2 associated with that X_1. Say, only small X_1 could associate with the full range of X_2, while large X_1 could only be associated with certain lower X_2. Then, such a relationship would be expressed as a cross-correlation factor and certain limits would be imposed for the drawing on both X_1 and associated X_2. In the present analysis, all distributed variables are considered to be independent – so that auto and cross-correlations need not be invoked.

4.2.4 Distribution Derived from Historical Data for Monte Carlo Analysis

In order to model the variability of the base data and its distribution through the Arctic effects, using the Monte Carlo approach, an appropriate distribution needs to be derived. As in the previous studies [12, 13], a Triangular Distribution was selected.

The Triangular Distribution is typically used as a descriptor of a population for which there is only limited sample data, as is the current case. The distribution is based on a knowledge of a minimum and maximum, which was derived from the historical data here, and an educated guess as to what the modal value might be. Here, the modal value was chosen to be a function of the average historical value, as given in Equation 2.1. Despite being a simplistic description of a population, the Triangular Distribution is a very useful one for modeling processes where the relationship between variables is understood, but data are scarce.

Also, when combining several variables in a functional relationship utilizing numerical methods, as is done in Monte Carlo Simulation, the Triangular Distribution is a preferred one due to its simplicity and relatively accurate probabilistic resultant when evaluated by a large number of random draws, as occurs in the Monte Carlo process. The data used here typifies sparse data with a preferred or modal value and an easily identifiable maximum and minimum. Then, for the case of the simple upper and lower 100% confidence interval (called High and Low), the expected value ***E*** (or mean value) of the Triangular Distribution can be expressed as:

$$E = (High + Mode + Low) / 3 \quad (4.4)$$

For maximum and minimum which are not at the 100% confidence interval level – such as those at 90% confidence levels – a Monte Carlo computation is used to evaluate the expected value of each distribution, giving results somewhat different from Equation 4.4. Based on the historical data earlier presented in Tables 2.4, 2.7, and 2.10, the Triangular Distribution expected values computed from the low, mode, and high values at 90% confidence intervals are given in Tables 4.1, 4.2, and 4.3, for pipelines, platforms, and wells respectively. The high and low values were calculated as described in Section 2.2.

Table 4.1
Pipeline Spill Frequency Triangular Distribution Properties
(App. Table 1.4)

GOM OCS Pipeline Spills, Categorized 1972-2006		Low Factor	High Factor	Frequency spill per 10^5 km-years				
By Diameter	*By Spill Size*			Historical	Low	Mode	High	Expected
<10”	**Small**	0	2.81	4.2557	0	0.8086	11.9585	6.0361
	Medium	0	2.81	7.4474	0	1.4150	20.9273	10.5632
	Large	0	2.81	3.7237	0	0.7075	10.4637	5.2816
	Huge	0	2.81	0.5320	0	0.1011	1.4948	0.7545
=>10"	**Small**	0	2.81	4.6586	0	0.8851	13.0906	6.6076
	Medium	0	2.81	10.4818	0	1.9915	29.4539	14.8670
	Large	0	2.81	5.8232	0	1.1064	16.3633	8.2595
	Huge	0	2.81	2.3293	0	0.4426	6.5453	3.3038

Table 4.2
Platform Spill Frequency Triangular Distribution Properties
(App. Table 1.7)

Spill Size	Frequency Unit	Low Factor	High Factor	Historical	Low	Mode	High	Expected
Small and Medium Spills (50-999 bbl)	Spill per 10^4 well-year	0	3	3.1460	0.0000	0.0000	9.4379	4.6009
Large and Huge Spills (=>1000 bbl)	Spill per 10^4 well-year	0	3	0.3287	0.0000	0.0000	0.9860	0.4807

Table 4.3
Well Blowout Frequency Triangular Distribution Properties
(App. Table 1.9)

EVENT	FREQUENCY UNIT	Low Factor	High Factor	Frequencies				
				Historical	Low	Mode	High	Expected
				Small and Medium Spills 50-999 bbl				
PRODUCTION WELL	spill per 10^4 well-year	0.448	1.545	0.147	0.066	0.148	0.227	0.147
EXPLORATION WELL DRILLING	spill per 10^4 wells	0.439	2.036	1.966	0.863	1.032	4.002	2.262
DEVELOPMENT WELL DRILLING	spill per 10^4 wells	0.437	1.760	0.654	0.286	0.526	1.151	0.692
				Large Spills 1000-9999 bbl				
PRODUCTION WELL	spill per 10^4 well-year	0.448	1.545	1.028	0.460	1.037	1.588	1.026
EXPLORATION WELL DRILLING	spill per 10^4 wells	0.439	2.036	13.754	6.039	7.220	28.001	15.824
DEVELOPMENT WELL DRILLING	spill per 10^4 wells	0.437	1.760	4.570	1.998	3.671	8.041	4.833
				Small, Medium and Large Spills 50-9999 bbl				
PRODUCTION WELL	spill per 10^4 well-year	0.448	1.545	1.175	0.526	1.185	1.815	1.173
EXPLORATION WELL DRILLING	spill per 10^4 wells	0.439	2.036	15.719	6.903	8.252	32.003	18.086
DEVELOPMENT WELL DRILLING	spill per 10^4 wells	0.437	1.760	5.224	2.284	4.197	9.192	5.525
				Spill 10000-149999 bbl				
PRODUCTION WELL	spill per 10^4 well-year	0.448	1.545	0.441	0.197	0.444	0.681	0.440
EXPLORATION WELL DRILLING	spill per 10^4 wells	0.439	2.036	5.909	2.595	3.102	12.031	6.799
DEVELOPMENT WELL DRILLING	spill per 10^4 wells	0.437	1.760	1.963	0.858	1.577	3.454	2.076
				Spill =>150000 bbl				
PRODUCTION WELL	spill per 10^4 well-year	0.448	1.545	0.294	0.132	0.296	0.454	0.293
EXPLORATION WELL DRILLING	spill per 10^4 wells	0.439	2.036	3.421	1.502	1.796	6.965	3.936
DEVELOPMENT WELL DRILLING	spill per 10^4 wells	0.437	1.760	1.963	0.858	1.577	3.454	2.076

4.2.5 Approaches to Assessment of Arctic Spill Frequency Variability

The method for assessment of Arctic spill frequency variability consists of systematically perturbing the variability of all the causal events, plus that of the Arctic unique effects. In this approach, the non-Arctic variable distribution is multiplied by an adjustment or correction distribution to obtain the Arctic variable distribution.

4.3 Pipeline Fault Tree Analysis

4.3.1 Arctic Pipeline Spill Causal Frequency Distributions

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 to 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 4.4 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 50% 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 Chukchi Sea.

Table 4.4
Pipeline Arctic Effect Derivation Summary
(App. Table 2.1)

CAUSE CLASSIFICATION	Spill Size	Shallow	Medium	Deep	Reason
		Historical Expected Frequency Change %			
CORROSION					
External	**All**	(30)	(30)	(30)	Low temperature and bio effects. Extra smart pigging.
Internal	**All**	(30)	(30)	(30)	Extra smart pigging.
THIRD PARTY IMPACT					
Anchor Impact	**All**	(50)	(50)	(50)	Low traffic.
Jackup Rig or Spud Barge	**All**	(50)	(50)	(50)	Low facility density.
Trawl/Fishing Net	**All**	(50)	(60)	(70)	Low fishing activity. Less bottom fishing in deeper water.
OPERATION IMPACT					
Rig Anchoring	**All**	(20)	(20)	(20)	Low marine traffic during ice season (8 months).
Work Boat Anchoring	**All**	(20)	(20)	(20)	Low work boat traffic during ice season (8 months).
MECHANICAL					
Connection Failure	**All**				
Material Failure	**All**				
NATURAL HAZARD					
Mud Slide	**All**	(60)	(50)	(40)	Gradient low. Mud slide potential (gradient) increases with water depth.
Storm/ Hurricane	**All**	(80)	(80)	(70)	Fewer severe storms.
		Freq. Increment per 10^5 km-year			
		Expected / Mode	Expected / Mode	Expected / Mode	
ARCTIC					
Ice Gouging	**S**	0.511	0.6763		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. Medium depth has 0.8 as many gouges as shallow.
		0.1054	0.1318		
	M	0.5411	0.6763		
		0.1054	0.1318		
	L	1.3527	0.6908		
		0.2635	0.3294		
	H	0.2705	0.3382		
		0.0527	0.0659		
Strudel Scour	**S**	0.0645			Only in shallow water. Average frequency of 4 scours/mile² and 100 ft of bridge length with 10% conditional Pipelines failure probability. The same spill size distribution as above.
		0.0235			
	M	0.0645			
		0.0235			
	L	0.1613			
		0.0587			
	H	0.0323			
		0.0117			
Upheaval Buckling	**S**	0.0129	0.0129	0.0129	All water depth. The failure frequency is 20% of that of Strudel Scour.
		0.0047	0.0047	0.0047	
	M	0.0129	0.0129	0.0129	
		0.0047	0.0047	0.0047	
	L	0.0323	0.0323	0.0323	
		0.0117	0.0117	0.0117	
	H	0.0065	0.0065	0.0065	
		0.0023	0.0023	0.0023	
Thaw Settlement	**S**	0.0065	0.0065	0.0065	All water depth. The failure frequency is 10% of that of Strudel Scour.
		0.0023	0.0023	0.0023	
	M	0.0065	0.0065	0.0065	
		0.0023	0.0023	0.0023	
	L	0.0161	0.0161	0.0161	
		0.0059	0.0059	0.0059	
	H	0.0032	0.0032	0.0032	
		0.0012	0.0012	0.0012	
Other Arctic	**S**	0.0625	0.0696	0.0019	10% of all Arctic effects.
		0.0136	0.0139	0.0007	
	M	0.0625	0.0696	0.0019	
		0.0136	0.0139	0.0007	
	L	0.1562	0.1739	0.0048	
		0.0340	0.0347	0.0018	
	H	0.0312	0.0348	0.0010	
		0.0068	0.0069	0.0004	

- *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 60% for shallow water to only 40% in deep water was included to account for the anticipated increase in gradient as deeper waters are encountered.
- *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 4.4. The frequency increments in this table are given as both the “mode” values and the “expected” values. The mode values are the mode values given in Table 2.11. The expected values, however, are those calculated using the Monte Carlo method with the low, mode, and high values from Table 2.11, as inputs to the Monte Carlo. The expected or mean values are clearly considerably higher than the mode or most likely values. This lack of coincidence between expected and mode values is due to the skewness of the distribution.

Derivation of the Arctic effect distributions is accomplished through the construction of a secondary triangular distribution by which the historical causal frequency distributions are multiplied to provide the resultant Arctic effect distribution. This secondary distribution utilizes the value of mode adjustments from Table 4.4, with appropriate second order perturbations for the upper and lower 90% confidence interval bounds. Table 4.5 summarizes these Arctic effect distributions. For the Arctic modified effects, given in the top of the table, the secondary distribution is simply the frequency change used as the mode of the distribution, and 90% upper and lower confidence interval changes given under the Min and Max columns. For the Arctic unique effects, total frequency increments are given, with the upper confidence interval value at approximately 12 times the mode, and the lower bound value at approximately $^{1}/_{12}$ of the modal value.

Table 4.5
Pipeline Arctic Effect Distribution Derivation Summary
(App. Table 2.2)

Cause Classification	Spill Size	Water Depth								
		Shallow			Medium			Deep		
		Frequency Increment per 10^5 km-year								
		Min	Mode	Max	Min	Mode	Max	Min	Mode	Max
CORROSION										
External	**All**	(90)	(30)	(10)	(90)	(30)	(10)	(90)	(30)	(10)
Internal	**All**	(90)	(30)	(10)	(90)	(30)	(10)	(90)	(30)	(10)
THIRD PARTY IMPACT										
Anchor Impact	**All**	(90)	(50)	(10)	(90)	(50)	(10)	(90)	(50)	(10)
Jackup Rig or	**All**	(90)	(50)	(10)	(90)	(50)	(10)	(90)	(50)	(10)
Trawl/Fishing	**All**	(90)	(50)	(10)	(90)	(60)	(10)	(90)	(70)	(10)
OPERATION IMPACT										
Rig Anchoring	**All**	(50)	(20)	(10)	(50)	(20)	(10)	(50)	(20)	(10)
Work Boat	**All**	(50)	(20)	(10)	(50)	(20)	(10)	(50)	(20)	(10)
MECHANICAL										
Connection Failure	**All**									
Material Failure	**All**									
NATURAL HAZARD										
Mud Slide	**All**	(90)	(60)	(10)	(90)	(50)	(10)	(90)	(40)	(10)
Storm/ Hurricane	**All**	(90)	(80)	(10)	(90)	(80)	(10)	(90)	(70)	(10)

Cause Classification	Spill Size	Water Depth								
		Shallow			Medium			Deep		
		Frequency Increment per 10^5 km-year								
		Min	Mode	Max	Min	Mode	Max	Min	Mode	Max
Ice Gouging	**S**	0.0087	0.1054	1.2841	0.0108	0.1318	1.6051			
	M	0.0087	0.1054	1.2841	0.0108	0.1318	1.6051			
	L	0.0216	0.2635	3.2103	0.0270	0.3294	4.0128			
	H	0.0043	0.0527	0.6421	0.0054	0.0659	0.8026			
Strudel Scour	**S**	0.0110	0.0235	0.1381						
	M	0.0110	0.0235	0.1381						
	L	0.0276	0.0587	0.3452						
	H	0.0055	0.0117	0.0690						
Upheaval Buckling	**S**	0.00221	0.00469	0.02761	0.00221	0.00469	0.02761	0.00221	0.00469	0.02761
	M	0.00221	0.00469	0.02761	0.00221	0.00469	0.02761	0.00221	0.00469	0.02761
	L	0.00552	0.01174	0.06904	0.00552	0.01174	0.06904	0.00552	0.01174	0.06904
	H	0.00110	0.00235	0.01381	0.00110	0.00235	0.01381	0.00110	0.00235	0.01381
Thaw Settlement	**S**	0.00110	0.00235	0.01381	0.00110	0.00235	0.01381	0.00110	0.00235	0.01381
	M	0.00110	0.00235	0.01381	0.00110	0.00235	0.01381	0.00110	0.00235	0.01381
	L	0.00276	0.00587	0.03452	0.00276	0.00587	0.03452	0.00276	0.00587	0.03452
	H	0.00055	0.00117	0.00690	0.00055	0.00117	0.00690	0.00055	0.00117	0.00690
Other Arctic	**S**	0.00230	0.01359	0.14636	0.00141	0.01388	0.16466	0.00033	0.00070	0.00414
	M	0.00230	0.01359	0.14636	0.00141	0.01388	0.16466	0.00033	0.00070	0.00414
	L	0.00575	0.03398	0.36590	0.00353	0.03470	0.41164	0.00083	0.00176	0.01036
	H	0.00115	0.00680	0.07318	0.00071	0.00694	0.08233	0.00017	0.00035	0.00207

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 less than or at least 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, large, and huge spills are presented in Appendix 2, where the complete calculations are given.

Of greatest importance, however, are the pipeline failure frequencies or failure rates per km-yr calculated from the first and second order input distributions using Monte Carlo simulation. These failure rates for the entire range of pipeline spill sizes, small, medium, large, and huge, are given in Tables 4.6, 4.7, 4.8, and 4.9, respectively.

Indeed, a huge array of numbers is shown in these tables. Consider Table 4.8, 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 < 10" diameter was 5.282 (per 10^5 km-yr) historically. With the first and second order frequency changes attributable to Arctic effects, this frequency is reduced to 4.402 for shallow water, to 4.575 for medium depth water, and to 2.707 for deep water. A similar trend in the reduction of failure frequencies with increasing water depth for pipelines >= 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 4.6 to 4.9) for each of the spill sizes for pipelines. Finally, Table 4.10 summarizes the expected values of the pipeline spill frequencies.

Note : All Values per 100000 km-year

Pipeline Large Spill 1000-9999 bbl

	Dia<=10"	Dia>10"	P/L Size
H	5.282	8.259	Historical Frequency
S	4.402	5.915	Shallow Water Depth Frequency
M	4.575	6.075	Medium Water Depth Frequency
D	2.707	4.203	Deep Water Depth Frequency

CORROSION

	Dia<=10"	Dia>10"
H	0.352	0.551
S	0.190	0.298
M	0.190	0.298
D	0.190	0.298

External

	Dia<=10"	Dia>10"
H	0.000	0.000
S	0.000	0.000
M	0.000	0.000
D	0.000	0.000

Internal

	Dia<=10"	Dia>10"
H	0.352	0.551
S	0.190	0.298
M	0.190	0.298
D	0.190	0.298

THIRD PARTY IMPACT

	Dia<=10"	Dia>10"
H	3.521	5.506
S	1.761	2.753
M	1.731	2.707
D	1.703	2.663

Anchor Impact

	Dia<=10"	Dia>10"
H	1.761	2.753
S	0.880	1.377
M	0.880	1.377
D	0.880	1.377

Jackup Rig or Spud Barge

	Dia<=10"	Dia>10"
H	0.352	0.551
S	0.176	0.275
M	0.176	0.275
D	0.176	0.275

Trawl/Fishing Net

	Dia<=10"	Dia>10"
H	1.408	2.203
S	0.704	1.101
M	0.675	1.056
D	0.647	1.011

OPERATION IMPACT

	Dia<=10"	Dia>10"
H	0.352	0.551
S	0.254	0.397
M	0.254	0.397
D	0.254	0.397

Rig Anchoring

	Dia<=10"	Dia>10"
H	0.000	0.000
S	0.000	0.000
M	0.000	0.000
D	0.000	0.000

Work Boat Anchoring

	Dia<=10"	Dia>10"
H	0.352	0.551
S	0.254	0.397
M	0.254	0.397
D	0.254	0.397

MECHANICAL

	Dia<=10"	Dia>10"
H	0.000	0.000
S	0.000	0.000
M	0.000	0.000
D	0.000	0.000

Connection Failure

	Dia<=10"	Dia>10"
H	0.000	0.000
S	0.000	0.000
M	0.000	0.000
D	0.000	0.000

Material Failure

	Dia<=10"	Dia>10"
H	0.000	0.000
S	0.000	0.000
M	0.000	0.000
D	0.000	0.000

NATURAL HAZARD

	Dia<=10"	Dia>10"
H	1.056	1.652
S	0.479	0.749
M	0.486	0.760
D	0.507	0.792

Mud Slide

	Dia<=10"	Dia>10"
H	0.352	0.551
S	0.169	0.264
M	0.176	0.275
D	0.183	0.287

Storm/ Hurricane

	Dia<=10"	Dia>10"
H	0.704	1.101
S	0.310	0.485
M	0.310	0.485
D	0.323	0.506

UNKNOWN

	Dia<=10"	Dia>10"
H	0.000	0.000
S	0.000	0.000
M	0.000	0.000
D	0.000	0.000

ARCTIC

	Dia<=10"	Dia>10"
H	0.000	0.000
S	1.719	1.719
M	1.913	1.913
D	0.053	0.053

Ice Gouging

	Dia<=10"	Dia>10"
H	0.000	0.000
S	1.353	1.353
M	1.691	1.691
D	0.000	0.000

Strudel Scour

	Dia<=10"	Dia>10"
H	0.000	0.000
S	0.161	0.161
M	0.000	0.000
D	0.000	0.000

Upheaval Buckling

	Dia<=10"	Dia>10"
H	0.000	0.000
S	0.032	0.032
M	0.032	0.032
D	0.032	0.032

Thaw Settlement

	Dia<=10"	Dia>10"
H	0.000	0.000
S	0.016	0.016
M	0.016	0.016
D	0.016	0.016

Other Arctic

	Dia<=10"	Dia>10"
H	0.000	0.000
S	0.156	0.156
M	0.174	0.174
D	0.005	0.005

Figure 4.4
Large Spill Frequencies Fault Tree for Pipeline
(Appendix Figure 2.3)

Table 4.6
Arctic Pipeline Small Spill (50-99 bbl) Frequencies
(App. Table 2.3)

CAUSE CLASSIFICATION	HIST. DISTRIBUTION %	Pipeline Diameter <= 10"										Pipeline Diameter > 10"									
			Shallow			Medium			Deep				Shallow			Medium			Deep		
		FREQUENCY spills per 10^5km-year	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %	FREQUENCY spills per 10^5km-year	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %
CORROSION	**8.57**	**0.517**	**(0.238)**	**0.280**	**5.11**	**(0.238)**	**0.280**	**5.04**	**(0.238)**	**0.280**	**5.81**	**0.566**	**(0.260)**	**0.306**	**5.17**	**(0.260)**	**0.306**	**5.10**	**(0.260)**	**0.306**	**5.82**
External	2.86	0.172	(0.079)	0.093	1.70	(0.079)	0.093	1.68	(0.079)	0.093	1.94	0.189	(0.087)	0.102	1.72	(0.087)	0.102	1.70	(0.087)	0.102	1.94
Internal	5.71	0.345	(0.158)	0.187	3.41	(0.158)	0.187	3.36	(0.158)	0.187	3.88	0.378	(0.173)	0.204	3.45	(0.173)	0.204	3.40	(0.173)	0.204	3.88
THIRD PARTY IMPACT	**22.86**	**1.380**	**(0.690)**	**0.690**	**12.61**	**(0.693)**	**0.686**	**12.36**	**(0.697)**	**0.683**	**14.19**	**1.510**	**(0.755)**	**0.755**	**12.75**	**(0.759)**	**0.751**	**12.51**	**(0.763)**	**0.747**	**14.19**
Anchor Impact	20.00	1.207	(0.604)	0.604	11.03	(0.604)	0.604	10.87	(0.604)	0.604	12.54	1.322	(0.661)	0.661	11.15	(0.661)	0.661	11.00	(0.661)	0.661	12.55
Jackup Rig or Spud Barge																					
Trawl/Fishing Net	2.86	0.172	(0.086)	0.086	1.58	(0.090)	0.083	1.49	(0.093)	0.079	1.64	0.189	(0.094)	0.094	1.59	(0.098)	0.090	1.51	(0.102)	0.087	1.65
OPERATION IMPACT	**8.57**	**0.517**	**(0.145)**	**0.373**	**6.81**	**(0.145)**	**0.373**	**6.71**	**(0.145)**	**0.373**	**7.74**	**0.566**	**(0.158)**	**0.408**	**6.89**	**(0.158)**	**0.408**	**6.79**	**(0.158)**	**0.408**	**7.75**
Rig Anchoring	2.86	0.172	(0.048)	0.124	2.27	(0.048)	0.124	2.24	(0.048)	0.124	2.58	0.189	(0.053)	0.136	2.30	(0.053)	0.136	2.26	(0.053)	0.136	2.58
Work Boat Anchoring	5.71	0.345	(0.096)	0.249	4.54	(0.096)	0.249	4.47	(0.096)	0.249	5.16	0.378	(0.106)	0.272	4.59	(0.106)	0.272	4.53	(0.106)	0.272	5.17
MECHANICAL	**5.71**	**0.345**		**0.345**	**6.30**		**0.345**	**6.21**		**0.345**	**7.17**	**0.378**		**0.378**	**6.37**		**0.378**	**6.29**		**0.378**	**7.17**
Connection Failure	2.86	0.172		0.172	3.15		0.172	3.11		0.172	3.58	0.189		0.189	3.19		0.189	3.14		0.189	3.58
Material Failure	2.86	0.172		0.172	3.15		0.172	3.11		0.172	3.58	0.189		0.189	3.19		0.189	3.14		0.189	3.58
NATURAL HAZARD	**48.57**	**2.932**	**(0.180)**	**2.752**	**50.30**	**(0.172)**	**2.759**	**49.69**	**(0.165)**	**2.767**	**57.48**	**3.209**	**(0.197)**	**3.013**	**50.85**	**(0.189)**	**3.021**	**50.29**	**(0.181)**	**3.028**	**57.50**
Mud Slide	5.71	0.345	(0.180)	0.165	3.02	(0.172)	0.172	3.11	(0.165)	0.180	3.73	0.378	(0.197)	0.181	3.05	(0.189)	0.189	3.14	(0.181)	0.197	3.73
Storm/ Hurricane	42.86	2.587		2.587	47.28		2.587	46.58		2.587	53.75	2.832		2.832	47.80		2.832	47.14		2.832	53.77
ARCTIC			**0.687**	**0.687**	**12.56**	**0.765**	**0.765**	**13.78**	**0.021**	**0.021**	**0.44**		**0.687**	**0.687**	**11.60**	**0.765**	**0.765**	**12.74**	**0.021**	**0.021**	**0.40**
Ice Gouging			0.5411	0.5411	9.89	0.6763	0.6763	12.18					0.5411	0.5411	9.13	0.6763	0.6763	11.26			
Strudel Scour			0.0645	0.0645	1.18								0.0645	0.0645	1.09						
Upheaval Buckling			0.0129	0.0129	0.24	0.0129	0.0129	0.23	0.0129	0.0129	0.27		0.0129	0.0129	0.22	0.0129	0.0129	0.21	0.0129	0.0129	0.24
Thaw Settlement			0.0065	0.0065	0.12	0.0065	0.0065	0.12	0.0065	0.0065	0.13		0.0065	0.0065	0.11	0.0065	0.0065	0.11	0.0065	0.0065	0.12
Other			0.0625	0.0625	1.14	0.0696	0.0696	1.25	0.0019	0.0019	0.04		0.0625	0.0625	1.05	0.0696	0.0696	1.16	0.0019	0.0019	0.04
UNKNOWN	**5.71**	**0.345**		**0.345**	**6.30**		**0.345**	**6.21**		**0.345**	**7.17**	**0.378**		**0.378**	**6.37**		**0.378**	**6.29**		**0.378**	**7.17**
TOTALS	**100.00**	**6.036**	**(0.564)**	**5.472**	**100.00**	**(0.483)**	**5.553**	**100.00**	**(1.223)**	**4.813**	**100.00**	**6.608**	**(0.683)**	**5.925**	**100.00**	**(0.601)**	**6.007**	**100.00**	**(1.341)**	**5.267**	**100.00**

Table 4.7
Arctic Pipeline Medium Spill (100-999 bbl) Frequencies
(App. Table 2.4)

CAUSE CLASSIFICATION	HIST. DISTRIBUTION %	Pipeline Diameter <= 10"										Pipeline Diameter > 10"									
			Shallow			Medium			Deep				Shallow			Medium			Deep		
		FREQUENCY spills per 10⁵km-year	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %	FREQUENCY spills per 10⁵km-year	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %
CORROSION	**8.57**	**0.517**	**(0.238)**	**0.280**	**5.11**	**(0.238)**	**0.280**	**5.04**	**(0.238)**	**0.280**	**5.81**	**0.566**	**(0.260)**	**0.306**	**5.17**	**(0.260)**	**0.306**	**5.10**	**(0.260)**	**0.306**	**5.82**
External	2.86	0.172	(0.079)	0.093	1.70	(0.079)	0.093	1.68	(0.079)	0.093	1.94	0.189	(0.087)	0.102	1.72	(0.087)	0.102	1.70	(0.087)	0.102	1.94
Internal	5.71	0.345	(0.158)	0.187	3.41	(0.158)	0.187	3.36	(0.158)	0.187	3.88	0.378	(0.173)	0.204	3.45	(0.173)	0.204	3.40	(0.173)	0.204	3.88
THIRD PARTY IMPACT	**22.86**	**1.380**	**(0.690)**	**0.690**	**12.61**	**(0.693)**	**0.686**	**12.36**	**(0.697)**	**0.683**	**14.19**	**1.510**	**(0.755)**	**0.755**	**12.75**	**(0.759)**	**0.751**	**12.51**	**(0.763)**	**0.747**	**14.19**
Anchor Impact	20.00	1.207	(0.604)	0.604	11.03	(0.604)	0.604	10.87	(0.604)	0.604	12.54	1.322	(0.661)	0.661	11.15	(0.661)	0.661	11.00	(0.661)	0.661	12.55
Jackup Rig or Spud Barge																					
Trawl/Fishing Net	2.86	0.172	(0.086)	0.086	1.58	(0.090)	0.083	1.49	(0.093)	0.079	1.64	0.189	(0.094)	0.094	1.59	(0.098)	0.090	1.51	(0.102)	0.087	1.65
OPERATION IMPACT	**8.57**	**0.517**	**(0.145)**	**0.373**	**6.81**	**(0.145)**	**0.373**	**6.71**	**(0.145)**	**0.373**	**7.74**	**0.566**	**(0.158)**	**0.408**	**6.89**	**(0.158)**	**0.408**	**6.79**	**(0.158)**	**0.408**	**7.75**
Rig Anchoring	2.86	0.172	(0.048)	0.124	2.27	(0.048)	0.124	2.24	(0.048)	0.124	2.58	0.189	(0.053)	0.136	2.30	(0.053)	0.136	2.26	(0.053)	0.136	2.58
Work Boat Anchoring	5.71	0.345	(0.096)	0.249	4.54	(0.096)	0.249	4.47	(0.096)	0.249	5.16	0.378	(0.106)	0.272	4.59	(0.106)	0.272	4.53	(0.106)	0.272	5.17
MECHANICAL	**5.71**	**0.345**		**0.345**	**6.30**		**0.345**	**6.21**		**0.345**	**7.17**	**0.378**		**0.378**	**6.37**		**0.378**	**6.29**		**0.378**	**7.17**
Connection Failure	2.86	0.172		0.172	3.15		0.172	3.11		0.172	3.58	0.189		0.189	3.19		0.189	3.14		0.189	3.58
Material Failure	2.86	0.172		0.172	3.15		0.172	3.11		0.172	3.58	0.189		0.189	3.19		0.189	3.14		0.189	3.58
NATURAL HAZARD	**48.57**	**2.932**	**(0.180)**	**2.752**	**50.30**	**(0.172)**	**2.759**	**49.69**	**(0.165)**	**2.767**	**57.48**	**3.209**	**(0.197)**	**3.013**	**50.85**	**(0.189)**	**3.021**	**50.29**	**(0.181)**	**3.028**	**57.50**
Mud Slide	5.71	0.345	(0.180)	0.165	3.02	(0.172)	0.172	3.11	(0.165)	0.180	3.73	0.378	(0.197)	0.181	3.05	(0.189)	0.189	3.14	(0.181)	0.197	3.73
Storm/ Hurricane	42.86	2.587		2.587	47.28		2.587	46.58		2.587	53.75	2.832		2.832	47.80		2.832	47.14		2.832	53.77
ARCTIC			**0.687**	**0.687**	**12.56**	**0.765**	**0.765**	**13.78**	**0.021**	**0.021**	**0.44**		**0.687**	**0.687**	**11.60**	**0.765**	**0.765**	**12.74**	**0.021**	**0.021**	**0.40**
Ice Gouging			0.5411	0.5411	9.89	0.6763	0.6763	12.18					0.5411	0.5411	9.13	0.6763	0.6763	11.26			
Strudel Scour			0.0645	0.0645	1.18								0.0645	0.0645	1.09						
Upheaval Buckling			0.0129	0.0129	0.24	0.0129	0.0129	0.23	0.0129	0.0129	0.27		0.0129	0.0129	0.22	0.0129	0.0129	0.21	0.0129	0.0129	0.24
Thaw Settlement			0.0065	0.0065	0.12	0.0065	0.0065	0.12	0.0065	0.0065	0.13		0.0065	0.0065	0.11	0.0065	0.0065	0.11	0.0065	0.0065	0.12
Other			0.0625	0.0625	1.14	0.0696	0.0696	1.25	0.0019	0.0019	0.04		0.0625	0.0625	1.05	0.0696	0.0696	1.16	0.0019	0.0019	0.04
UNKNOWN	**5.71**	**0.345**		**0.345**	**6.30**		**0.345**	**6.21**		**0.345**	**7.17**	**0.378**		**0.378**	**6.37**		**0.378**	**6.29**		**0.378**	**7.17**
TOTALS	**100.00**	**6.036**	**(0.564)**	**5.472**	**100.00**	**(0.483)**	**5.553**	**100.00**	**(1.223)**	**4.813**	**100.00**	**6.608**	**(0.683)**	**5.925**	**100.00**	**(0.601)**	**6.007**	**100.00**	**(1.341)**	**5.267**	**100.00**

Table 4.8
Arctic Pipeline Large Spill (1,000-9,999 bbl) Frequencies

(App. Table 2.5)

CAUSE CLASSIFICATION	HIST. DISTRIBUTION %	Pipeline Diameter <= 10"										Pipeline Diameter > 10"									
			Shallow			Medium			Deep				Shallow			Medium			Deep		
		FREQUENCY spills per 10^5km-year	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %	FREQUENCY spills per 10^5km-year	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %
CORROSION	**6.67**	**0.352**	**(0.162)**	**0.190**	**4.33**	**(0.162)**	**0.190**	**4.16**	**(0.162)**	**0.190**	**7.04**	**0.551**	**(0.253)**	**0.298**	**5.04**	**(0.253)**	**0.298**	**4.90**	**(0.253)**	**0.298**	**7.09**
External																					
Internal	6.67	0.352	(0.162)	0.190	4.33	(0.162)	0.190	4.16	(0.162)	0.190	7.04	0.551	(0.253)	0.298	5.04	(0.253)	0.298	4.90	(0.253)	0.298	7.09
THIRD PARTY IMPACT	**66.67**	**3.521**	**(1.761)**	**1.761**	**39.99**	**(1.790)**	**1.731**	**37.85**	**(1.818)**	**1.703**	**62.91**	**5.506**	**(2.753)**	**2.753**	**46.54**	**(2.799)**	**2.707**	**44.56**	**(2.843)**	**2.663**	**63.36**
Anchor Impact	33.33	1.761	(0.880)	0.880	20.00	(0.880)	0.880	19.24	(0.880)	0.880	32.52	2.753	(1.377)	1.377	23.27	(1.377)	1.377	22.66	(1.377)	1.377	32.75
Jackup Rig or Spud Barge	6.67	0.352	(0.176)	0.176	4.00	(0.176)	0.176	3.85	(0.176)	0.176	6.50	0.551	(0.275)	0.275	4.65	(0.275)	0.275	4.53	(0.275)	0.275	6.55
Trawl/Fishing Net	26.67	1.408	(0.704)	0.704	16.00	(0.733)	0.675	14.76	(0.762)	0.647	23.89	2.203	(1.101)	1.101	18.62	(1.147)	1.056	17.37	(1.191)	1.011	24.06
OPERATION IMPACT	**6.67**	**0.352**	**(0.098)**	**0.254**	**5.76**	**(0.098)**	**0.254**	**5.55**	**(0.098)**	**0.254**	**9.37**	**0.551**	**(0.154)**	**0.397**	**6.71**	**(0.154)**	**0.397**	**6.53**	**(0.154)**	**0.397**	**9.44**
Rig Anchoring																					
Work Boat Anchoring	6.67	0.352	(0.098)	0.254	5.76	(0.098)	0.254	5.55	(0.098)	0.254	9.37	0.551	(0.154)	0.397	6.71	(0.154)	0.397	6.53	(0.154)	0.397	9.44
MECHANICAL																					
Connection Failure																					
Material Failure																					
NATURAL HAZARD	**20.00**	**1.056**	**(0.577)**	**0.479**	**10.88**	**(0.570)**	**0.486**	**10.63**	**(0.550)**	**0.507**	**18.72**	**1.652**	**(0.903)**	**0.749**	**12.66**	**(0.892)**	**0.760**	**12.51**	**(0.860)**	**0.792**	**18.85**
Mud Slide	6.67	0.352	(0.183)	0.169	3.83	(0.176)	0.176	3.85	(0.169)	0.183	6.77	0.551	(0.287)	0.264	4.46	(0.275)	0.275	4.53	(0.264)	0.287	6.82
Storm/ Hurricane	13.33	0.704	(0.394)	0.310	7.04	(0.394)	0.310	6.78	(0.381)	0.323	11.94	1.101	(0.616)	0.485	8.20	(0.616)	0.485	7.98	(0.596)	0.506	12.03
ARCTIC			**1.719**	**1.719**	**39.04**	**1.913**	**1.913**	**41.82**	**0.053**	**0.053**	**1.97**		**1.719**	**1.719**	**29.05**	**1.913**	**1.913**	**31.49**	**0.053**	**0.053**	**1.27**
Ice Gouging			1.3527	1.3527	30.73	1.6908	1.6908	36.96					1.3527	1.3527	22.87	1.6908	1.6908	27.83			
Strudel Scour			0.1613	0.1613	3.66								0.1613	0.1613	2.73						
Upheaval Buckling			0.0323	0.0323	0.73	0.0323	0.0323	0.71	0.0323	0.0323	1.19		0.0323	0.0323	0.55	0.0323	0.0323	0.53	0.0323	0.0323	0.77
Thaw Settlement			0.0161	0.0161	0.37	0.0161	0.0161	0.35	0.0161	0.0161	0.60		0.0161	0.0161	0.27	0.0161	0.0161	0.27	0.0161	0.0161	0.38
Other			0.1562	0.1562	3.55	0.1739	0.1739	3.80	0.0048	0.0048	0.18		0.1562	0.1562	2.64	0.1739	0.1739	2.86	0.0048	0.0048	0.12
UNKNOWN																					
TOTALS	**100.00**	**5.282**	**(0.880)**	**4.402**	**100.00**	**(0.707)**	**4.575**	**100.00**	**(2.575)**	**2.707**	**100.00**	**8.259**	**(2.344)**	**5.915**	**100.00**	**(2.184)**	**6.075**	**100.00**	**(4.056)**	**4.203**	**100.00**

Table 4.9
Arctic Pipeline Huge Spill (>= 10,000 bbl) Frequencies
(App. Table 2.6)

CAUSE CLASSIFICATION	HIST. DISTRIBUTION %	*Pipeline Diameter <= 10"*										*Pipeline Diameter > 10"*									
			Shallow			Medium			Deep				Shallow			Medium			Deep		
		FREQUENCY spills per 10⁵km-year	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %	FREQUENCY spills per 10⁵km-year	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %
CORROSION	**6.67**	**0.050**	**(0.023)**	**0.027**	**3.74**	**(0.023)**	**0.027**	**3.57**	**(0.023)**	**0.027**	**6.98**	**0.220**	**(0.101)**	**0.119**	**5.89**	**(0.101)**	**0.119**	**5.82**	**(0.101)**	**0.119**	**7.13**
External																					
Internal	6.67	0.050	(0.023)	0.027	3.74	(0.023)	0.027	3.57	(0.023)	0.027	6.98	0.220	(0.101)	0.119	5.89	(0.101)	0.119	5.82	(0.101)	0.119	7.13
THIRD PARTY IMPACT	**66.67**	**0.503**	**(0.252)**	**0.252**	**34.59**	**(0.256)**	**0.247**	**32.42**	**(0.260)**	**0.243**	**62.42**	**2.203**	**(1.101)**	**1.101**	**54.45**	**(1.120)**	**1.083**	**52.89**	**(1.137)**	**1.065**	**63.76**
Anchor Impact	33.33	0.252	(0.126)	0.126	17.30	(0.126)	0.126	16.48	(0.126)	0.126	32.27	1.101	(0.551)	0.551	27.23	(0.551)	0.551	26.89	(0.551)	0.551	32.96
Jackup Rig or Spud Barge	6.67	0.050	(0.025)	0.025	3.46	(0.025)	0.025	3.30	(0.025)	0.025	6.45	0.220	(0.110)	0.110	5.45	(0.110)	0.110	5.38	(0.110)	0.110	6.59
Trawl/Fishing Net	26.67	0.201	(0.101)	0.101	13.84	(0.105)	0.096	12.64	(0.109)	0.092	23.70	0.881	(0.441)	0.441	21.78	(0.459)	0.422	20.62	(0.477)	0.404	24.21
OPERATION IMPACT	**6.67**	**0.050**	**(0.014)**	**0.036**	**4.98**	**(0.014)**	**0.036**	**4.75**	**(0.014)**	**0.036**	**9.30**	**0.220**	**(0.062)**	**0.159**	**7.85**	**(0.062)**	**0.159**	**7.75**	**(0.062)**	**0.159**	**9.50**
Rig Anchoring																					
Work Boat Anchoring	6.67	0.050	(0.014)	0.036	4.98	(0.014)	0.036	4.75	(0.014)	0.036	9.30	0.220	(0.062)	0.159	7.85	(0.062)	0.159	7.75	(0.062)	0.159	9.50
MECHANICAL																					
Connection Failure																					
Material Failure																					
NATURAL HAZARD	**20.00**	**0.151**	**(0.082)**	**0.068**	**9.41**	**(0.081)**	**0.069**	**9.10**	**(0.079)**	**0.072**	**18.57**	**0.661**	**(0.361)**	**0.300**	**14.81**	**(0.357)**	**0.304**	**14.85**	**(0.344)**	**0.317**	**18.97**
Mud Slide	6.67	0.050	(0.026)	0.024	3.32	(0.025)	0.025	3.30	(0.024)	0.026	6.72	0.220	(0.115)	0.106	5.22	(0.110)	0.110	5.38	(0.106)	0.115	6.87
Storm/ Hurricane	13.33	0.101	(0.056)	0.044	6.09	(0.056)	0.044	5.81	(0.054)	0.046	11.85	0.441	(0.247)	0.194	9.59	(0.247)	0.194	9.47	(0.238)	0.202	12.10
ARCTIC			**0.344**	**0.344**	**47.27**	**0.383**	**0.383**	**50.16**	**0.011**	**0.011**	**2.73**		**0.344**	**0.344**	**17.00**	**0.383**	**0.383**	**18.69**	**0.011**	**0.011**	**0.64**
Ice Gouging			0.2705	0.2705	37.21	0.3382	0.3382	44.33					0.2705	0.2705	13.38	0.3382	0.3382	16.52			
Strudel Scour			0.0323	0.0323	4.44								0.0323	0.0323	1.59						
Upheaval Buckling			0.0065	0.0065	0.89	0.0065	0.0065	0.85	0.0065	0.0065	1.66		0.0065	0.0065	0.32	0.0065	0.0065	0.32	0.0065	0.0065	0.39
Thaw Settlement			0.0032	0.0032	0.44	0.0032	0.0032	0.42	0.0032	0.0032	0.83		0.0032	0.0032	0.16	0.0032	0.0032	0.16	0.0032	0.0032	0.19
Other			0.0312	0.0312	4.30	0.0348	0.0348	4.56	0.0010	0.0010	0.25		0.0312	0.0312	1.55	0.0348	0.0348	1.70	0.0010	0.0010	0.06
UNKNOWN																					
TOTALS	**100.00**	**0.755**	**(0.027)**	**0.727**	**100.00**	**0.008**	**0.763**	**100.00**	**(0.365)**	**0.390**	**100.00**	**3.304**	**(1.281)**	**2.022**	**100.00**	**(1.256)**	**2.048**	**100.00**	**(1.633)**	**1.671**	**100.00**

Table 4.10
Arctic Pipeline Spill Frequencies Expected Value Summary
(App. Table 2.2A)

Pipeline Spill Size	Pipeline Diameter <=10"				Pipeline Diameter >10"			
	Historical Frequency spills per 10^5km-year	Arctic Frequency			Historical Frequency spills per 10^5km-year	Arctic Frequency		
		Shallow	Medium	Deep		Shallow	Medium	Deep
SMALL SPILLS 50-99 bbl	**6.036**	5.472	5.553	4.813	**6.608**	5.925	6.007	5.267
MEDIUM SPILLS 100-999 bbl	**10.563**	9.060	9.144	8.407	**14.867**	12.472	12.558	11.823
LARGE SPILLS 1000-9999 bbl	**5.282**	4.402	4.575	2.707	**8.259**	5.915	6.075	4.203
HUGE SPILLS >=10000 bbl	**0.755**	0.727	0.763	0.390	**3.304**	2.022	2.048	1.671

4.4 Platform Fault Tree Analysis

4.4.1 Arctic Platform Spill Causal Frequency Distributions

Table 4.11 summarizes the variations in the modified and unique Arctic effect inputs for platforms. As for pipeline unique effects, both the Triangular Distribution expected and modal values are given.

The first three modified cause classifications – equipment failure, human error, and tank failure – were reduced by 20 to 30% primarily as a result of the state-of-the-art engineering, construction, and operational standards and practices expected. Due to the extremely low traffic density, as for the case of pipelines, the ship collision cause has been reduced by 50%. As before, storms tend to be less severe in the Arctic, and certainly during the ice season would have limited impact on the facility. And hurricanes are so far not known to occur in the Beaufort, so a validation of 80% was used.

Unique effects are also included. 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 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.

Changes in frequency distribution attributable to Arctic effects were calculated using the secondary effect probability distribution, as was done for pipelines. Table 4.12 summarizes the principal distribution parameters for both the Arctic modified and Arctic unique effect distributions.

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 at least 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 4.13 and 4.14 show the frequency calculations for platforms for small and medium and large and huge spill sizes, respectively. Table 4.15 summarizes the historical and derived Arctic expected values of platform spill frequencies.

Table 4.11
Platform Arctic Effect Derivation Summary
(App. Table 2.7)

CAUSE CLASSIFICATION	Spill Size	Historical Expected Frequency Change %			Reason
		Shallow	Medium	Deep	
EQUIPMENT FAILURE	**All**				
Process Equipment	**All**	(30)	(30)	(30)	State of the art now, High QC, High Inspection and Maintenance Requirements
Transfer Hose	**All**	(30)	(30)	(30)	State of the art now, High QC, High Inspection and Maintenance Requirements
Incorrect Operation	**All**	(30)	(30)	(30)	State of the art now, High QC, High Inspection and Maintenance Requirements
HUMAN ERROR	**All**	(20)	(20)	(20)	More qualified personnel - training, education, but colder
TANK FAILURE	**All**	(30)	(30)	(30)	State of the art now, High QC, High Inspection and Maintenance Requirements
SHIP COLLISION	**All**	(50)	(50)	(50)	Very low traffic density.
WEATHER	**All**	20	20	20	Cold Temperatures, cycling
HURRICANE	**All**	(80)	(80)	(70)	Less severe storms. More intensity in deep water.
OTHER	**All**				
		Freq. Increment per 10^4 well-year			
		Expected	**Expected**	**Expected**	
		Mode	**Mode**	**Mode**	
ARCTIC					
Ice Force	**SM**	0.1447	0.2170	0.3256	Assumed 10,000 year return period ice force causes spill 4% of occurrences (96% reliability). 85% of the spills are SM.
		0.0340	0.0510	0.0765	
	LH	0.0255	0.0383	0.0575	
		0.0060	0.0090	0.0135	
Facility Low Temperature	**SM**	0.0986	0.0986	0.0986	Assumed fraction of Historical Equipment Failure release frequency with 6% for SM and 1% for LH spill sizes.
		0.0986	0.0986	0.0986	
	LH	0.0164	0.0164	0.0164	
		0.0164	0.0164	0.0164	
Other Arctic	**SM**	0.0242	0.0315	0.0423	10% of sum of above.
		0.0133	0.0150	0.0175	
	LH	0.0042	0.0055	0.0074	
		0.0022	0.0025	0.0030	

Table 4.12
Platform Arctic Effect Distribution Derivation Summary
(App. Table 2.8)

CAUSE CLASSIFICATION	Spill Size	Shallow			Medium			Deep		
		Frequency Change %								
		Min	Mode	Max	Min	Mode	Max	Min	Mode	Max
EQUIPMENT FAILURE	**All**									
~ Process Equipment	**All**	(60)	(30)	(10)	(60)	(30)	(10)	(60)	(30)	(10)
~ Transfer Hose	**All**	(60)	(30)	(10)	(60)	(30)	(10)	(60)	(30)	(10)
~ Incorrect Operation	**All**	(60)	(30)	(10)	(60)	(30)	(10)	(60)	(30)	(10)
HUMAN ERROR	**All**	(60)	(20)	(10)	(60)	(20)	(10)	(60)	(20)	(10)
TANK FAILURE	**All**	(60)	(30)	(10)	(60)	(30)	(10)	(60)	(30)	(10)
SHIP COLLISION	**All**	(60)	(50)	(10)	(60)	(50)	(10)	(60)	(50)	(10)
WEATHER	**All**	10	20	30	10	20	30	10	20	30
HURRICANE	**All**	(90)	(80)	(10)	(90)	(80)	(10)	(90)	(70)	(10)
OTHER	**All**									
Frequency Increment per 10^4 well-year										
ARCTIC										
Ice Force	**SM**	0.003	0.034	0.340	0.005	0.051	0.510	0.008	0.077	0.765
	LH	0.001	0.006	0.060	0.001	0.009	0.090	0.001	0.014	0.135
Facility Low Temperature	**SM**	0.049	0.099	0.148	0.049	0.099	0.148	0.049	0.099	0.148
	LH	0.008	0.016	0.025	0.008	0.016	0.025	0.008	0.016	0.025
Other Arctic	**SM**	0.005	0.013	0.049	0.005	0.015	0.066	0.006	0.018	0.091
	LH	0.001	0.002	0.008	0.001	0.003	0.011	0.001	0.003	0.016

Note: All Values per 10000 well-years

Platform Spill

	SM 50-999 bbl	LH =>1000 bbl	Spill Size
H	4.601	0.481	Historical Frequency
S	3.053	0.390	Shallow Water Depth Frequency
M	3.686	0.404	Medium Water Depth Frequency
D	3.809	0.429	Deep Water Depth Frequency

EQUIPMENT FAILURE

	SM	LH
H	2.403	0.000
S	1.587	0.000
M	1.587	0.000
D	1.587	0.000

Process Equipment

	SM	LH
H	0.961	0.000
S	0.635	0.000
M	0.635	0.000
D	0.635	0.000

Transfer Hose

	SM	LH
H	0.824	0.000
S	0.544	0.000
M	0.544	0.000
D	0.544	0.000

Incorrect Operation

	SM	LH
H	0.618	0.000
S	0.408	0.000
M	0.408	0.000
D	0.408	0.000

HUMAN ERROR

	SM	LH
H	0.824	0.000
S	0.008	0.000
M	0.561	0.000
D	0.561	0.000

TANK FAILURE

	SM	LH
H	0.137	0.069
S	0.091	0.045
M	0.091	0.045
D	0.091	0.045

SHIP COLLISION

	SM	LH
H	0.343	0.069
S	0.213	0.043
M	0.213	0.043
D	0.213	0.043

WHEATHER

	SM	LH
H	0.549	0.137
S	0.659	0.165
M	0.659	0.165
D	0.659	0.165

HURRICANE

	SM	LH
H	0.206	0.206
S	0.091	0.091
M	0.091	0.091
D	0.095	0.095

OTHER

	SM	LH
H	0.137	0.000
S	0.137	0.000
M	0.137	0.000
D	0.137	0.000

ARCTIC

	SM	LH
H	0.000	0.000
S	0.268	0.046
M	0.347	0.060
D	0.466	0.081

Ice Force

	SM	LH
H	0.000	0.000
S	0.145	0.026
M	0.217	0.038
D	0.326	0.057

Facility Low Temperature

	SM	LH
H	0.000	0.000
S	0.099	0.016
M	0.099	0.016
D	0.099	0.016

Other Arctic

	SM	LH
H	0.000	0.000
S	0.024	0.004
M	0.031	0.005
D	0.042	0.007

Figure 4.5
Spill Frequencies Platform Fault Tree
(Appendix Figure 2.5)

Table 4.13
Arctic Platform Small and Medium Spill Frequencies
(App. Table 2.9)

CAUSE CLASSIFICATION	HIST. DISTRIBUTION %	SMALL AND MEDIUM SPILLS 50-999 bbl									
			Shallow			Medium			Deep		
		FREQUENCY spills per 10^4well-year	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %
EQUIPMENT FAILURE	**52.24**	**2.403**	**(0.816)**	**1.587**	**51.98**	**(0.816)**	**1.587**	**43.06**	**(0.816)**	**1.587**	**41.67**
Process Equipment	**20.90**	**0.961**	**(0.327)**	**0.635**	**20.79**	**(0.327)**	**0.635**	**17.23**	**(0.327)**	**0.635**	**16.67**
Transfer Hose	**17.91**	**0.824**	**(0.280)**	**0.544**	**17.82**	**(0.280)**	**0.544**	**14.76**	**(0.280)**	**0.544**	**14.29**
Incorrect Operation	**13.43**	**0.618**	**(0.210)**	**0.408**	**13.37**	**(0.210)**	**0.408**	**11.07**	**(0.210)**	**0.408**	**10.72**
HUMAN ERROR	**17.91**	**0.824**	**(0.816)**	**0.008**	**0.25**	**(0.263)**	**0.561**	**15.21**	**(0.263)**	**0.561**	**14.72**
TANK FAILURE	**2.99**	**0.137**	**(0.047)**	**0.091**	**2.97**	**(0.047)**	**0.091**	**2.46**	**(0.047)**	**0.091**	**2.38**
SHIP COLLISION	**7.46**	**0.343**	**(0.131)**	**0.213**	**6.97**	**(0.131)**	**0.213**	**5.77**	**(0.131)**	**0.213**	**5.58**
WEATHER	**11.94**	**0.549**	**0.110**	**0.659**	**21.59**	**0.110**	**0.659**	**17.89**	**0.110**	**0.659**	**17.31**
HURRICANE	**4.48**	**0.206**	**(0.115)**	**0.091**	**2.97**	**(0.115)**	**0.091**	**2.46**	**(0.111)**	**0.095**	**2.48**
OTHER	**2.99**	**0.137**		**0.137**	**4.50**		**0.137**	**3.73**		**0.137**	**3.61**
ARCTIC			**0.268**	**0.268**	**8.76**	**0.347**	**0.347**	**9.42**	**0.466**	**0.466**	**12.25**
Ice Force			0.145	0.145	4.74	0.217	0.217	5.89	0.326	0.326	8.55
Facility Low Temperature			0.099	0.099	3.23	0.099	0.099	2.68	0.099	0.099	2.59
Other Arctic			0.024	0.024	0.79	0.031	0.031	0.85	0.042	0.042	1.11
TOTALS	**100.00**	**4.601**	**(1.548)**	**3.053**	**100.00**	**(0.915)**	**3.686**	**100.00**	**(0.792)**	**3.809**	**100.00**

Table 4.14
Arctic Platform Large and Huge Spill Frequencies
(App. Table 2.10)

CAUSE CLASSIFICATION	HIST. DISTRIBUTION %	SMALL AND MEDIUM SPILLS 50-999 bbl									
			Shallow			Medium			Deep		
		FREQUENCY spills per 10^4well-year	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %	Frequency Change	New Frequency	New Distribution %
EQUIPMENT FAILURE											
Process Equipment											
Transfer Hose											
Incorrect Operation											
HUMAN ERROR											
TANK FAILURE	**14.29**	**0.069**	**(0.023)**	**0.045**	**11.64**	**(0.023)**	**0.045**	**11.24**	**(0.023)**	**0.045**	**10.58**
SHIP COLLISION	**14.29**	**0.069**	**(0.026)**	**0.043**	**10.92**	**(0.026)**	**0.043**	**10.54**	**(0.026)**	**0.043**	**9.93**
WEATHER	**28.57**	**0.137**	**0.027**	**0.165**	**42.31**	**0.027**	**0.165**	**40.83**	**0.027**	**0.165**	**38.46**
HURRICANE	**42.86**	**0.206**	**(0.115)**	**0.091**	**23.29**	**(0.115)**	**0.091**	**22.48**	**(0.111)**	**0.095**	**22.07**
OTHER											
ARCTIC			**0.046**	**0.046**	**11.85**	**0.060**	**0.060**	**14.91**	**0.081**	**0.081**	**18.96**
Ice Force			0.026	0.026	6.55	0.038	0.038	9.49	0.057	0.057	13.41
Facility Low Temperature			0.016	0.016	4.22	0.016	0.016	4.07	0.016	0.016	3.84
Other Arctic			0.004	0.004	1.07	0.005	0.005	1.35	0.007	0.007	1.72
TOTALS	**100.00**	**0.481**	**(0.091)**	**0.390**	**100.00**	**(0.077)**	**0.404**	**100.00**	**(0.052)**	**0.429**	**100.00**

Table 4.15
Arctic Platforms Spill Frequency Expected Value Summary
(App. Table 2.8A)

Platform Spill Size	Historical Frequency spills per 10^4 well-year	Arctic Frequency		
		Shallow	Medium	Deep
SMALL AND MEDIUM SPILLS 50-999 bbl	**4.601**	3.053	3.686	3.809
LARGE AND HUGE SPILLS >=1,000 bbl	**0.481**	0.390	0.404	0.429

4.5 Blowout Frequency Analysis

4.5.1 Well Blowout First Order Arctic Effects

The historical data, as described in Chapter 2, was modified for each well type, spill size, and water depth range, as described in Table 4.16. No Arctic unique effects were introduced for well blowouts.

4.5.2 Arctic Well Blowout Spill Frequency Calculation

Table 4.17 gives the details of the frequency calculation for well blowouts. No fault tree was required here, as only base events with no causal distributions were modeled for each case. The modifications given in Table 4.16 were applied to all three values (minimum, mode, maximum) to yield the values summarized in Table 4.17.

4.6 Spill Volume Distributions

Table 4.18 summarizes the spill volume distribution parameters for each facility type, including the expected value that was calculated utilizing a Monte Carlo calculation. The spill volume parameters were derived from the historical data as described in Section 2.7.

Table 4.16
Well Fault Tree Analysis Arctic Effect Summary
(App. Table 2.11)

SPILL SIZE	EVENT	FREQUENCY UNIT	Historical Expected Frequency Change %			Reason
			Shallow	Medium	Deep	
Small and Medium Spills 50-999 bbl	PRODUCTION WELL	spill per 10^4 well-year	(30)	(30)	(30)	State of the art now, High QC, High Inspection and Maintenance Requirements
	EXPLORATION WELL DRILLING	spill per 10^4 wells	(30)	(20)	(10)	Highly qualified drilling contractor. Better logistics support in shallow water.
	DEVELOPMENT WELL DRILLING	spill per 10^4 wells	(30)	(20)	(10)	Highly qualified drilling contractor. Better logistics support in shallow water.
Large Spills 1000-9999 bbl	PRODUCTION WELL	spill per 10^4 well-year	(30)	(30)	(30)	State of the art now, High QC, High Inspection and Maintenance Requirements
	EXPLORATION WELL DRILLING	spill per 10^4 wells	(30)	(20)	(10)	Highly qualified drilling contractor. Better logistics support in shallow water.
	DEVELOPMENT WELL DRILLING	spill per 10^4 wells	(30)	(20)	(10)	Highly qualified drilling contractor. Better logistics support in shallow water.
Spill 10000 - 149999 bbl	PRODUCTION WELL	spill per 10^4 well-year	(30)	(30)	(30)	State of the art now, High QC, High Inspection and Maintenance Requirements
	EXPLORATION WELL DRILLING	spill per 10^4 wells	(30)	(20)	(10)	Highly qualified drilling contractor. Better logistics support in shallow water.
	DEVELOPMENT WELL DRILLING	spill per 10^4 wells	(30)	(20)	(10)	Highly qualified drilling contractor. Better logistics support in shallow water.
Spill >=150000 bbl	PRODUCTION WELL	spill per 10^4 well-year	(30)	(30)	(30)	State of the art now, High QC, High Inspection and Maintenance Requirements
	EXPLORATION WELL DRILLING	spill per 10^4 wells	(30)	(20)	(10)	Highly qualified drilling contractor. Better logistics support in shallow water.
	DEVELOPMENT WELL DRILLING	spill per 10^4 wells	(30)	(20)	(10)	Highly qualified drilling contractor. Better logistics support in shallow water.

Table 4.17
Arctic Well Blowout Frequencies
(App. Table 2.12)

EVENT	FREQUENCY UNIT	HISTORICAL FREQUENCY	Shallow		Medium		Deep	
			Frequency Change	New Frequency	Frequency Change	New Frequency	Frequency Change	New Frequency
		Small and Medium Spills 50-999 bbl						
PRODUCTION WELL	spill per 10^4 well-year	0.147	-0.044	0.103	-0.044	0.103	-0.044	0.103
EXPLORATION WELL DRILLING	spill per 10^4 wells	2.262	-0.678	1.583	-0.452	1.809	-0.226	2.035
DEVELOPMENT WELL DRILLING	spill per 10^4 wells	0.692	-0.208	0.484	-0.138	0.554	-0.069	0.623
		Large Spills 1000-9999 bbl						
PRODUCTION WELL	spill per 10^4 well-year	1.026	-0.308	0.718	-0.308	0.718	-0.308	0.718
EXPLORATION WELL DRILLING	spill per 10^4 wells	15.824	-4.747	11.077	-3.165	12.659	-1.582	14.242
DEVELOPMENT WELL DRILLING	spill per 10^4 wells	4.833	-1.450	3.383	-0.967	3.867	-0.483	4.350
		Spills 10000-149999 bbl						
PRODUCTION WELL	spill per 10^4 well-year	0.440	-0.132	0.308	-0.132	0.308	-0.132	0.308
EXPLORATION WELL DRILLING	spill per 10^4 wells	6.799	-2.040	4.759	-1.360	5.439	-0.680	6.119
DEVELOPMENT WELL DRILLING	spill per 10^4 wells	2.076	-0.623	1.453	-0.415	1.661	-0.208	1.868
		Spills >=150000 bbl						
PRODUCTION WELL	spill per 10^4 well-year	0.293	-0.088	0.205	-0.088	0.205	-0.088	0.205
EXPLORATION WELL DRILLING	spill per 10^4 wells	3.936	-1.181	2.755	-0.787	3.149	-0.394	3.543
DEVELOPMENT WELL DRILLING	spill per 10^4 wells	2.076	-0.623	1.453	-0.415	1.661	-0.208	1.868

Table 4.18
Summary of Spill Size Distribution Parameters
(App. Table 2.13)

	PIPELINE SPILL VOLUMES															
Spill Size	Small Spills 50-99 bbl				Medium Spills 100-999 bbl				Large Spills 1000-9999 bbl				Huge Spills >=10000 bbl			
Spill Expectation	Low	Mode	High	Expected	Low	Mode	High	Expected	Low	Mode	High	Expected	Low	Mode	High	Expected
Pipelines Diameter 10" Spill	50	58	99	71	100	226	999	485	1000	4436	9999	5279	10000	14423	20000	14880
Pipelines Diameter 10" Spill	50	58	99	71	100	387	999	516	1000	3932	9999	5176	10000	17705	20000	15552

	PLATFORM SPILL VOLUMES							
Spill Size	Small and Medium Spills 50-999 bbl				Large and Huge Spills >=1000 bbl			
Spill Expectation	Low	Mode	High	Expected	Low	Mode	High	Expected
Platform Spill	50	158	999	452	1000	6130	10000	5631

	WELL SPILL VOLUMES															
Spill Size	Small and Med ium Spills 50-999 bbl				Large Spills 1000-9999 bbl				Spills 10000-149999 bbl				Spills >=150000 bbl			
Spill Expectation	Low	Mode	High	Expected	Low	Mode	High	Expected	Low	Mode	High	Expected	Low	Mode	High	Expected
Well Spill	50	500	999	519	1000	4500	9999	5292	10000	20000	149999	68349	150000	200000	250000	200000

CHAPTER 5

OIL SPILL OCCURRENCE INDICATOR QUANTIFICATION

5.1 Definition of Oil Spill Occurrence Indicators

Four 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.
- Life of field indicators.

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

- By scenario (three scenarios)
- By water depth (three ranges)
- By facility type (six types)
- By spill size (four sizes)
- By year for three cases:
  - High Case: 30 years (2010-2039)
  - Low Case: 25 years (2010-2034)
  - Non-Arctic High Case: 30 years (2010-2039)

For the High Case and the Non-Arctic High Case, this results in 2,160 combinations each. For the Low Case, there are 1,800 sets of spill indicators. This totals 6,120 spill indicators. In this chapter, we will summarize only the salient results of the indicators; Appendix 4 gives a full calculation printout for the Monte Carlo results used in the body of this report for each of the three cases. Further, in this chapter, results from the principal calculation steps are given only for the High Case, while the Low Case and the Non-Arctic High Case reporting is restricted to a summary of the 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 1.2, and again presented as Figure 5.1. This chapter discusses the spill occurrence indicator calculations as shown in the shaded rectangle in Figure 5.1. Previous chapters covered the balance of the items in that figure.

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 6,000), 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 6,000 combinations needs to be sampled, in this case a sampling of 6,000 iterations was carried out for each combination studied. This translates into roughly 30 million arithmetic operations to generate the Monte Carlo results.

Chapter 5

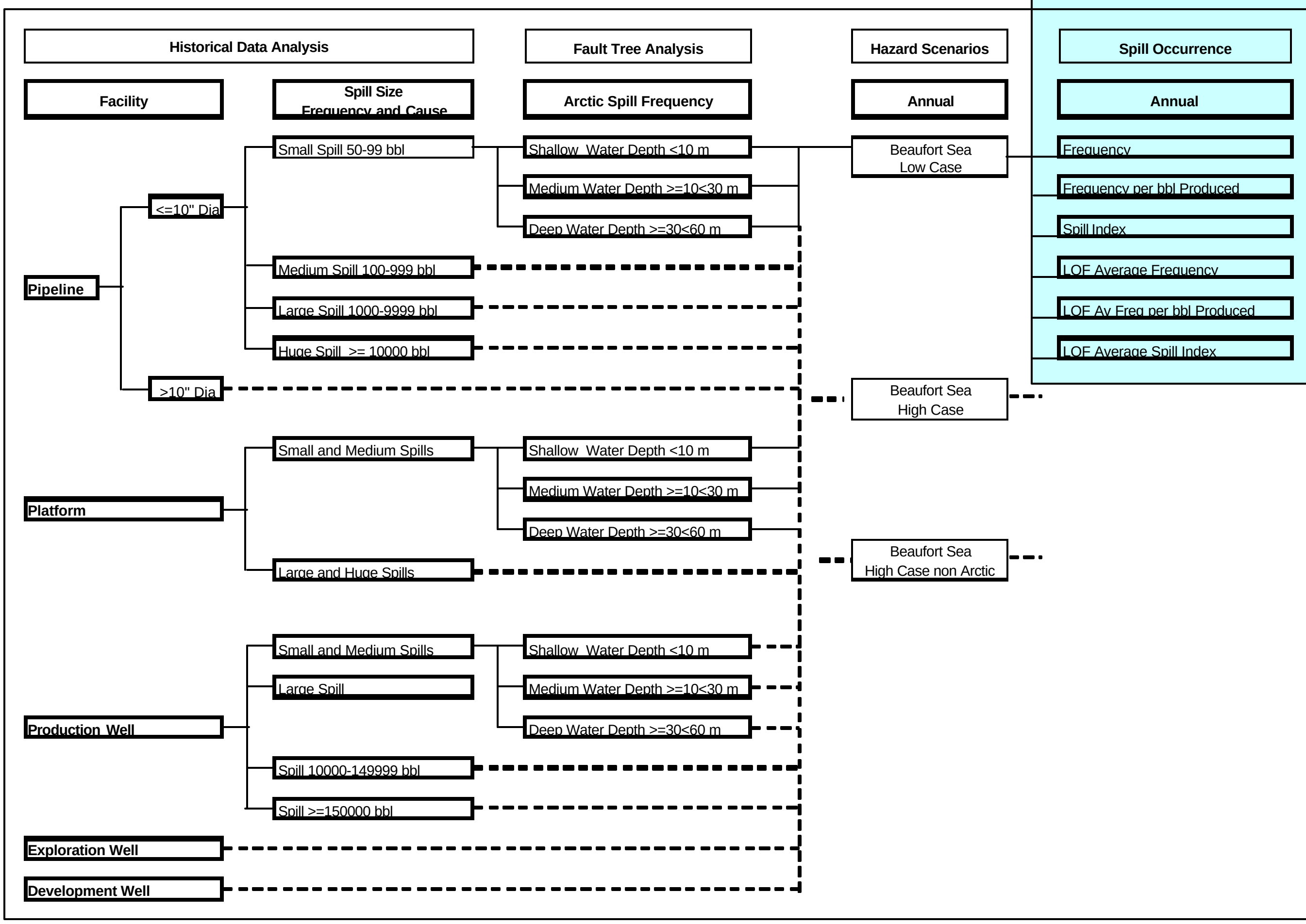


Figure 5.1
Calculation Flow Chart

5.3 Summary of Beaufort Sea Oil Spill Occurrence Indicators

5.3.1 Beaufort Sea High Case Oil Spill Occurrence Indicators

Each of the principal oil spill occurrence indicators calculated for the pipelines, platforms, and wells for the High Case for each year 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 2039 as described in Table 3.3. Further, each of the indicators has been subdivided into three segments for each year, those corresponding to spills 50-999 bbl (small and medium), spills 1,000-9,999 bbl (large), and spills >=10,000 bbl (huge). It should be noted that the spill frequency associated with each spill size is only the shaded increment shown in each of the bars. Thus, for example, for the year 2030, small and medium spills are approximately 52.0 per thousand years. Next, in that year, large spills are approximately 10.0 per thousand years, as shown in the second bar increment (i.e., 58.0 – 48.0 = 10.0). Finally, the top increment corresponds to huge spills, and is approximately 8.0 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. For years in which no production exists, the spills per barrel produced are not applicable. Clearly, the spill index is dominated by the huge spills. The spills per barrel produced continue to rise to the second final production years (2037), 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 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. The graph ordinate axes have intentionally been kept the same to facilitate comparison. 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 the Beaufort Sea development scenario, a Monte Carlo analysis was carried out for each year, with the distributed inputs described earlier. The tabular results of the Monte Carlo simulation of 5,000 iterations, 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 (2030). 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 right side central graph, for significant spills >= 1,000 bbl (large and huge), there is a 50% probability that a spill frequency will be no more than 0.65 per billion barrels produced in year 2030. This is the same as the mean value in Table 5.1

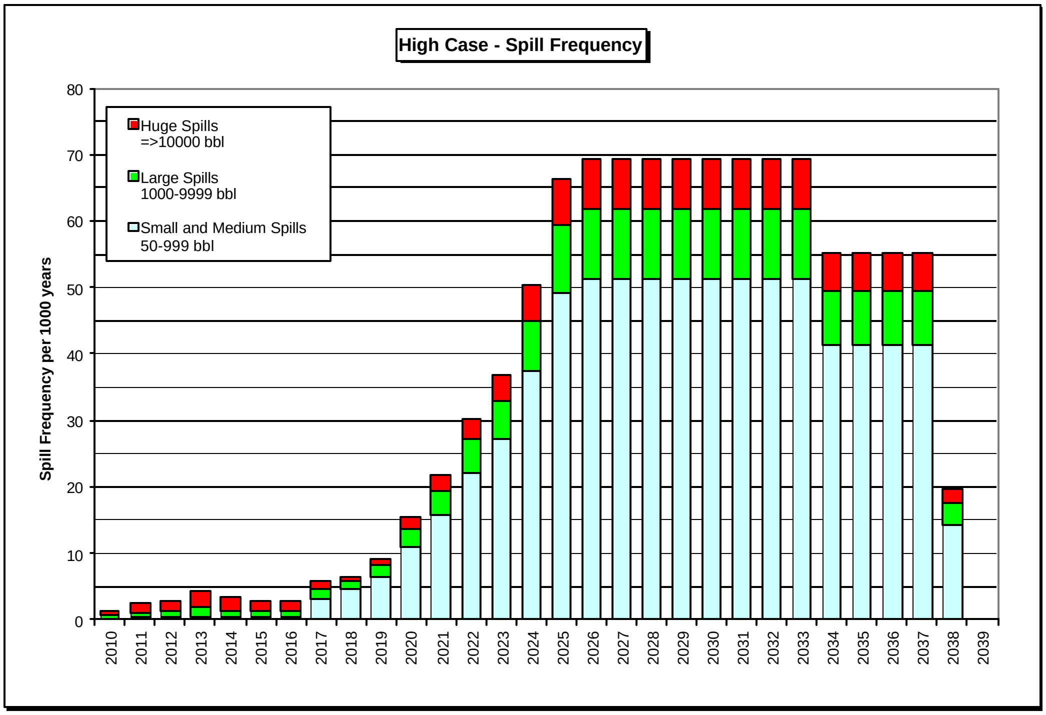


Figure 5.2
Beaufort Sea High Case Spill Frequency per 1,000 Years

(Appendix Figure 4.2.01)

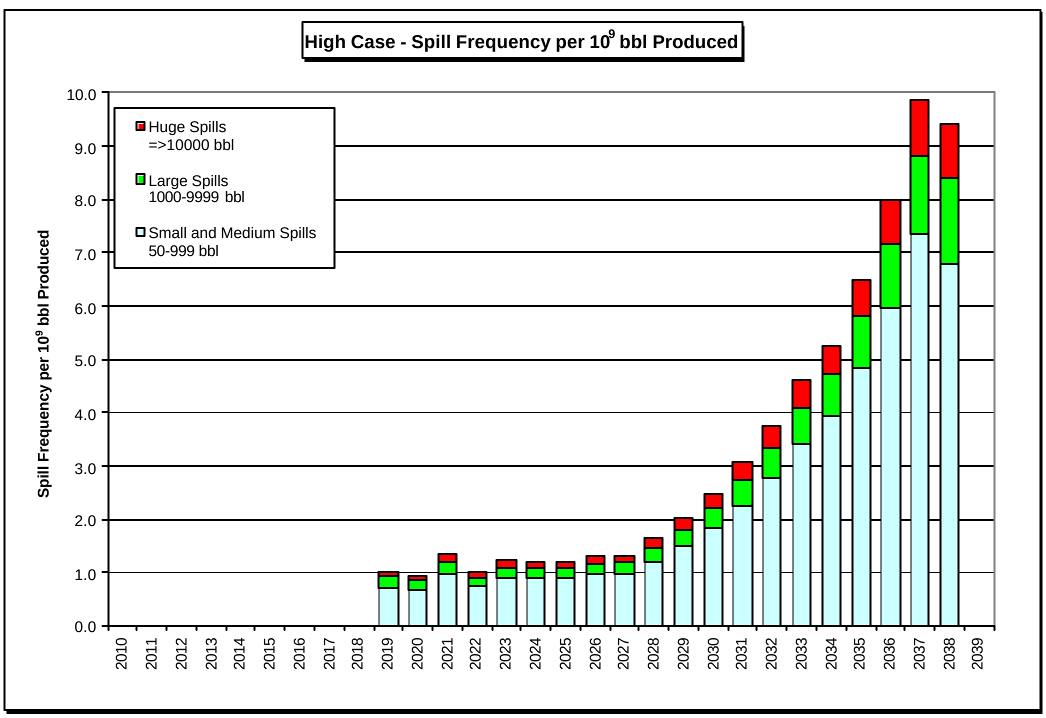


Figure 5.3
Beaufort Sea High Case Spill Frequency per 10^9 Barrels Produced
(Appendix Figure 4.2.02)

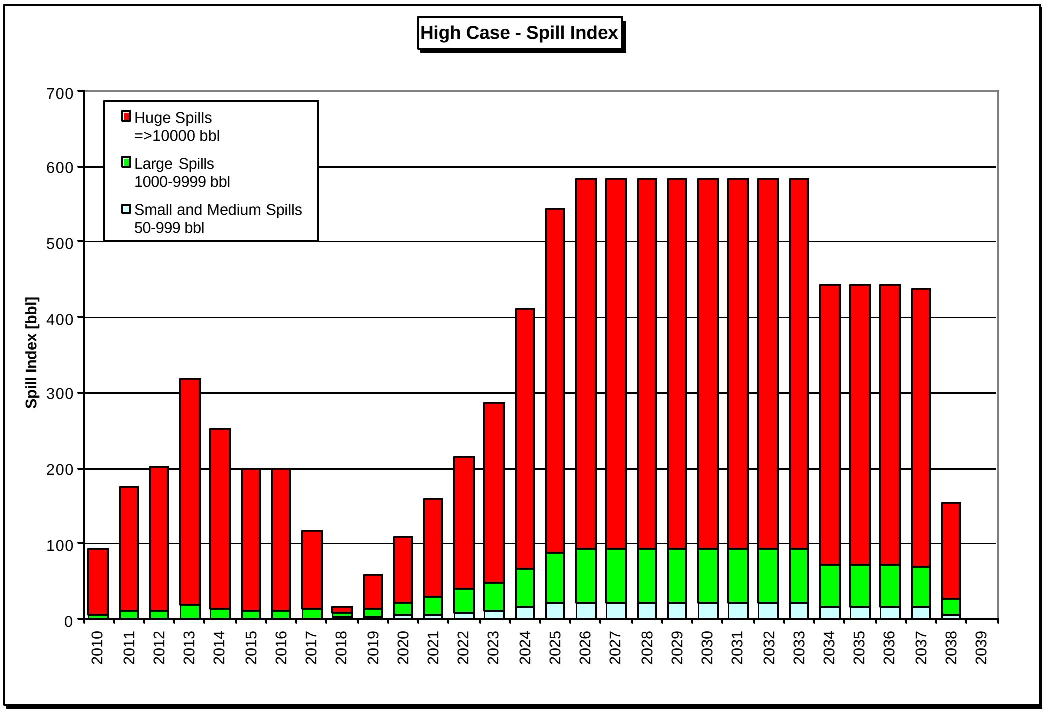


Figure 5.4
Beaufort Sea High Case Spill Index

(Appendix Figure 4.2.03)

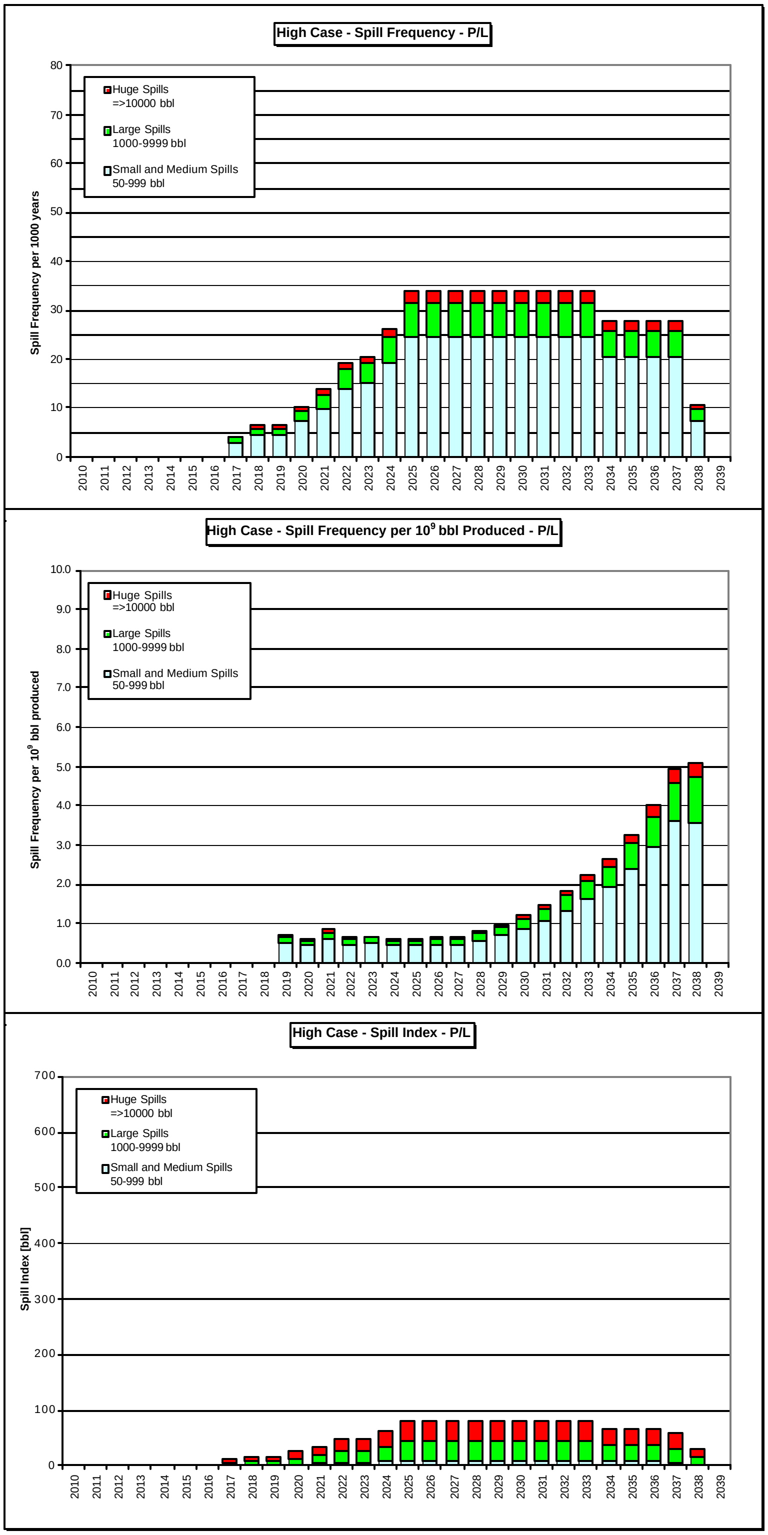


Figure 5.5
Beaufort Sea High Case Spill Indicators – Pipeline
(Appendix Figures 4.2.04, 4.2.05, 4.2.06)

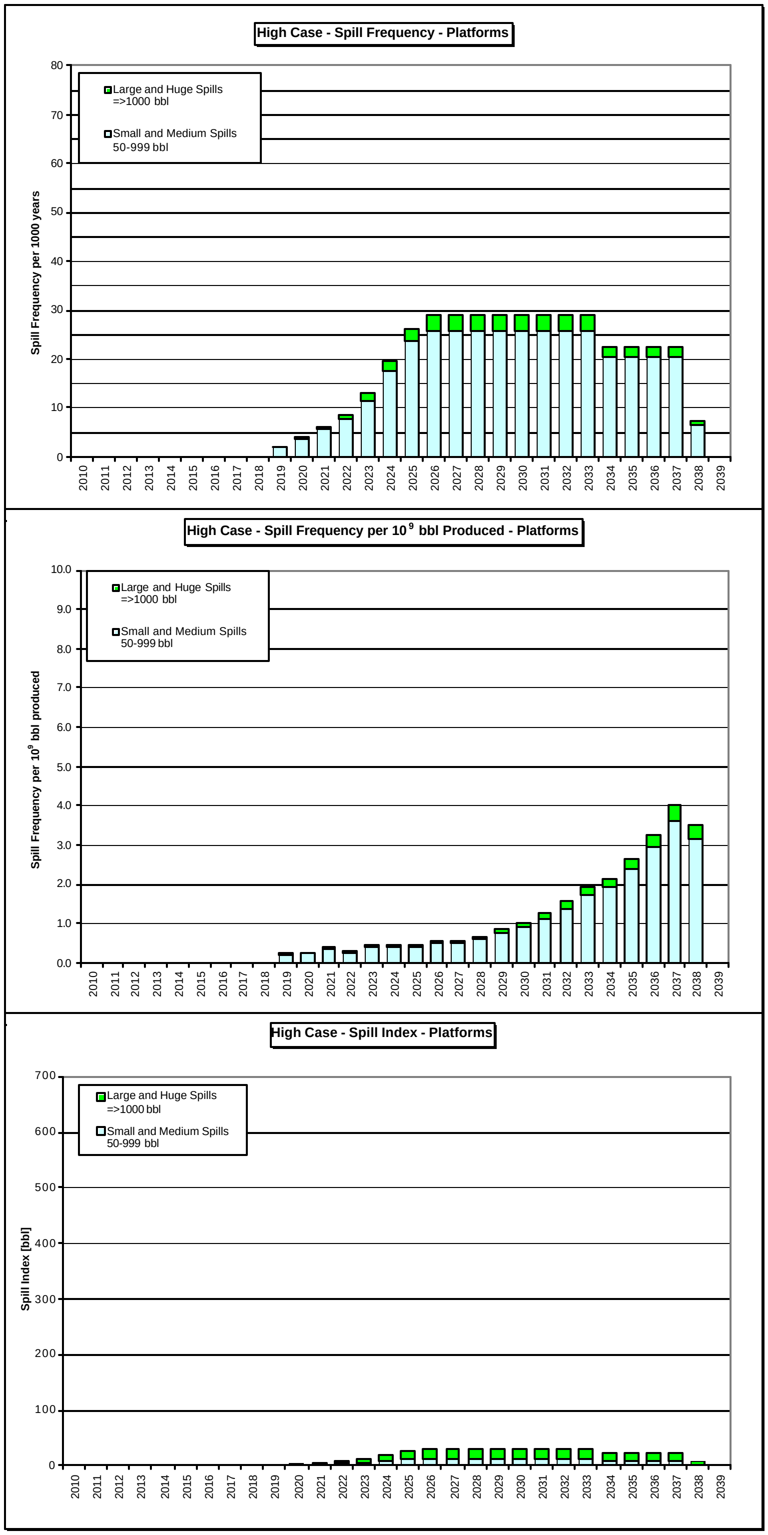


Figure 5.6
Beaufort Sea High Case Spill Indicators – Platforms
(Appendix Figures 4.2.07, 4.2.08, 4.2.09)

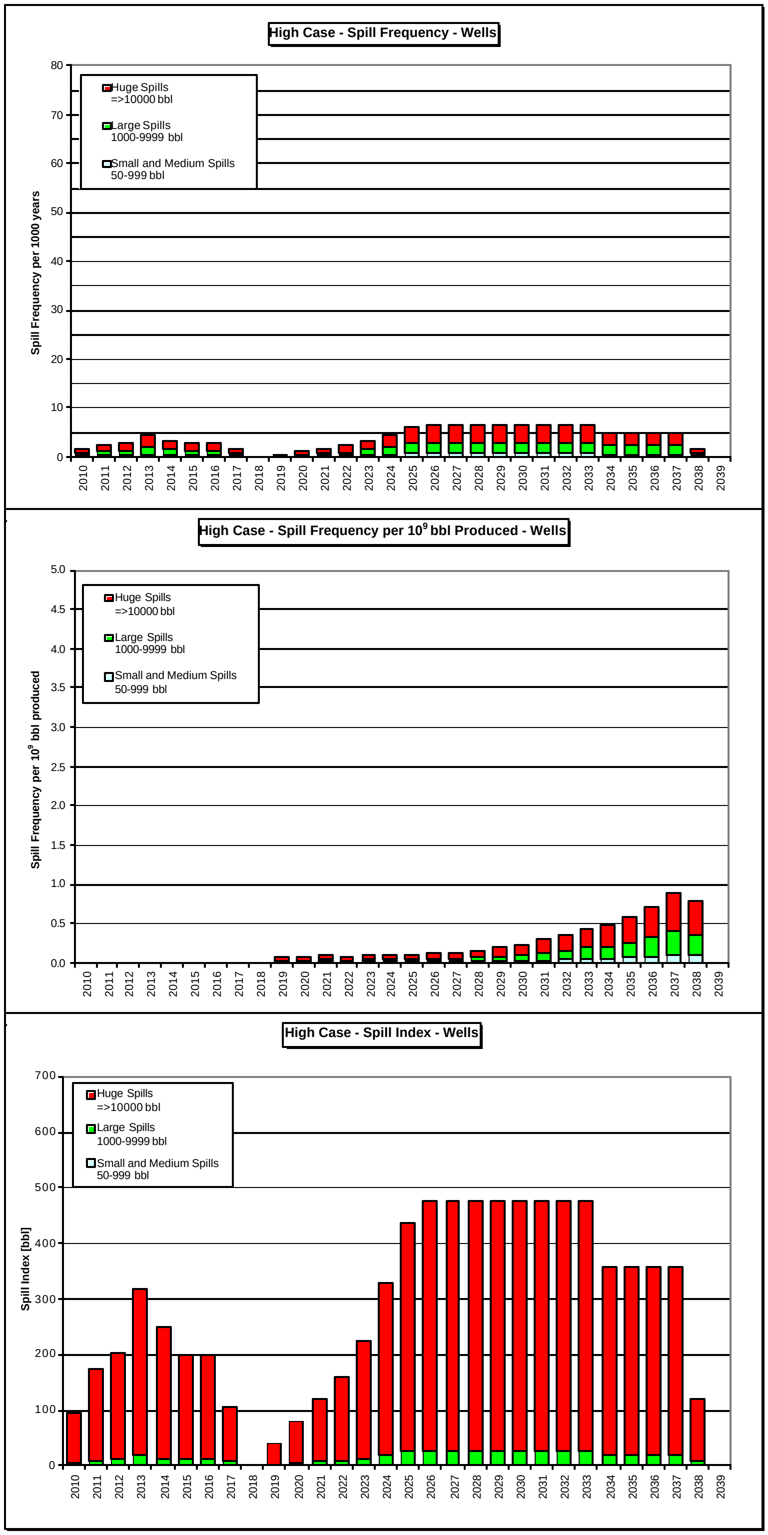


Figure 5.7
Beaufort Sea High Case Spill Indicators – Wells
(Appendix Figures 4.2.10, 4.2.11, 4.2.12)

Table 5.1
Beaufort Sea High Case Year 2030 – Monte Carlo Results
(App. Table 4.2.14)

High Case Year 2030	Small and Medium Spills 50-999 bbl	Large Spills 1000-9999 bbl	Huge Spills =>10000 bbl	Significant Spills =>1000 bbl	All Spills	Small and Medium Spills 50-999 bbl	Large Spills 1000-9999 bbl	Huge Spills =>10000 bbl	Significant Spills =>1000 bbl	All Spills	Small and Medium Spills 50-999 bbl	Large Spills 1000-9999 bbl	Huge Spills =>10000 bbl	Significant Spills =>1000 bbl	All Spills
	Frequency Spills per 10^3 years					Frequency Spills per 10^9 bbl Produced					Spill Index [bbl]				
Mean =	51.28	10.60	7.52	18.13	69.41	1.83	0.38	0.27	0.65	2.48	21.21	71.33	491.71	563.04	584.25
Std Deviation =	19.44	3.74	1.97	4.58	19.96	0.69	0.13	0.07	0.16	0.71	13.56	33.17	178.32	181.51	182.11
Variance =	377.998	13.989	3.877	20.966	398.438	0.482	0.018	0.005	0.027	0.508	183.771	1100.468	31797.980	32946.170	33164.640
Skewness =	0.42	0.54	0.30	0.34	0.40	0.42	0.54	0.30	0.34	0.40	1.30	0.92	0.45	0.42	0.42
Kurtosis =	2.66	2.77	2.96	2.85	2.72	2.66	2.77	2.96	2.85	2.72	5.14	4.13	3.09	3.08	3.08
Mode =	71.07	6.97	5.34	16.17	46.94	1.54	0.48	0.19	0.58	1.68	8.75	40.22	325.16	458.45	476.20
Minimum =	8.187	2.032	1.482	4.991	22.983	0.292	0.073	0.053	0.178	0.821	0.064	3.197	60.101	100.742	130.353
5% Perc =	22.719	5.389	4.482	11.124	39.524	0.811	0.192	0.160	0.397	1.412	5.312	26.808	222.457	286.804	307.398
10% Perc =	27.384	6.180	5.078	12.493	44.751	0.978	0.221	0.181	0.446	1.598	7.098	33.459	271.545	339.492	358.193
15% Perc =	30.674	6.760	5.460	13.426	48.541	1.096	0.241	0.195	0.480	1.734	8.632	38.793	308.502	376.638	396.569
20% Perc =	33.600	7.250	5.818	14.162	51.569	1.200	0.259	0.208	0.506	1.842	9.952	43.164	337.495	405.394	427.285
25% Perc =	36.507	7.731	6.124	14.801	54.458	1.304	0.276	0.219	0.529	1.945	11.144	47.115	363.157	433.984	454.829
30% Perc =	39.133	8.203	6.410	15.451	56.917	1.398	0.293	0.229	0.552	2.033	12.461	51.085	387.827	458.453	479.775
35% Perc =	41.590	8.631	6.677	16.047	59.601	1.485	0.308	0.238	0.573	2.129	13.758	54.667	410.997	482.887	504.145
40% Perc =	44.149	9.086	6.916	16.611	62.153	1.577	0.325	0.247	0.593	2.220	15.080	58.848	432.732	506.134	526.888
45% Perc =	46.551	9.548	7.170	17.195	65.034	1.663	0.341	0.256	0.614	2.323	16.489	62.366	454.688	526.781	547.199
50% Perc =	49.191	10.034	7.417	17.804	67.702	1.757	0.358	0.265	0.636	2.418	18.076	66.063	476.169	547.416	569.974
55% Perc =	51.891	10.573	7.663	18.375	70.304	1.853	0.378	0.274	0.656	2.511	19.621	69.916	500.021	570.307	592.075
60% Perc =	54.883	11.136	7.911	18.944	73.117	1.960	0.398	0.283	0.677	2.611	21.483	74.260	523.610	595.026	615.860
65% Perc =	57.797	11.730	8.171	19.581	76.114	2.064	0.419	0.292	0.699	2.718	23.400	79.144	548.968	621.246	641.803
70% Perc =	61.119	12.383	8.482	20.325	79.330	2.183	0.442	0.303	0.726	2.833	25.646	84.259	576.143	648.377	670.750
75% Perc =	64.529	13.067	8.811	21.157	82.938	2.305	0.467	0.315	0.756	2.962	28.080	90.096	605.128	677.459	700.516
80% Perc =	68.465	13.822	9.176	22.033	86.727	2.445	0.494	0.328	0.787	3.097	31.062	96.521	636.941	712.308	732.494
85% Perc =	72.799	14.788	9.614	23.033	91.498	2.600	0.528	0.343	0.823	3.268	34.475	104.665	677.985	753.098	776.324
90% Perc =	78.323	16.002	10.166	24.402	96.995	2.797	0.572	0.363	0.871	3.464	39.295	115.142	730.956	807.119	828.041
95% Perc =	86.487	17.543	10.948	26.319	105.045	3.089	0.627	0.391	0.940	3.752	48.128	134.545	810.522	884.107	904.597
Maximum =	124.637	26.607	15.232	36.664	143.184	4.451	0.950	0.544	1.309	5.114	97.373	249.105	1203.819	1297.845	1331.919

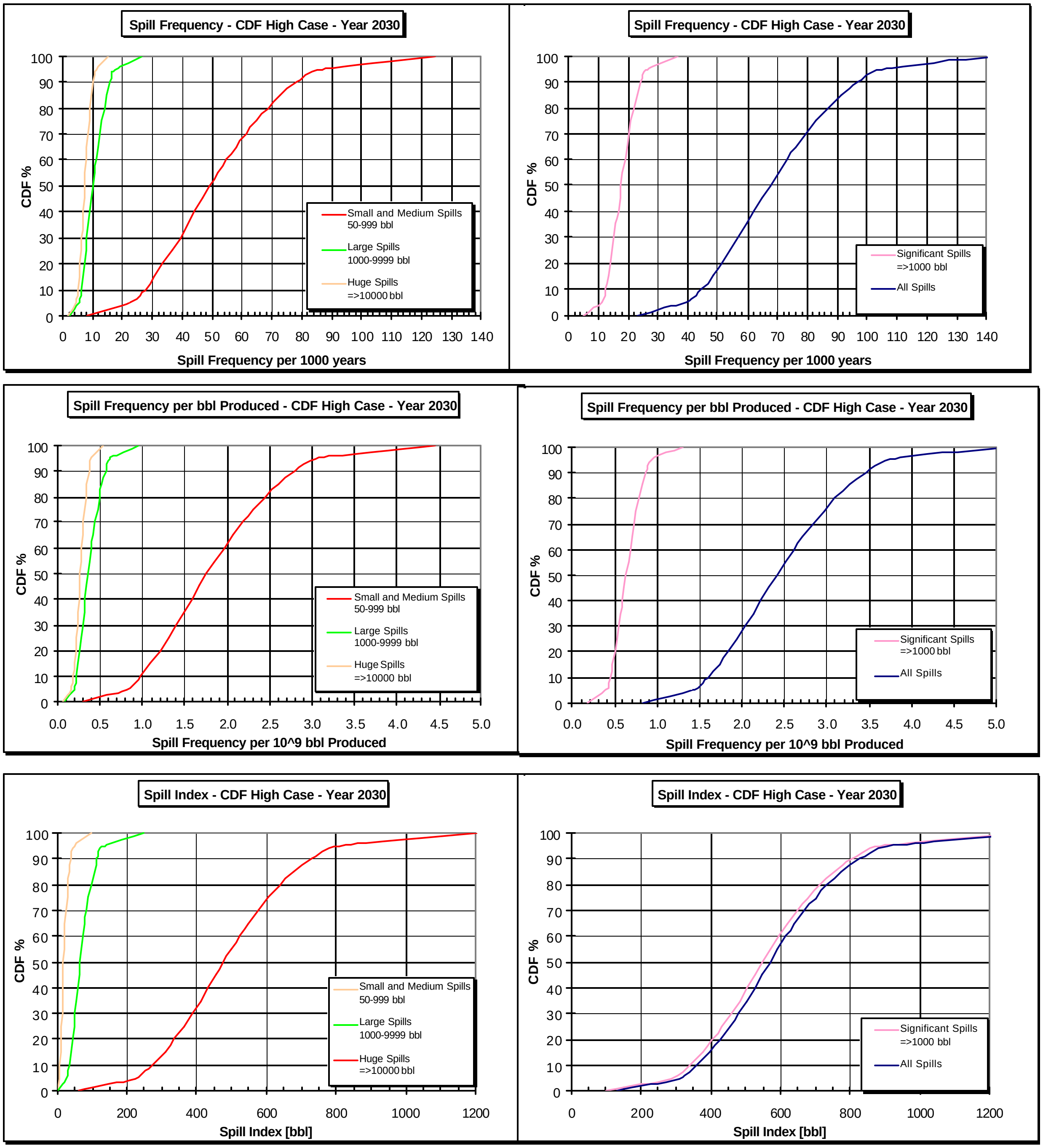


Figure 5.8
Beaufort Sea High Case Spill Indicator Distributions – Year 2030
(Appendix Figure 4.2.13)

In other words, there is a 50% chance that large and huge spills will occur at a rate of 0.65 per billion bbl or less.

The flattening or decrease in slope of the CDFs above 90% and below 10% can be attributed to the use of the triangular distribution with designated limits at corresponding (± 10%) levels.

In addition, since the Life of Field (LOF) averages were calculated, results from these are available for each scenario. Only selected ones are given in the text, with the balance given in the appendix. Table 5.2 shows the composition of the spill indicators for the High Case Life of Field average. The composition both by spill size (on the left hand side of the table) and by facility contribution (on the right hand side of the table). The variability of the spill frequencies Life of Field averages is shown in the following figures: Figure 5.9 illustrates the variability of the spill frequency, while Figure 5.10 shows variability of frequency per billion barrels produced.

5.3.2 Comparative Non-Arctic Indicator Assessment

To give an idea of the effect of the frequency variations introduced in Chapter 4, the 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 scenario would behave as if they were designed for and located in the Gulf of Mexico environment rather than in the Arctic environment, with the same facility quantities and production rates as their Arctic counterparts. Figures 5.11, 5.12, and 5.13 show the 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 5.12. The spill index (Figure 5.13) also shows a reduction of approximately 30%. What the comparison shows is that the Arctic development scenarios can be expected to have a lower oil spill occurrence rate than similar development scenarios would have in the GOM.

Table 5.2
Composition of Spill Indicators – Life of Field Average *(App. Table 4.2.21)*

Spill Size	Spill Source									
	P/L		Platforms		Wells		Platforms and Wells		All	
	LOF Average - Spill Frequency per 10^3 years									
Small and Medium Spills 50-999 bbl	13.395	73%	12.633	90%	0.441	11%	13.074	72%	26.468	73%
Large Spills 1000-9999 bbl	3.725	20%	0.726	5%	1.322	33%	2.048	11%	5.773	16%
Huge Spills =>10000 bbl	1.282	7%	0.726	5%	2.214	56%	2.940	16%	4.222	12%
Significant Spills =>1000 bbl	5.007	27%	1.452	10%	3.536	89%	4.988	28%	9.995	27%
All Spills	**18.402**	**100%**	**14.085**	**100%**	**3.977**	**100%**	**18.062**	**100%**	**36.463**	**100%**
	LOF Average - Spill Frequency per 10^9 bbl produced									
Small and Medium Spills 50-999 bbl	0.776	73%	0.732	90%	0.026	11%	0.758	72%	1.534	73%
Large Spills 1000-9999 bbl	0.216	20%	0.042	5%	0.077	33%	0.119	11%	0.335	16%
Huge Spills =>10000 bbl	0.074	7%	0.042	5%	0.128	56%	0.170	16%	0.245	12%
Significant Spills =>1000 bbl	0.290	27%	0.084	10%	0.205	89%	0.289	28%	0.579	27%
All Spills	**1.066**	**100%**	**0.816**	**100%**	**0.230**	**100%**	**1.047**	**100%**	**2.113**	**100%**
	LOF Average - Spill Index [bbl]									
Small and Medium Spills 50-999 bbl	5	11%	6	41%	0	0%	6	2%	11	3%
Large Spills 1000-9999 bbl	19	44%	4	29%	16	6%	20	7%	40	12%
Huge Spills =>10000 bbl	20	45%	4	29%	269	94%	273	91%	293	85%
Significant Spills =>1000 bbl	39	89%	8	59%	285	100%	293	98%	332	97%
All Spills	**44**	**100%**	**14**	**100%**	**285**	**100%**	**299**	**100%**	**343**	**100%**

Spill Source	Spill Size									
	S+M 50-999 bbl		Large 1000-9999 bbl		Huge =>10000 bbl		Significant =>1000 bbl		All Spills	
	LOF Average - Spill Frequency per 10^3 years									
Pipelines	13.395	51%	3.725	65%	1.282	30%	5.007	50%	18.402	13.395
Platforms	12.633	48%	0.726	13%	0.726	17%	1.452	15%	14.085	12.633
Wells	0.441	2%	1.322	23%	2.214	52%	3.536	35%	3.977	0.441
Platforms and Wells	13.074	49%	2.048	35%	2.940	70%	4.988	50%	18.062	13.074
All	**26.468**	**100%**	**5.773**	**100%**	**4.222**	**100%**	**9.995**	**100%**	**36.463**	**26.468**
	LOF Average - Spill Frequency per 10^9 bbl produced									
Pipelines	0.776	51%	0.216	65%	0.074	30%	0.290	50%	1.066	0.776
Platforms	0.732	48%	0.042	13%	0.042	17%	0.084	15%	0.816	0.732
Wells	0.026	2%	0.077	23%	0.128	52%	0.205	35%	0.230	0.026
Platforms and Wells	0.758	49%	0.119	35%	0.170	70%	0.289	50%	1.047	0.758
All	**1.534**	**100%**	**0.335**	**100%**	**0.245**	**100%**	**0.579**	**100%**	**2.113**	**1.534**
	LOF Average - Spill Index [bbl]									
Pipelines	5	45%	19	48%	20	7%	39	12%	44	5
Platforms	6	53%	4	10%	4	1%	8	2%	14	6
Wells	0	2%	16	41%	269	92%	285	86%	285	0
Platforms and Wells	6	55%	20	52%	273	93%	293	88%	299	6
All	**11**	**100%**	**40**	**100%**	**293**	**100%**	**332**	**100%**	**343**	**11**

Figure 5.9
Beaufort Sea High Case Life of Field Average Spill Frequency
(Appendix Figure 4.2.14)

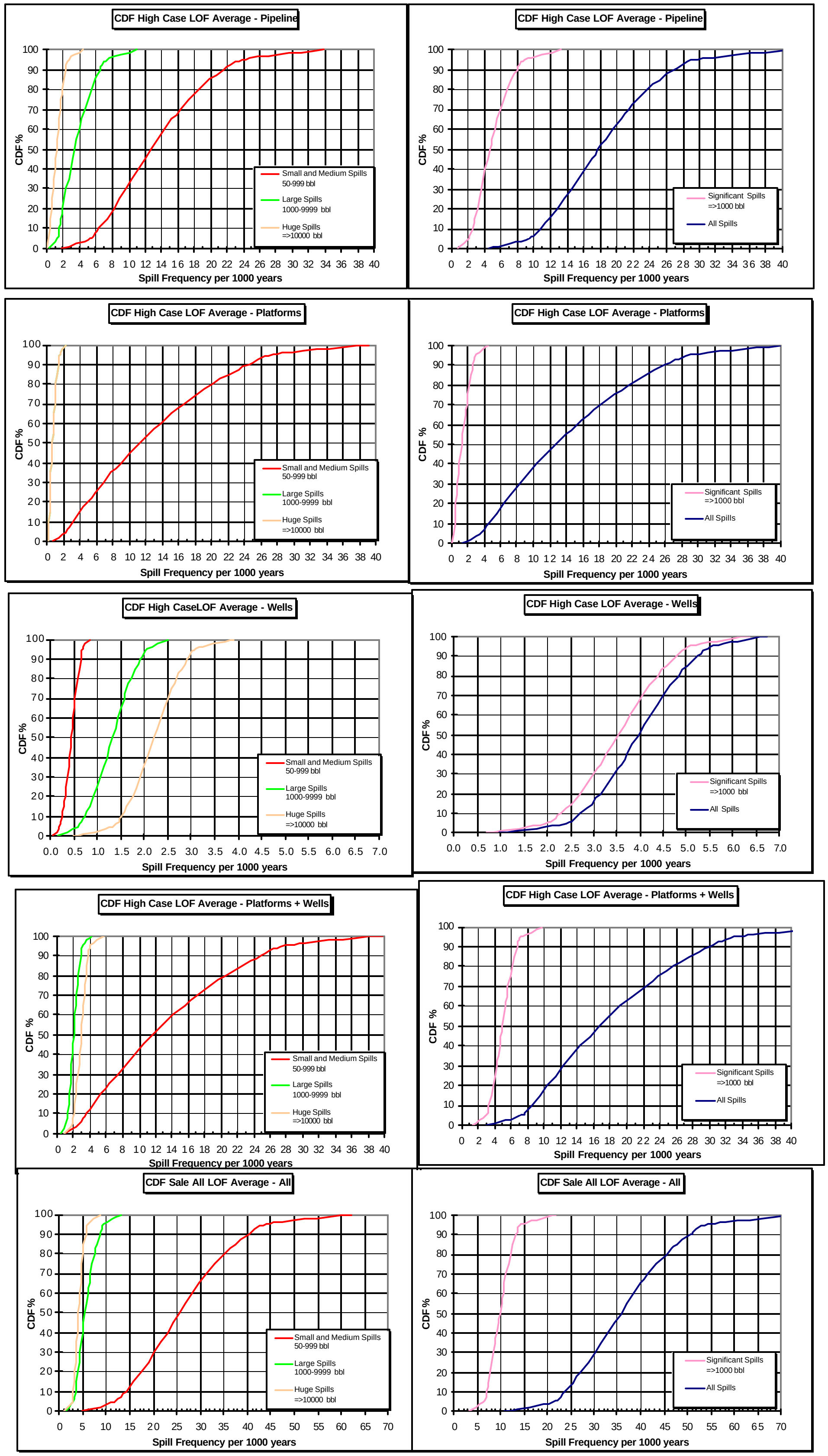
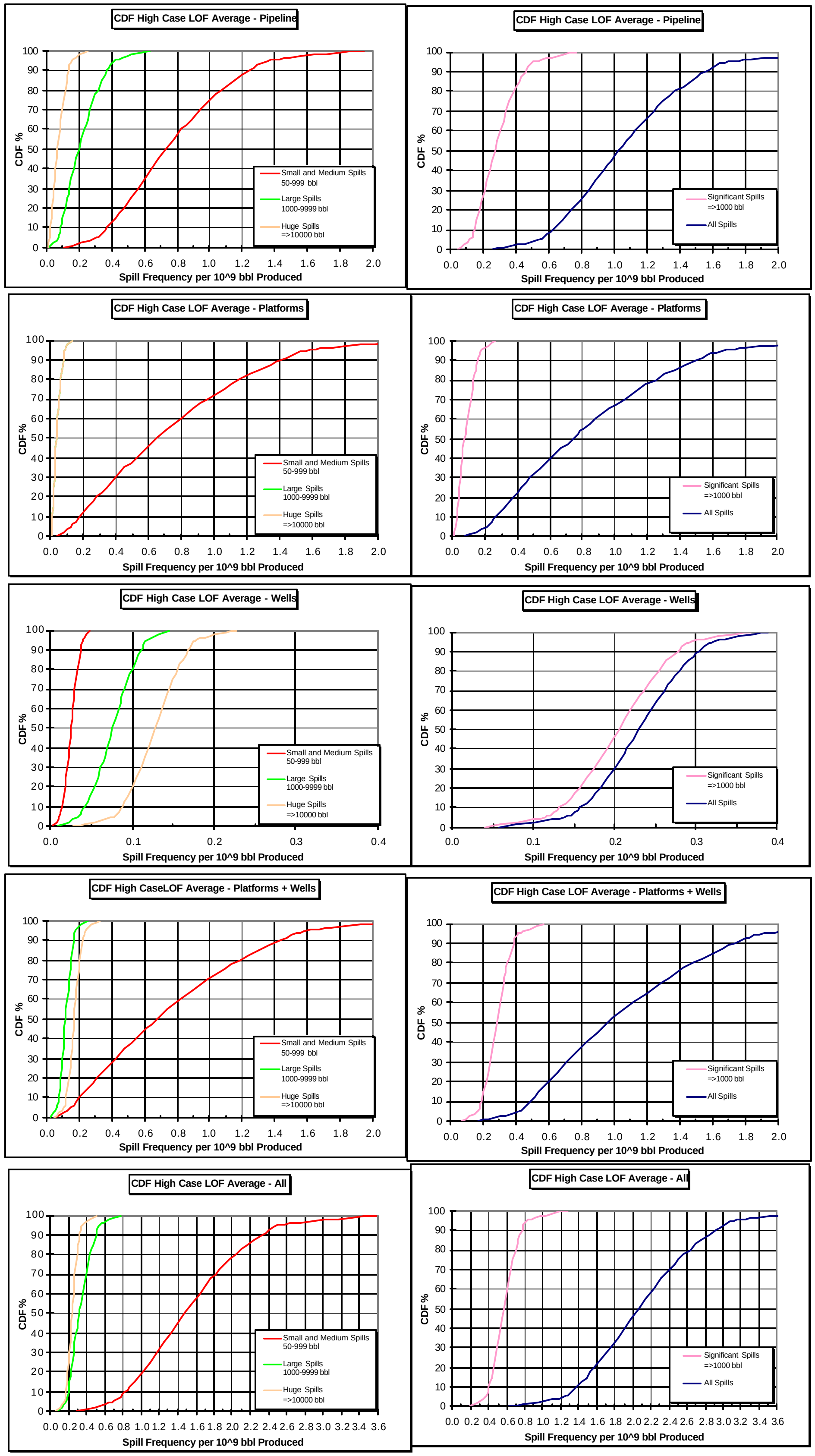


Figure 5.10 Beaufort Sea High Case Life of Field Average Spills per Barrel Produced
(Appendix Figure 4.2.15)



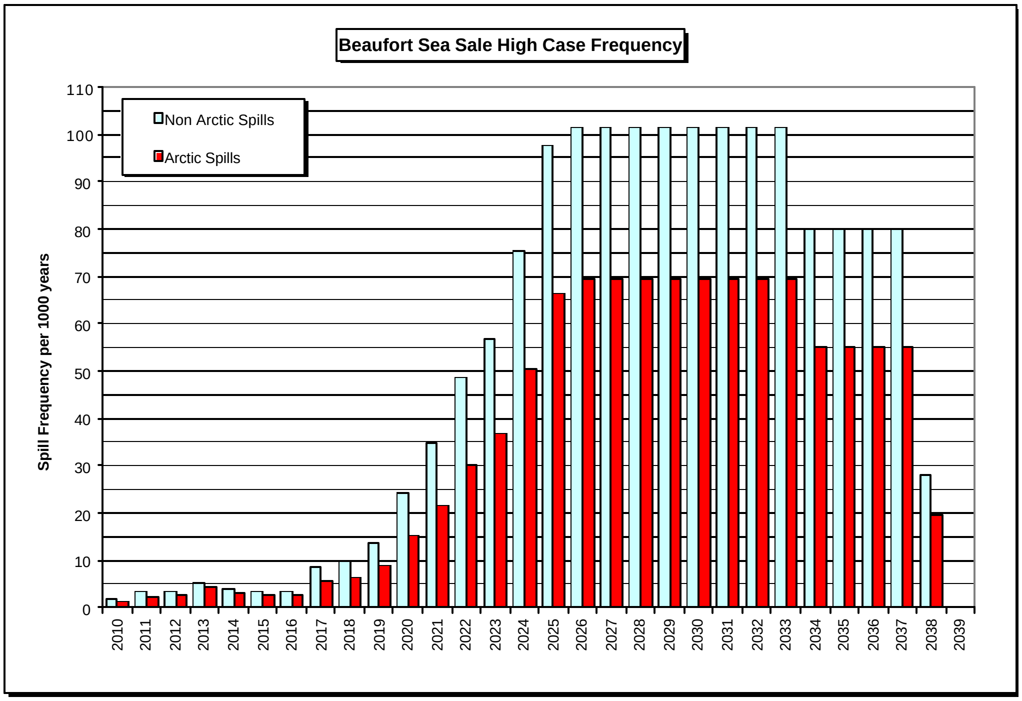


Figure 5.11
Beaufort Sea High Case Spill Frequency – Arctic and Non-Arctic
(Appendix Figure 5.3)

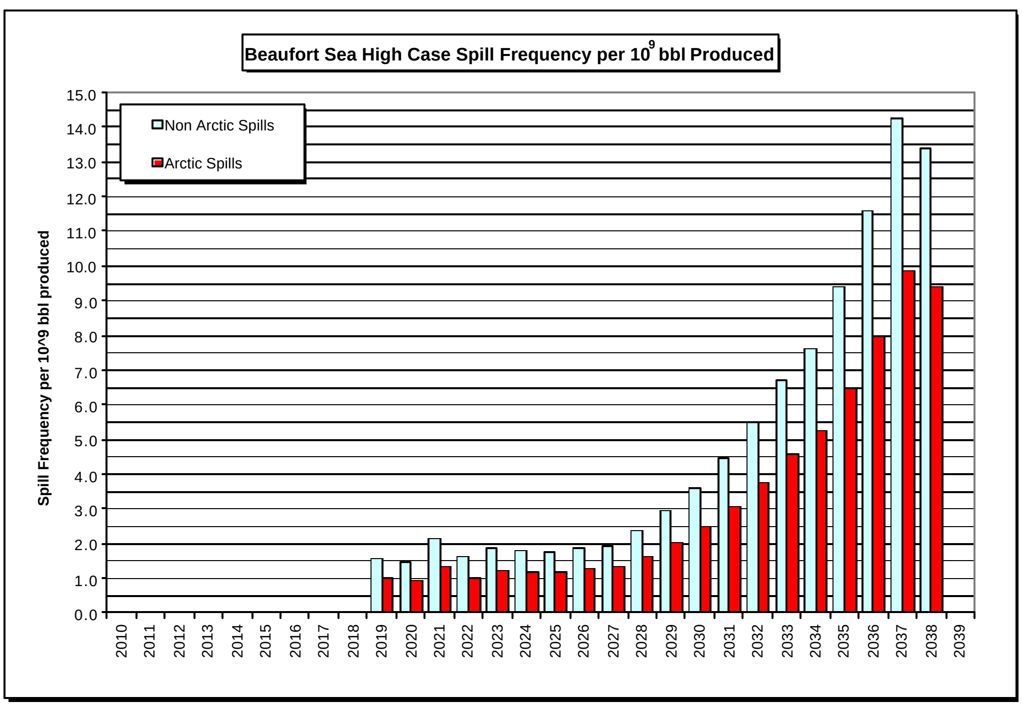


Figure 5.12
Beaufort Sea High Case Spill Frequency per 10^9 Barrels Produced – Arctic and Non-Arctic
(Appendix Figure 5.4)

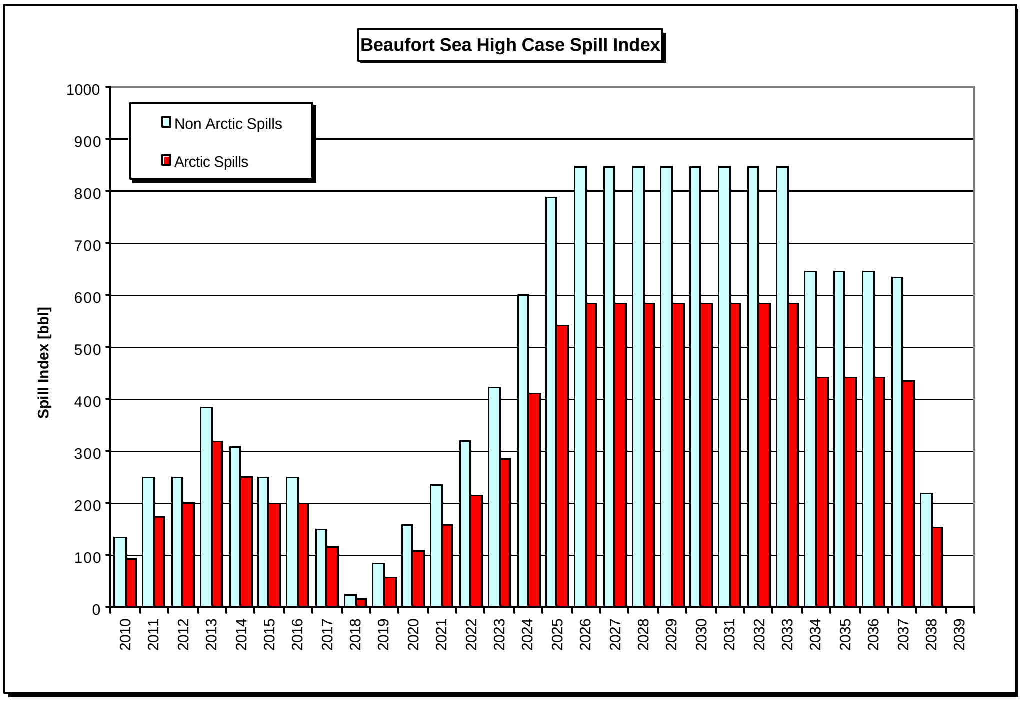


Figure 5.13
Beaufort Sea High Case Spill Index – Arctic and Non-Arctic
(Appendix Figure 5.5)

5.4 Summary of Representative Oil Spill Occurrence Indicator Results

How do spill indicators for the Beaufort scenario and for its non-Arctic counterpart vary by spill size and location? Table 5.3 and Figures 5.14 and 5.15 summarize the Life of Field average spill indicator values by spill source and size for the Low and High Cases and Non-Arctic High Case scenarios. The following can be observed from Table 5.3.

- Spill frequency per year and per barrel-year decreases significantly with increasing spill size for all three scenarios.
- The spill index increases significantly with spill size for all scenarios.
- All non-Arctic scenario spill indicators are greater than their Arctic counterparts.

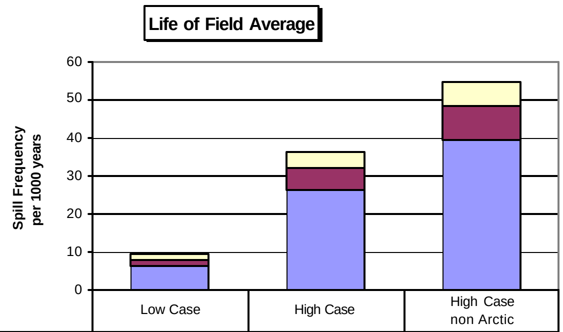
How do the spill indicators vary by facility type for representative scenarios? The contributions of spill indicators by facility have been summarized in Table 5.3 and also in Figure 5.15. Table 5.3 and Figure 5.15 give the component contributions, in absolute value and percent, for each of the main facility types; namely, pipelines (P/L), platforms, and wells. The following may be noted from these for the High Case:

- Pipelines contribute the most (50%) to the spill frequency indicators.
- Platforms are next in relative contribution to spill frequencies (39%) and least in contribution to spill index (4%).
- Wells are by far (at 83%) the highest contributors to spill index.
- It can be concluded that pipelines are likely to have the most, but smaller spills, while wells will have the least number, but largest spills.

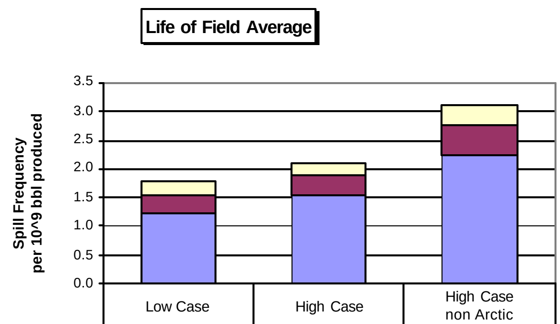
Figures 5.16 and 5.17 show relative contributions by facility and spill size to the maximum production year 2030 and Life of Field average spill indicators, respectively. Although Life of Field average absolute values are significantly smaller than the maximum production year values, the proportional contributions by spill facility source and spill size are almost identical. In Figures 5.16 and 5.17, "TOTAL" designates the sum of the spill indicators for all spill sizes and facility types.

Table 5.3
Summary of Life of Field Average Spill Indicators by Spill Source and Size
(App Table 5.1)

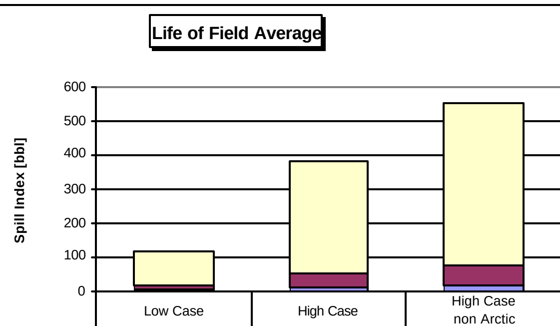
Spill Indicators LOF Average	Low Case			High Case			High Case Non-Arctic		
	Spill Frequency per 10^3 years	Spill Frequency per 10^9 bbl produced	Spill Index [bbl]	Spill Frequency per 10^3 years	Spill Frequency per 10^9 bbl produced	Spill Index [bbl]	Spill Frequency per 10^3 years	Spill Frequency per 10^9 bbl produced	Spill Index [bbl]
Small and Medium Spills 50-999 bbl	6.431	1.232	3	26.468	1.534	11	39.306	2.233	14
	69%	**69%**	**2%**	**73%**	**73%**	**3%**	**72%**	**72%**	**3%**
Large Spills 1000-9999 bbl	1.623	0.311	12	5.773	0.335	40	9.029	0.511	60
	17%	**17%**	**11%**	**16%**	**16%**	**12%**	**17%**	**16%**	**12%**
Huge Spills =>10000 bbl	1.256	0.241	93	4.222	0.245	293	6.312	0.361	417
	13%	**13%**	**87%**	**12%**	**12%**	**85%**	**12%**	**12%**	**85%**
Significant Spills =>1000 bbl	2.879	0.551	104	9.995	0.579	332	15.341	0.871	477
	31%	**31%**	**98%**	**27%**	**27%**	**97%**	**28%**	**28%**	**97%**
All Spills	9.310	1.783	107	36.463	2.113	343	54.647	3.104	492
	100%	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**
Pipeline Spills	4.414	0.845	12	18.402	1.066	44	31.209	1.746	76
	47%	**47%**	**11%**	**50%**	**50%**	**13%**	**57%**	**56%**	**15%**
Platform Spills	3.615	0.692	4	14.085	0.816	14	17.873	1.036	17
	39%	**39%**	**4%**	**39%**	**39%**	**4%**	**33%**	**33%**	**3%**
Well Spills	1.281	0.245	92	3.977	0.230	285	5.565	0.322	399
	14%	**14%**	**86%**	**11%**	**11%**	**83%**	**10%**	**10%**	**81%**
Platform and Well Spills	4.896	0.938	95	18.062	1.047	299	23.438	1.358	416
	53%	**53%**	**89%**	**50%**	**50%**	**87%**	**43%**	**44%**	**85%**
All Spills	9.310	1.783	107	36.463	2.113	343	54.647	3.104	492
	100%	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**



	Low Case	High Case	High Case non Arctic
Huge Spills =>10000 bbl	1.256	4.222	6.312
Large Spills 1000-9999 bbl	1.623	5.773	9.029
Small and Medium Spills 50-999 bbl	6.431	26.468	39.306

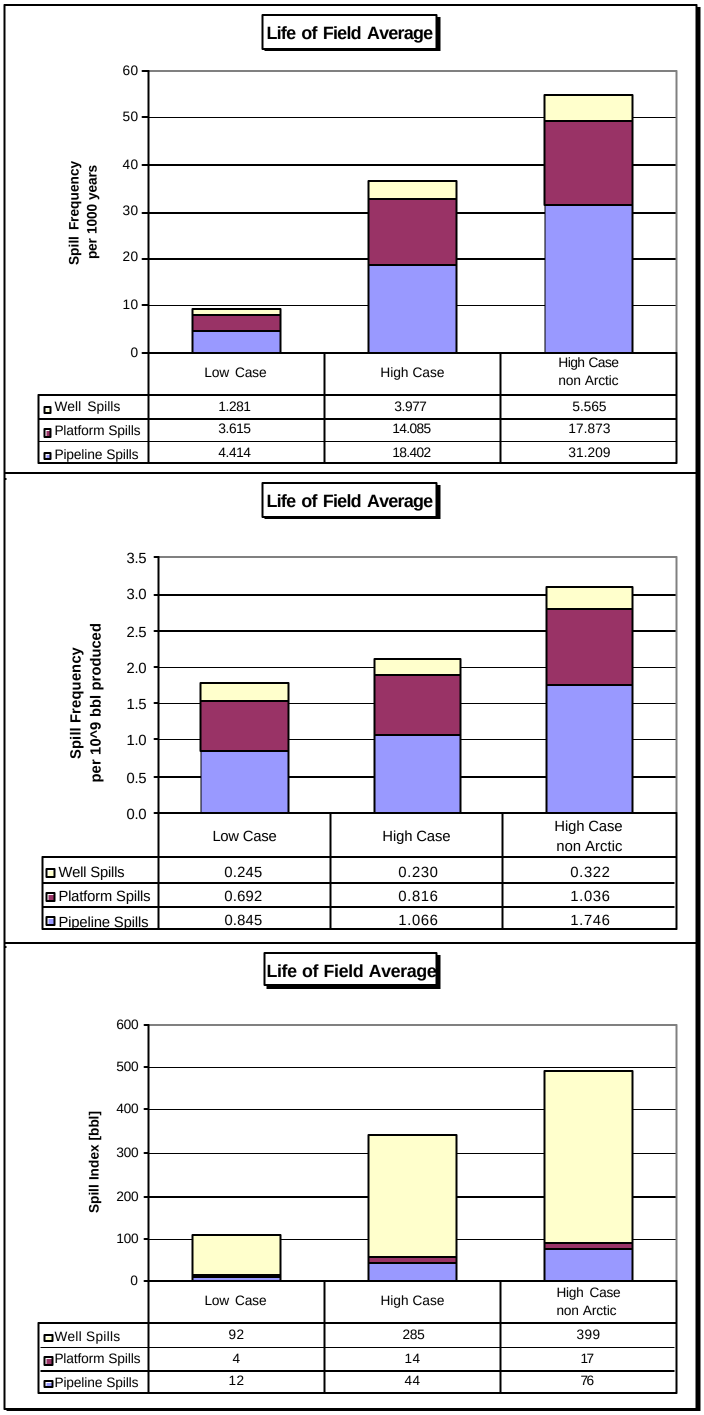


	Low Case	High Case	High Case non Arctic
Huge Spills =>10000 bbl	0.241	0.245	0.361
Large Spills 1000-9999 bbl	0.311	0.335	0.511
Small and Medium Spills 50-999 bb	1.232	1.534	2.233



	Low Case	High Case	High Case non Arctic
Huge Spills =>10000 bbl	104	332	477
Large Spills 1000-9999 bbl	12	40	60
Small and Medium Spills 50-999 bbl	3	11	14

Figure 5.14
Life of Field Spill Indicators – By Spill Size
(Appendix Figure 5.1)



	Low Case	High Case	High Case non Arctic
Well Spills	1.281	3.977	5.565
Platform Spills	3.615	14.085	17.873
Pipeline Spills	4.414	18.402	31.209

	Low Case	High Case	High Case non Arctic
Well Spills	0.245	0.230	0.322
Platform Spills	0.692	0.816	1.036
Pipeline Spills	0.845	1.066	1.746

	Low Case	High Case	High Case non Arctic
Well Spills	92	285	399
Platform Spills	4	14	17
Pipeline Spills	12	44	76

Figure 5.15
Life of Field Spill Indicators – By Source Composition
(Appendix Figure 5.2)

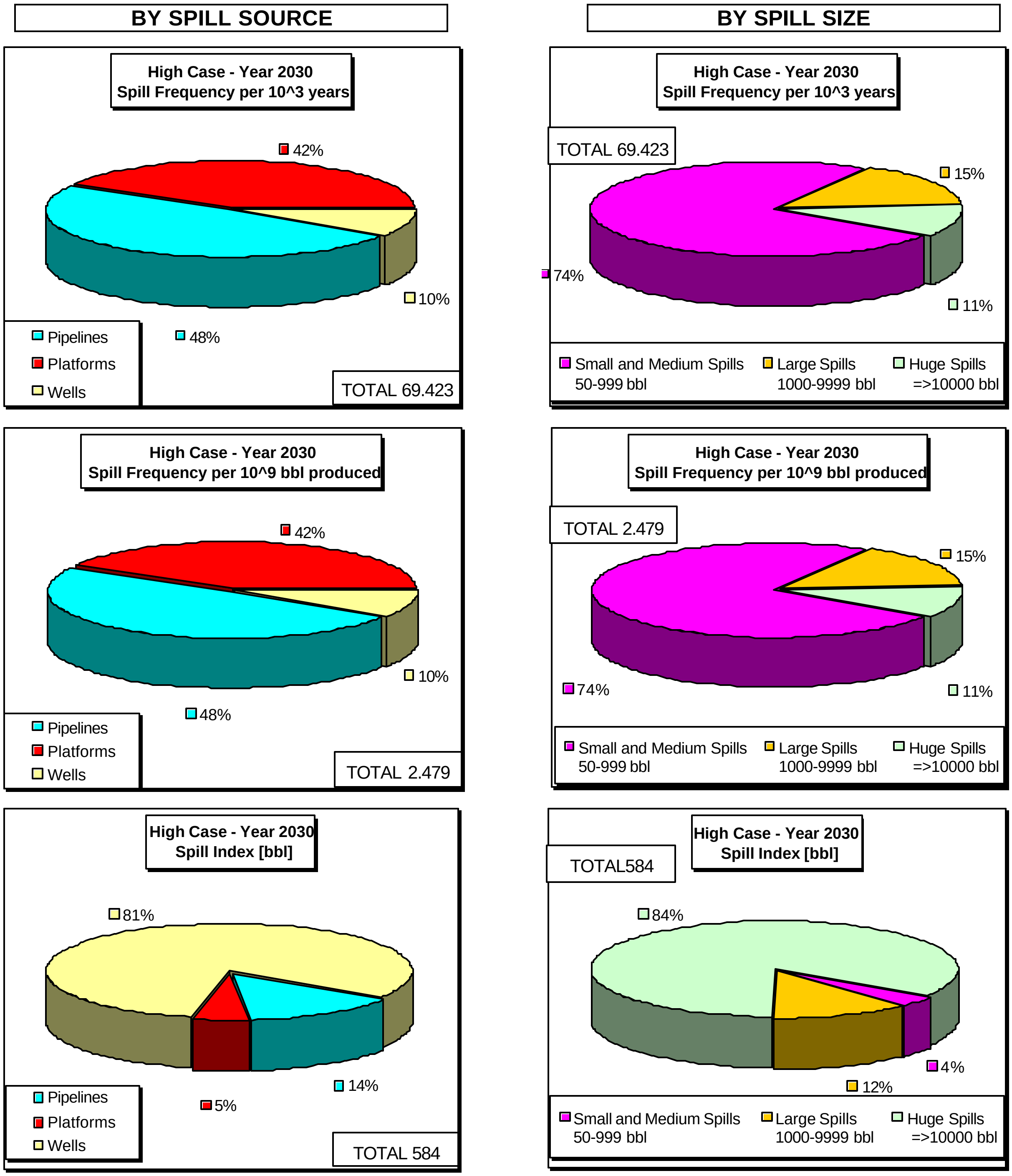


Figure 5.16
Beaufort Sea High Case – Year 2030 – Spill Indicator Composition by Source and Spill Size
(Appendix Figure 4.2.17)

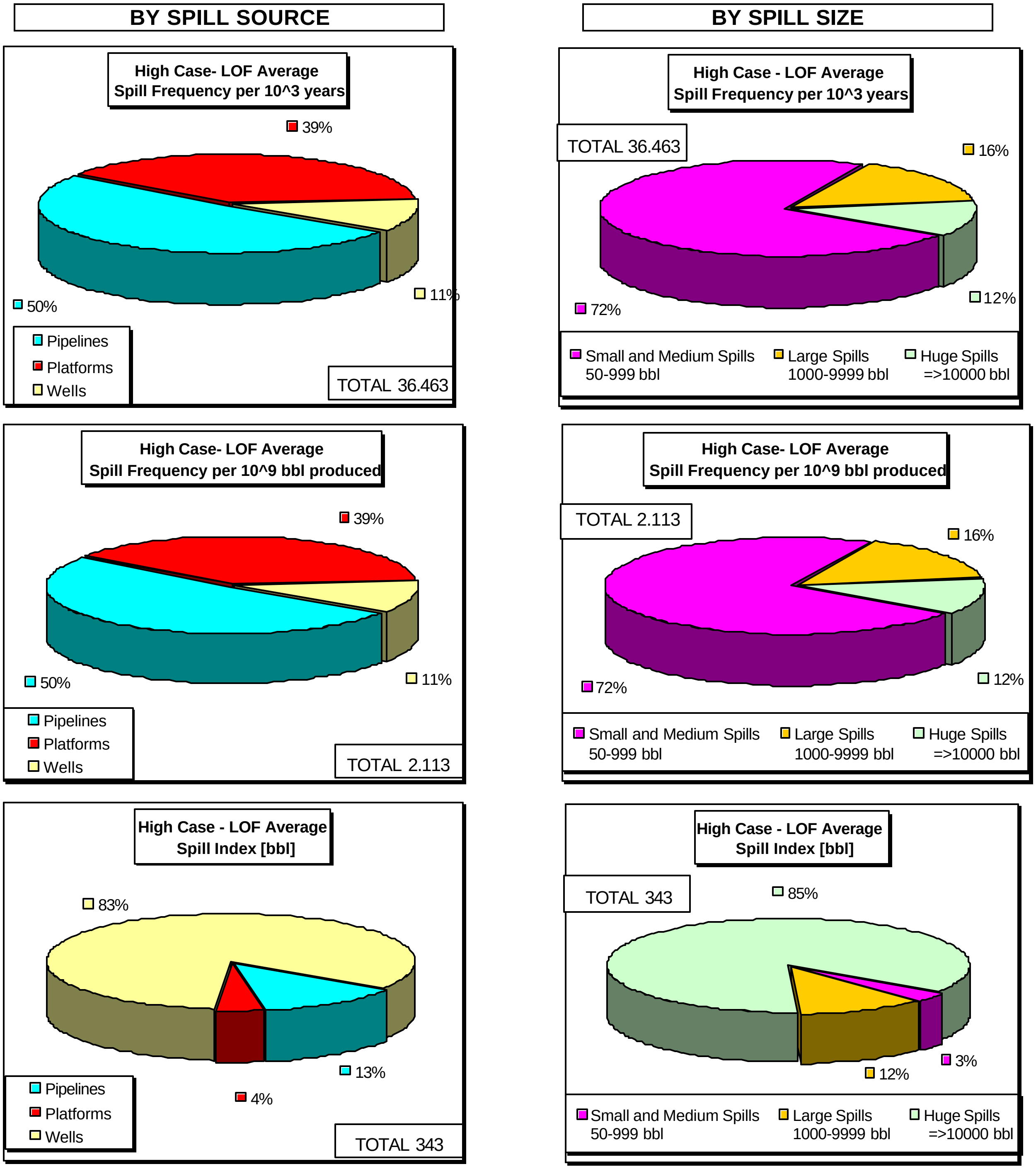


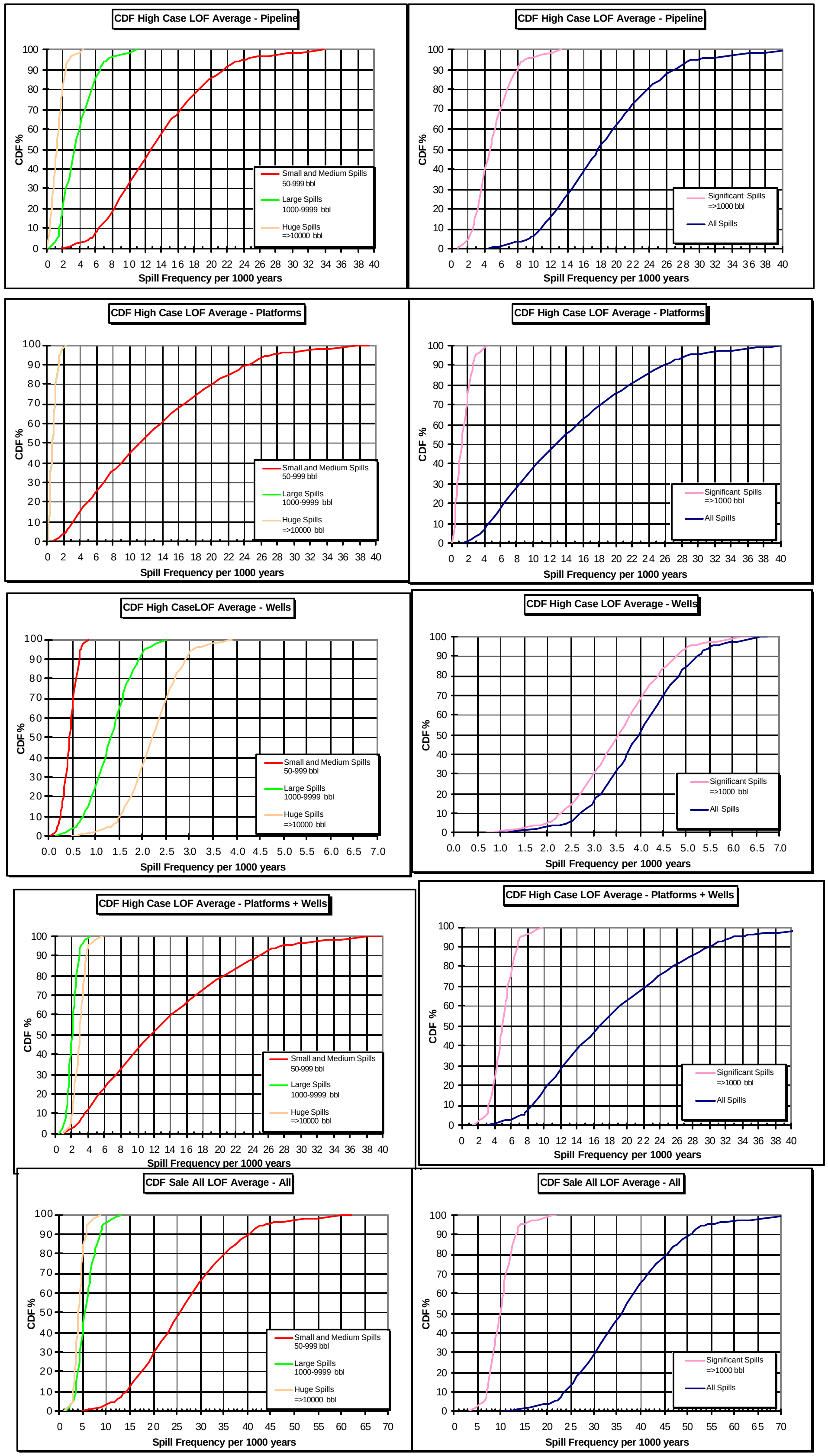
Figure 5.17
Beaufort Sea High Case – Life of Field Average Spill Indicator Composition by Source and Spill Size
(Appendix Figure 4.2.18)

Figures 5.18, 5.19, and 5.20 show the Cumulative Distribution Functions (CDF) for the Beaufort Sea Life of Field average spill indicators. (Figures 5.18 and 5.19 previously appeared as Figures 5.9 and 5.10, and are repeated here for convenience). The variability of these indicators is fairly representative of the trends in variability for spill indicators for the Low Case as well. Generally, the following can be observed from the figures:

- The variance of the frequency spill indicators (Figures 5.18 and 5.19) decreases as spill size increases for pipelines and platforms. In other words, small and medium spills illustrate the largest variability; huge spills show the least variability for pipelines and platforms.
- For wells, the frequency variability for different spill sizes does not change as much as that for platforms and pipelines.
- The variability of the spill index (Figure 5.20) shows an increasing variability with increasing spill size.

The Cumulative Distribution Functions contain extensive information on the statistical properties of the spill indicators. For example, from Figure 5.18, it can be seen, for all significant spills, that the Life of Field average mean (50%) value of 10 (spills per 1,000 years) ranges between 15 and 5 at the upper and lower 95% confidence intervals. A similar percentage variation is shown for the Life of Field average spill frequency per barrel produced in Figure 5.19. The spill index variability shown in Figure 5.20 is proportionally higher. For example, in Figure 5.20, the mean value of the significant spills index of 325 per billion barrels produced ranges from 200 to 500 over the 5% to 95% confidence interval.

Figure 5.18
Beaufort Sea
High Case
Life of Field
Average Spill
Frequency
(Appendix
Figure 4.2.14)



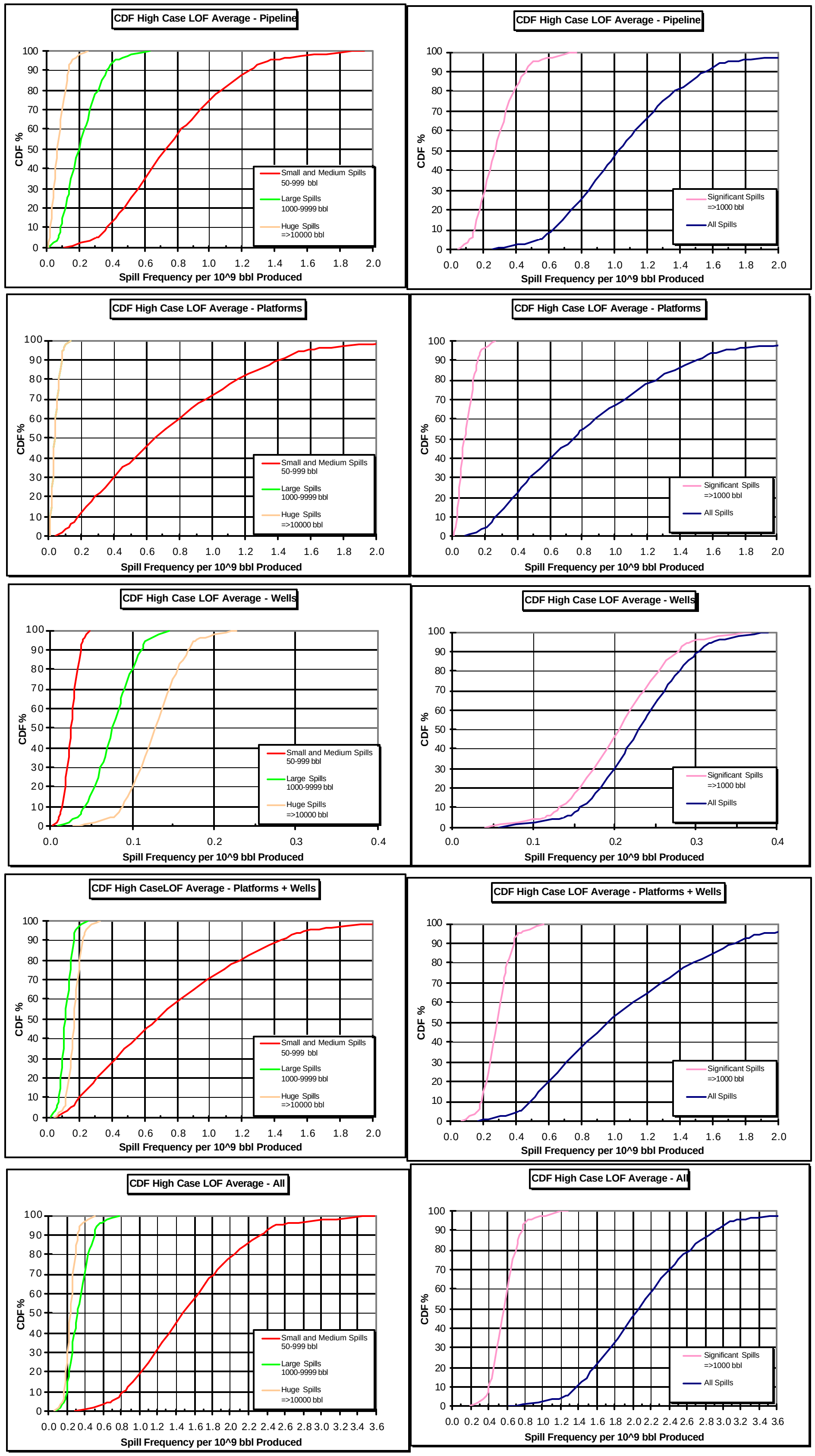


Figure 5.19 Beaufort Sea High Case Life of Field Average Spills per Barrel Produced
(Appendix Figure 4.2.15)

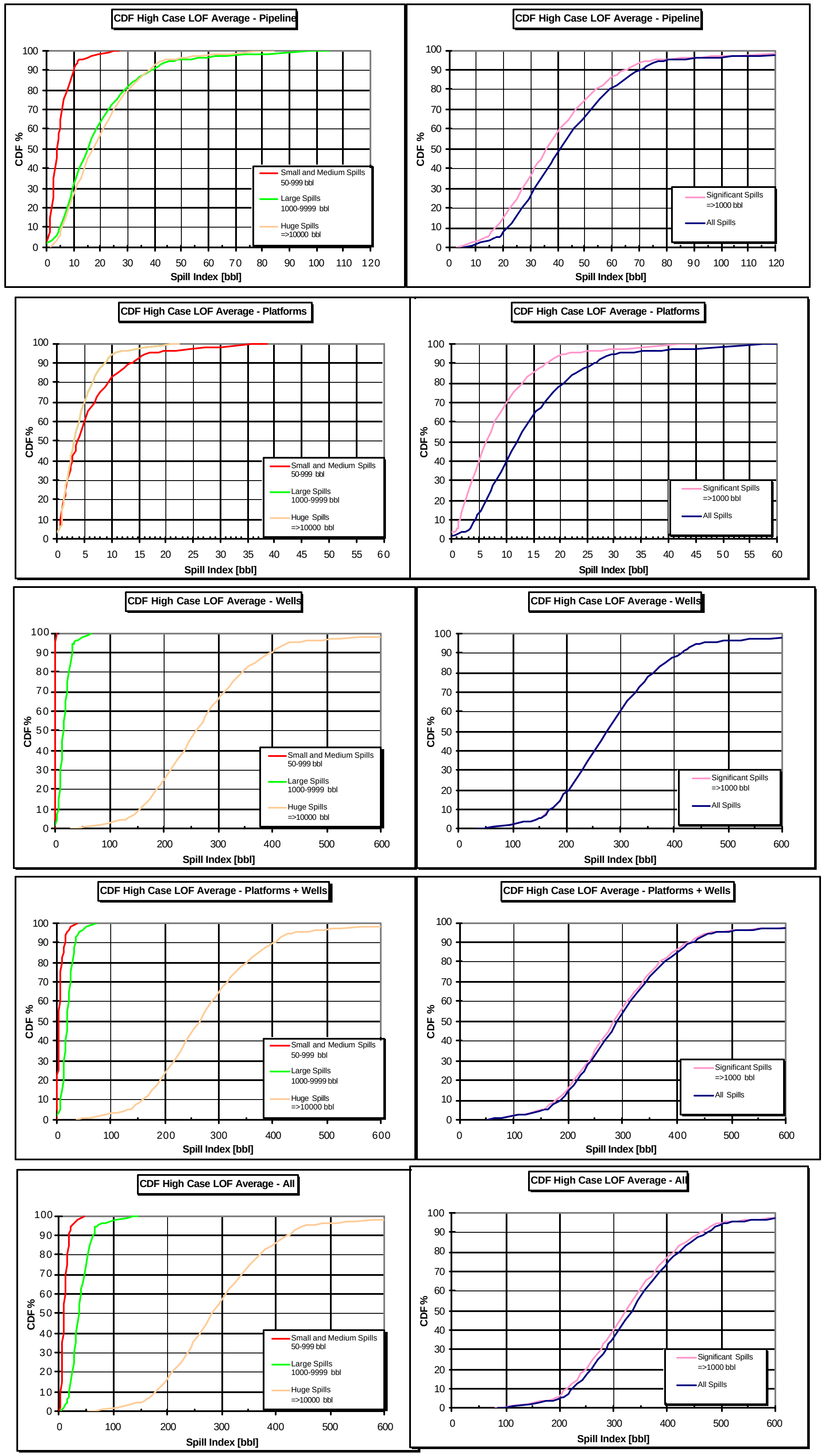


Figure 5.20 Beaufort Sea High Case Life of Field Average Spill Index (bbl) – CDF *(Appendix Figure 4.2.16)*

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

6.1.1 General Conclusions

Oil spill occurrence indicators were quantified for future offshore development scenarios in the Beaufort Sea in the area of MMS jurisdiction. The quantification included the consideration of the variability of historical and future scenario data, as well as that of Arctic effects in predicting oil spill occurrence indicators. Consideration of the variability of all input data yields both higher variability and a higher expected value of the spill occurrence indicators. The three types of spill occurrence indicators were: annual oil spill frequency, annual oil spill frequency per billion barrels produced, and annual spill index – and, additionally, the life of field averages for each of these three oil spill indicators were assessed.

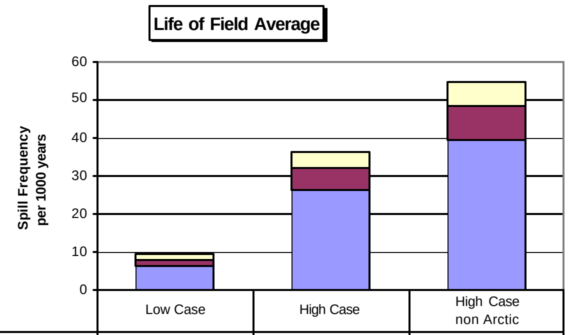
6.1.2 Oil Spill Occurrence Indicators by Spill Size

How do spill indicators for the Beaufort scenario and for its non-Arctic counterpart vary by spill size and location? Table 6.1 and Figures 6.1 and 6.2 summarize the Life of Field average spill indicator values by spill source and size for the Low and High Cases and Non-Arctic High Case scenarios. The following can be observed from Table 6.1.

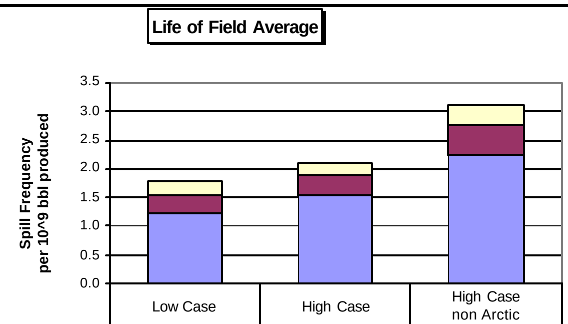
- Spill frequency per year and per barrel-year decreases significantly with increasing spill size for all scenarios.
- The spill index increases significantly with spill size for all scenarios.
- All non-Arctic scenario spill indicators are greater than their Arctic counterparts.

Table 6.1
Summary of Life of Field Average Spill Indicators by Spill Source and Size
(Appendix Table 5.1)

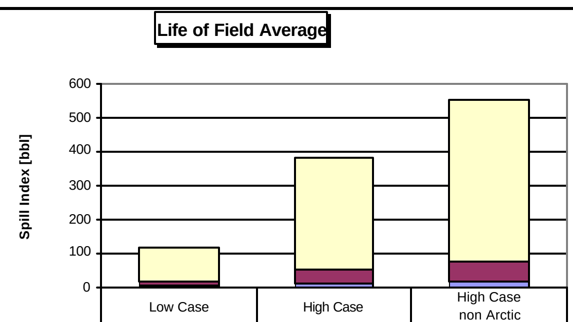
Spill Indicators LOF Average	Low Case			High Case			High Case Non-Arctic		
	Spill Frequency per 10^3 years	Spill Frequency per 10^9 bbl produced	Spill Index [bbl]	Spill Frequency per 10^3 years	Spill Frequency per 10^9 bbl produced	Spill Index [bbl]	Spill Frequency per 10^3 years	Spill Frequency per 10^9 bbl produced	Spill Index [bbl]
Small and Medium Spills 50-999 bbl	6.431	1.232	3	26.468	1.534	11	39.306	2.233	14
	69%	**69%**	**2%**	**73%**	**73%**	**3%**	**72%**	**72%**	**3%**
Large Spills 1000-9999 bbl	1.623	0.311	12	5.773	0.335	40	9.029	0.511	60
	17%	**17%**	**11%**	**16%**	**16%**	**12%**	**17%**	**16%**	**12%**
Huge Spills =>10000 bbl	1.256	0.241	93	4.222	0.245	293	6.312	0.361	417
	13%	**13%**	**87%**	**12%**	**12%**	**85%**	**12%**	**12%**	**85%**
Significant Spills =>1000 bbl	2.879	0.551	104	9.995	0.579	332	15.341	0.871	477
	31%	**31%**	**98%**	**27%**	**27%**	**97%**	**28%**	**28%**	**97%**
All Spills	9.310	1.783	107	36.463	2.113	343	54.647	3.104	492
	100%	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**
Pipeline Spills	4.414	0.845	12	18.402	1.066	44	31.209	1.746	76
	47%	**47%**	**11%**	**50%**	**50%**	**13%**	**57%**	**56%**	**15%**
Platform Spills	3.615	0.692	4	14.085	0.816	14	17.873	1.036	17
	39%	**39%**	**4%**	**39%**	**39%**	**4%**	**33%**	**33%**	**3%**
Well Spills	1.281	0.245	92	3.977	0.230	285	5.565	0.322	399
	14%	**14%**	**86%**	**11%**	**11%**	**83%**	**10%**	**10%**	**81%**
Platform and Well Spills	4.896	0.938	95	18.062	1.047	299	23.438	1.358	416
	53%	**53%**	**89%**	**50%**	**50%**	**87%**	**43%**	**44%**	**85%**
All Spills	9.310	1.783	107	36.463	2.113	343	54.647	3.104	492
	100%	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**



	Low Case	High Case	High Case non Arctic
Huge Spills =>10000 bbl	1.256	4.222	6.312
Large Spills 1000-9999 bbl	1.623	5.773	9.029
Small and Medium Spills 50-999 bbl	6.431	26.468	39.306

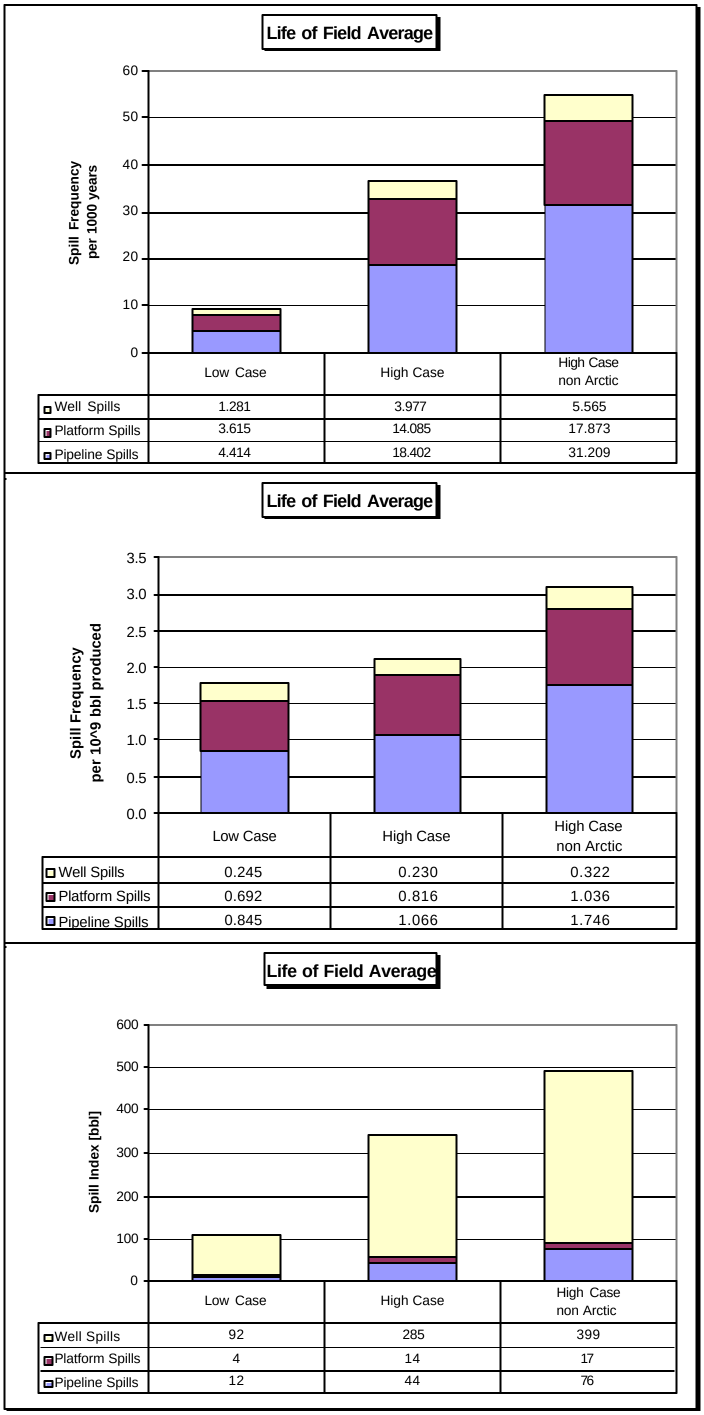


	Low Case	High Case	High Case non Arctic
Huge Spills =>10000 bbl	0.241	0.245	0.361
Large Spills 1000-9999 bbl	0.311	0.335	0.511
Small and Medium Spills 50-999 bb	1.232	1.534	2.233



	Low Case	High Case	High Case non Arctic
Huge Spills =>10000 bbl	104	332	477
Large Spills 1000-9999 bbl	12	40	60
Small and Medium Spills 50-999 bbl	3	11	14

Figure 6.1
Life of Field Spill Indicators – By Spill Size
Appendix Figure 5.1



	Low Case	High Case	High Case non Arctic
Well Spills	1.281	3.977	5.565
Platform Spills	3.615	14.085	17.873
Pipeline Spills	4.414	18.402	31.209

	Low Case	High Case	High Case non Arctic
Well Spills	0.245	0.230	0.322
Platform Spills	0.692	0.816	1.036
Pipeline Spills	0.845	1.066	1.746

	Low Case	High Case	High Case non Arctic
Well Spills	92	285	399
Platform Spills	4	14	17
Pipeline Spills	12	44	76

Figure 6.2
Life of Field Spill Indicators – By Source Composition
(Appendix Figure 5.2)

6.1.3 Oil Spill Occurrence Indicators by Spill Source

How do the spill indicators vary by facility type for representative scenarios? The contributions of spill indicators by facility have been summarized in Table 6.1 and also in Figure 6.2. Table 6.1 and Figure 6.2 give 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 these for the High Case:

- Pipelines contribute the most (50%) to the spill frequency indicators.
- Platforms are next in relative contribution to spill frequencies (39%) and least in contribution to spill index (4%).
- Wells are by far (at 83%) the highest contributors to spill index.
- It can be concluded that pipelines are likely to have the most, but smaller spills, while wells will have the least number, but largest spills.

Figures 6.3 and 6.4 show relative contributions by facility and spill size to the maximum production year 2030 and Life of Field average spill indicators, respectively. Although Life of Field average absolute values are significantly smaller than the maximum production year values, the proportional contributions by spill facility source and spill size are almost identical. In Figures 6.3 and 6.4, "TOTAL" designates the sum of the spill indicators for all spill sizes and facility types.

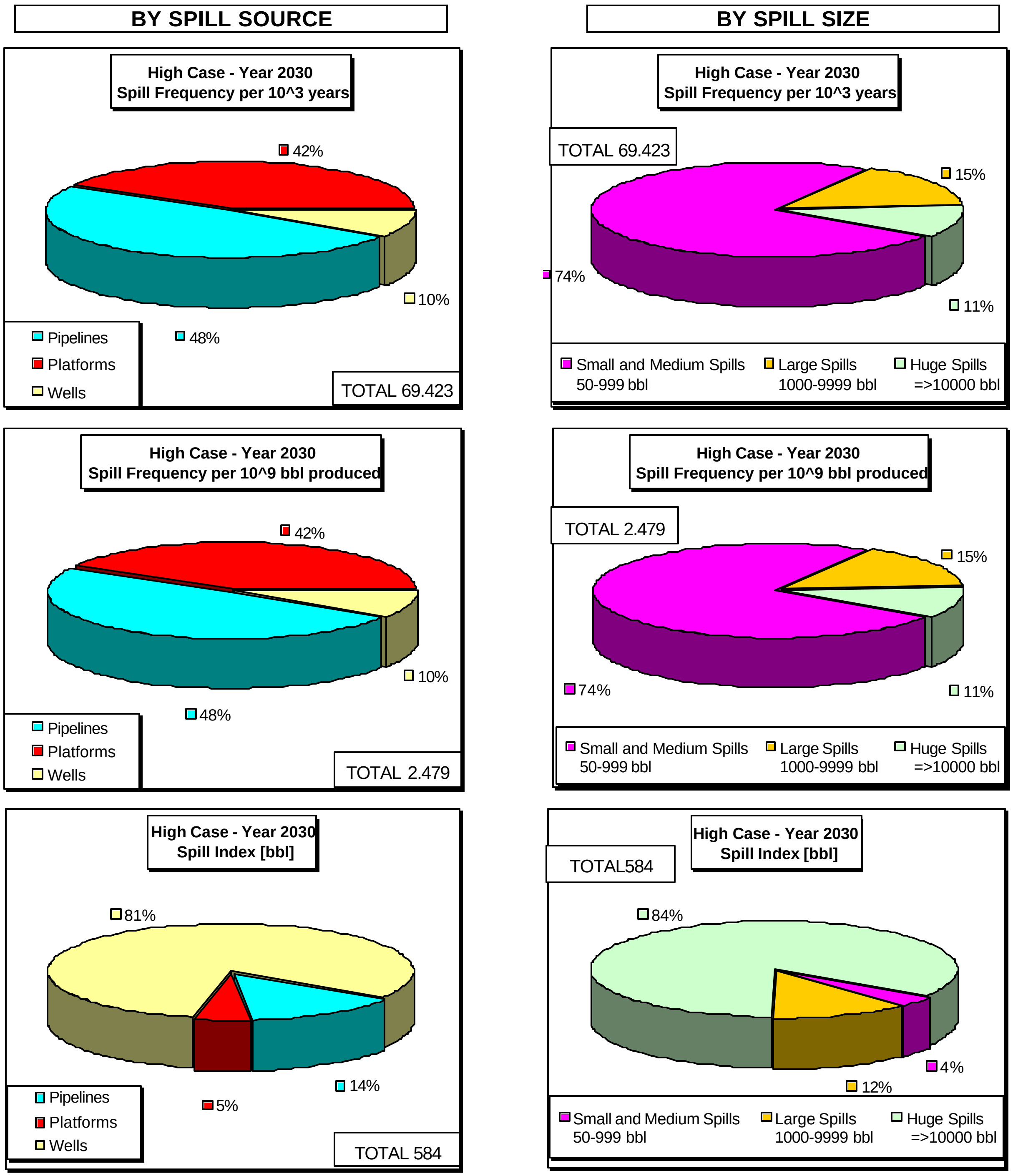


Figure 6.3
Beaufort Sea High Case – Year 2030 – Spill Indicator Composition by Source and Spill Size
(Appendix Figure 4.2.17)

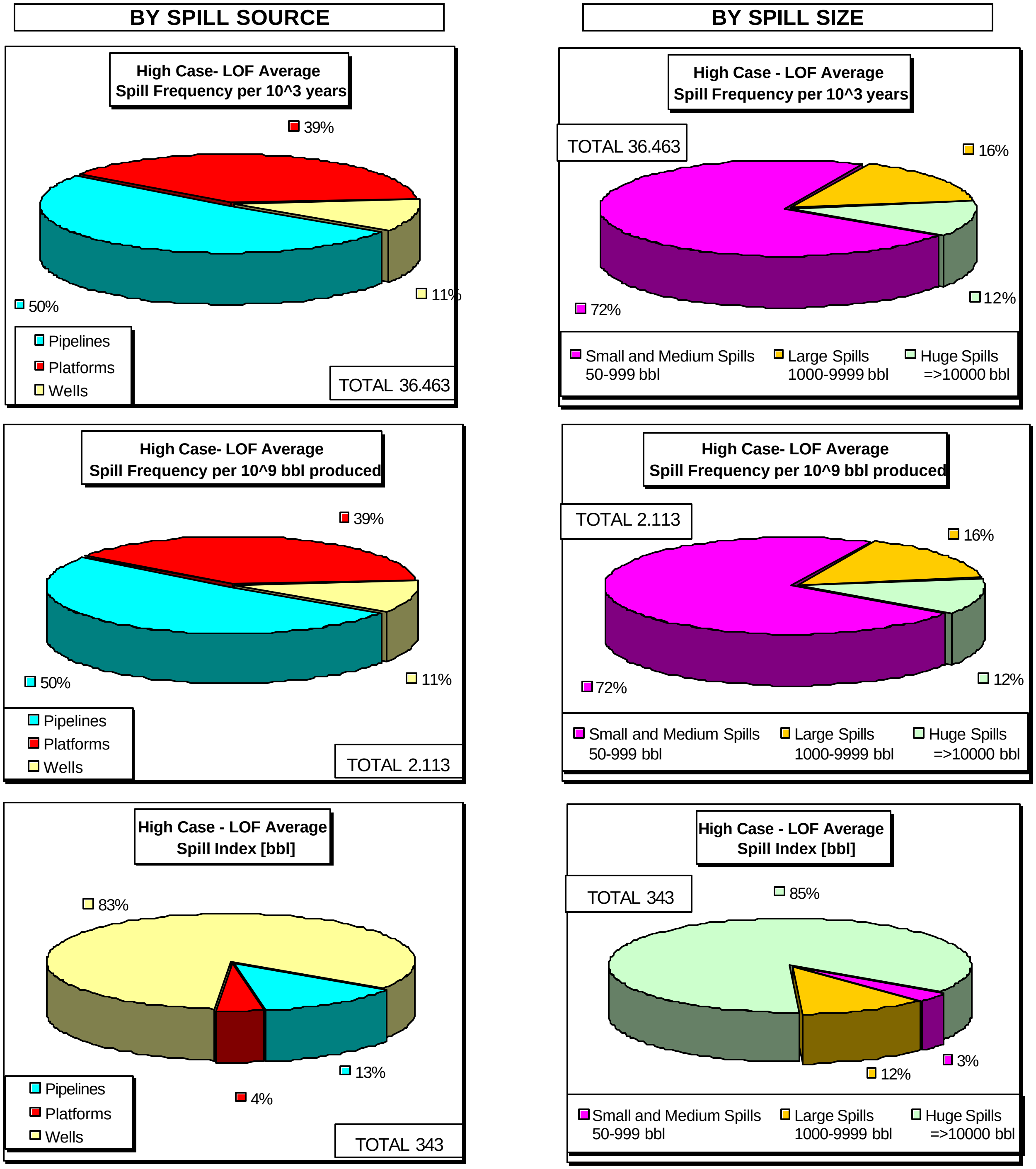


Figure 6.4
Beaufort Sea High Case – Life of Field Average Spill Indicator Composition by Source and Spill Size
(Appendix Figure 4.2.18)

6.1.4 Variability of Oil Spill Occurrence Indicators

Figures 6.5, 6.6, and 6.7 show the Cumulative Distribution Functions (CDF) for the Beaufort Sea Life of Field average spill indicators. The variability of these indicators is fairly representative of the trends in variability for spill indicators for the Low Case as well. Generally, the following can be observed from the figures:

- The variance of the frequency spill indicators (Figures 6.5 and 6.6) decreases as spill size increases for pipelines and platforms. In other words, small and medium spills illustrate the largest variability; huge spills show the least variability for pipelines and platforms.
- For wells, the frequency variability for different spill sizes does not change as much as that for platforms and pipelines.
- The variability of the spill index (Figure 6.7) shows an increasing variability with increasing spill size.

The Cumulative Distribution Functions contain extensive information on the statistical properties of the spill indicators. For example, from Figure 6.5 (bottom right-hand graph), it can be seen, for all significant spills, that the Life of Field average mean (50%) value of 10 (spills per 1,000 years) ranges between about 5 and 15 at the lower and 5% to 95% confidence intervals. A similar percentage variation is shown for the Life of Field average spill frequency per barrel produced in Figure 6.6. The spill index variability shown in Figure 6.7 is proportionally higher. For example, in Figure 6.7 (bottom right-hand corner graph), the mean value of the significant spills index of 325 per billion barrels produced ranges from 200 to 500 over the 5% to 95% confidence interval.

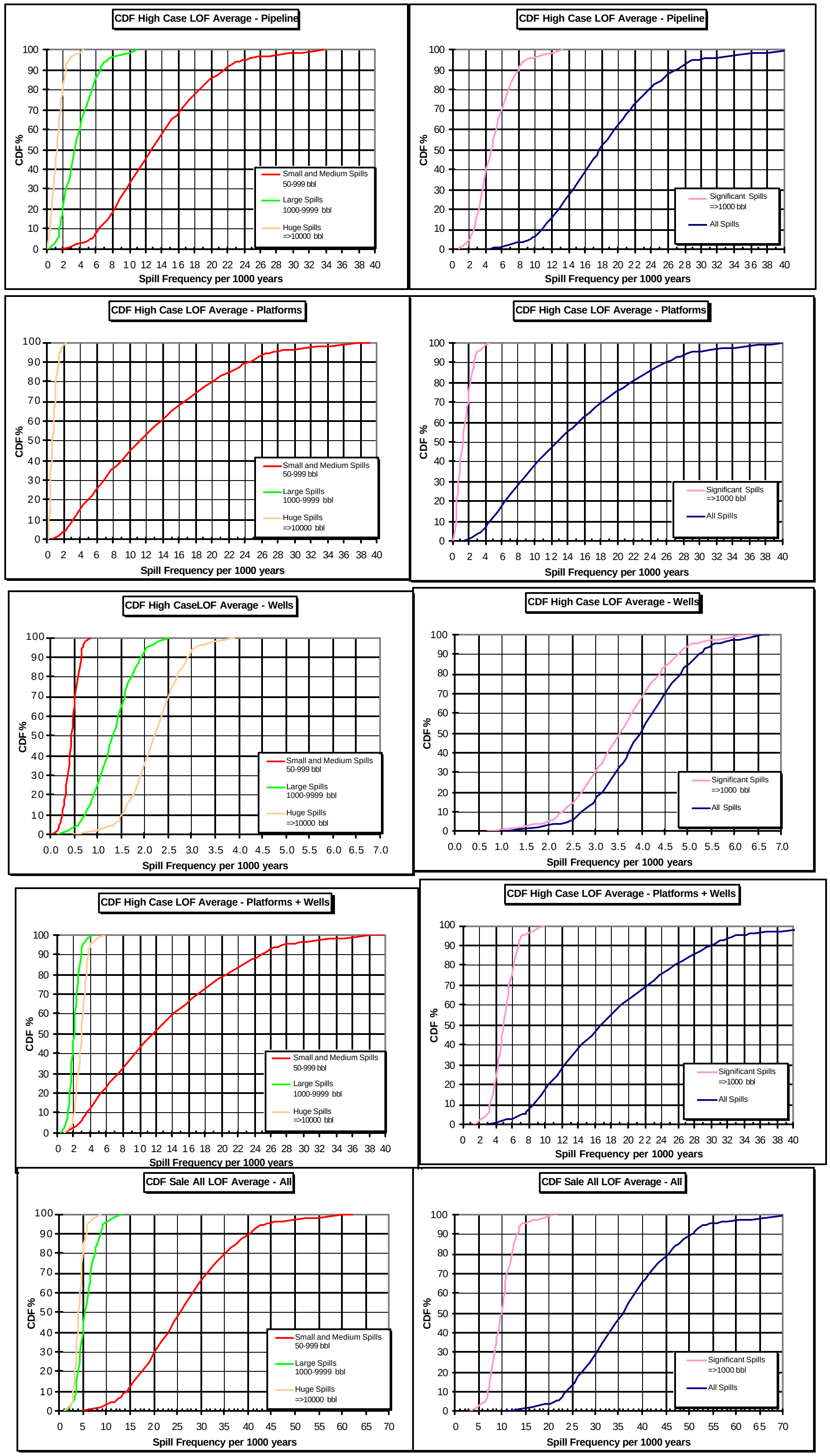


Figure 6.5 Beaufort Sea High Case Life of Field Average Spill Frequency *(Appendix Figure 4.2.14)*

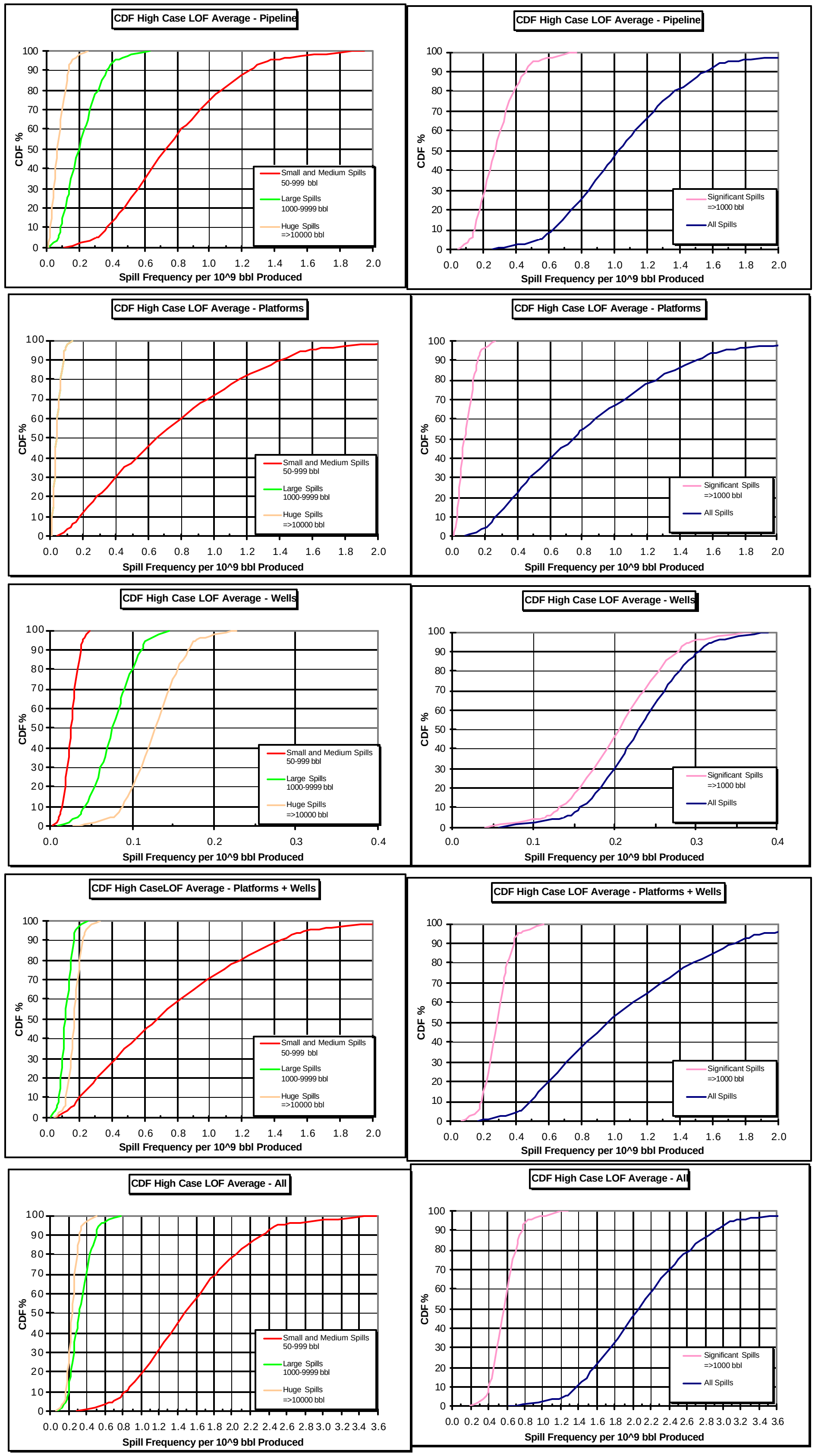
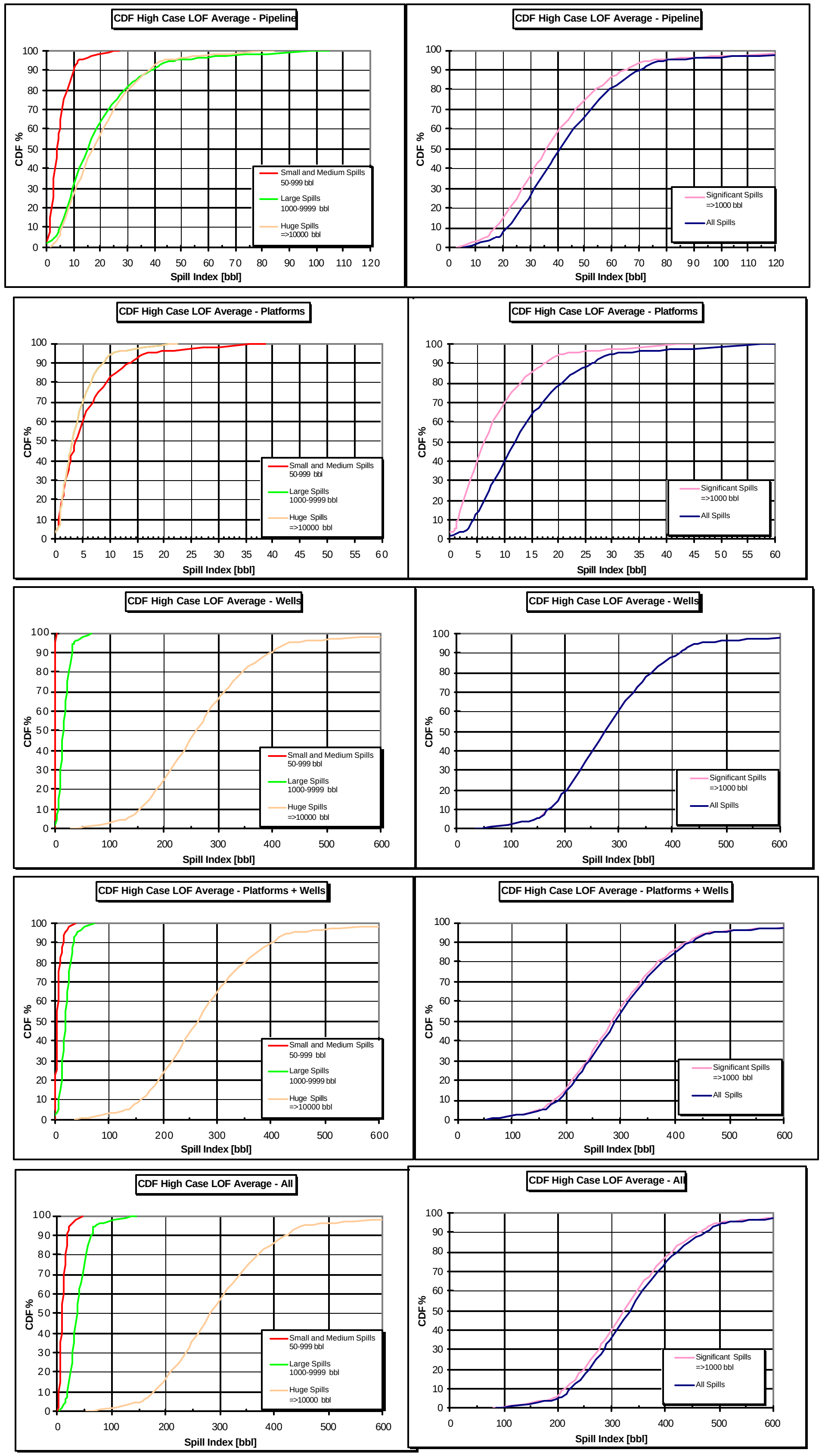


Figure 6.6 Beaufort Sea High Case Life of Field Average Spills per Barrel Produced
(Appendix Figure 4.2.15)

Figure 6.7 Beaufort Sea High Case Life of Field Average Spill Index (bbl) – CDF
(Appendix Figure 4.2.16)



6.2 Conclusions on the Methodology and its Applicability

An analytical tool for the prediction of oil spill occurrence indicators for systems without history, such as future offshore oil production developments in the Beaufort Sea, 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. In addition, the predictive model is setup so that any input variables can be entered as distributions.

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 or other 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 life of field (Life of Field) averages.
- 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.

6.3 Limitations of the Methodology and Results

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.

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 for pipelines and facilities, and were used as a starting point for the fault tree analysis. Although these data are adequate, a broader population base would be expected to give more robust statistics. Unfortunately, data from a broader population base, such as the North Sea, do not contain the level of detail provided in the GOM data.

- 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 systematic manner dependent on engineering judgment.

- A reproducible but relatively elementary analysis of gouging and scour effects was carried out.
- Upheaval buckling 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, as they are highly variable for different locations and pipeline characteristics.

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. The only shortcoming appears to be that the facility abandonment rate is significantly lower than the rate of decline in production.

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

- The indicators have inherited the deficiencies of the input and scenario data noted above.

- 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), global warming, and production volume non-linear effects.

6.4 Recommendations

The following recommendations based on the work may be made:

- Continue to utilize the Monte Carlo spill occurrence indicator model for new scenarios to support MMS needs, as it is currently the best predictive spill occurrence model available.
- Utilize this 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.
- Generalize the model so that it can be run both in an adjusted 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.

REFERENCES

1. AIChE, "Guidelines for Chemical Process Quantitative Risk Analysis", 2nd Edition, Center for Chemical Process Safety, NY, 2000.
2. Anderson, Cheryl McMahon, and Robert P. LaBelle, "Update of Comparative Occurrence Rates for Offshore Oil Spills", Spill Science & Technology Bulletin, Vol. 6., No. 5/6, pp. 303-321, 2000.
3. Beaumont, S., "Refinery Construction in Arctic Weather Conditions – Some Construction, Inspection, and Corrosion Concerns", in Material Performance, Vol. 26:8, pp 53-56, 01 August 1987.
4. Bercha F.G., "Special Problems in Pipeline Risk Assessment", Proceedings of IPC 2000, International Pipeline Conference, Calgary, AB, October 1-5, 2000.
5. Bercha, F.G., A.C. Churcher, and M. Cerovšek, "Escape, Evacuation, and Rescue Modeling for Frontier Offshore Installations", Offshore Technology Conference, Houston, Texas, USA, 2000.
6. Bercha, F.G., and M. Cerovšek, Large Arctic Offshore Project Risk Analysis" Proceeding of Russian Arctic Offshore Conference, St. Petersburg, Russia, 1997.
7. Bercha, F.G., "Fault Trees for Everyday Risk Analysis", Proceedings of Canadian Society for Chemical Engineering, Risk Analysis Seminar, Edmonton, 1990.
8. Bercha, F.G., and Associates (Alberta) Limited, "Ice Scour Methodology Study", Final Report to Gulf Canada Resources, Calgary, AB, March 1986.
9. Bercha, F.G., "Application of Risk Analysis to Offshore Drilling and Risk Mitigation," Proceedings, Risk Analysis Seminar, Royal Commission of the Ocean Ranger Marine Disaster, Toronto, 1984.
10. Bercha, F.G., "Probabilities of Blowouts in the Canadian Arctic", North Sea Offshore Conference, Stavanger, Norway, 1978.
11. Bercha International Inc., "Alternative Oil Spill Occurrence Estimators for the Beaufort and Chukchi Seas – Fault Tree Method", Volumes I and II, OCS Study MMS 2002-047, Final Report to US Department of the Interior, Minerals Management Service, Alaska Outer Continental Shelf Region, August 2002.
12. Bercha International Inc., "Alternative Oil Spill Occurrence Estimators for their Variability for the Beaufort Sea – Fault Tree Method", Volumes I and II, OCS Study MMS 2005-061, Final Report to US Department of the Interior, Minerals Management Service, Alaska Outer Continental Shelf Region, January 2006.
13. Bercha International Inc., "Alternative Oil Spill Occurrence Estimators and their Variability for the Chukchi Sea – Fault Tree Method", Volumes I and II, OCS Study MMS 2006-033, Final Task 1 Report to US Department of the Interior, Minerals Management Service, Alaska Outer Continental Shelf Region, October 2006.
14. Bercha International Inc., "Alternative Oil Spill Occurrence Estimators and their Variability for the Beaufort Sea – Fault Tree Method. Update of GOM OCS Statistics to 2006", OCS

Study MMS 2008-025, Final Task 3.1 Report to US Department of the Interior, Minerals Management Service, Alaska Outer Continental Shelf Region, March 2008.

15. Energy Resources Conservation Board of Alberta, "GASRISK – A Model to Estimate Risk to Public Safety for Uncontrolled Sour Gas Releases", Volume 6, April 1990.
16. E&P Forum, Quantitative Risk Assessment (QRA) Data Sheet Directory, The Oil Industry International Exploration and Production Forum, 25-28 Old Burlington Street, London, 1996.
17. Fairweather E&P Services, Inc., "Historical Blowout Study, North Slope, Alaska", Study for BP-Amoco Exploration (Alaska), Anchorage, AK, June 2000.
18. Fussell, J.B., "How to Hand Calculate System Reliability and Safety Characteristics", in IEEE Transactions on Reliability, R-24(3), 169-174, 1975.
19. Gadd, P.E., G. Hearon, C.B. Leidersdorf, W.G. McDougal, J. Ellsworth, and D. Thomas, "Slope Armor Design and Construction Northstar Production Island", in Proceedings, Volume 1, 16th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC), Ottawa, ON, August 12-17, 2001.
20. Goff, R., J. Hammond, and A.C. Nogueira, "Northstar Sub Sea Pipeline Design of Metallurgy, Weldability, and Supporting Full Scale Bending Tests", in Proceedings, Volume 1, 16th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC), Ottawa, ON, August 12-17, 2001.
21. Gulf Canada, "Analysis of Accidents in Offshore Operations Where Hydrocarbons Were Lost", Report by the Houston Technical Services Center of Gulf Research and Development Company for Gulf Canada Resources, Inc., Calgary, AB, 1981.
22. Hart Crowser Inc., "Estimation of Oil Spill Risk From Alaska North Slope, Trans-Alaskan Pipeline, and Arctic Canada Oil Spill Data Sets", OCS Study MMS 2000-007, Study for US Department of the Interior, Minerals Management Service, Alaska Outer Continental Shelf Region, Anchorage, AK, April 2000.
23. Henley, E.J., and H. Kumamoto, "Reliability Engineering and Risk Assessment", Printice-Hall, Englewood Cliffs, NJ, (ISBN 0-13-772251-6), 1981.
24. Hnatiuk, J., and K.D. Brown, "Sea Bottom Scouring in the Canadian Beaufort Sea", 9th Annual OTC, Houston, TX, May 2-5, 1983.
25. Holand, Per, Offshore Blowouts, Causes and Control, Gulf Publishing, Houston, Texas, USA, 1997.
26. Hoyland, A., and M. Rausand, "System Reliability Theory: Models and Statistical Methods", John Wiley and Sons, New York, NY, 1994.
27. Hunt, D.M., K.R. McClusky, R. Shirley, and R. Spitzenberger, "Facility Engineering for Arctic Conditions", in Proceedings, Volume 1, 16th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC), Ottawa, ON, August 12-17, 2001.
28. ISO WG8, Arctic Structures, Reliability, Chapter 7, Section 7.2.2.3, October 30, 2006..
29. Lanan, G.A., and J.O. Ennis, "Northstar Offshore Arctic Pipeline Project", in Proceedings, Volume 1, 16th International Conference on Port and Ocean Engineering under Arctic

Conditions (POAC), Ottawa, ON, August 12-17, 2001.

30. Leidersdorf, C.B., G.E. Hearon, R.C. Hollar, P.E. Gadd, and T.C. Sullivan, "Ice Gouge and Strudel Scour Data for the Northstar Pipelines", in Proceedings, Volume 1, 16th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC), Ottawa, ON, August 12-17, 2001.
31. Lowrance, W.W., "Of Acceptable Risk", Kaufmann Inc., 1976.
32. Masterson, D.M., A.B. Christopherson, and J.W. Pickering, "Sheet Pile Design for Offshore Gravel Islands", in Proceedings, Volume 1, 16th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC), Ottawa, ON, August 12-17, 2001.
33. Miller, D.L., "Hypersaline Permafrost under a Lagoon of the Arctic Ocean", in Proceedings, Volume 1, 16th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC), Ottawa, ON, August 12-17, 2001.
34. MMS (Minerals Management Service), "Accidents Associated with Oil and Gas Operations: Outer Continental Shelf 1956-1990", OCS Report MMS 92-0058, 1992.
35. MMS (Minerals Management Service), "Federal Offshore Statistics: 1995. Leasing, exploration, production and revenues to December 31, 1995", US Department of the Interior, Mineral Management Service, Operations and Safety Management, OCS Report MMS 97-0007, 1997.
36. MMS (US Department of the Interior, Minerals Management Service, Alaska OCS Region), "Alaska Outer Continental Shelf - Beaufort Sea Planning Area Oil and Gas Lease Sale 144 - Final Environmental Impact Statement", Vol. II, OCS EIS/EA MMS 96-0012, May 1996.
37. MMS (US Department of the Interior, Minerals Management Service, Alaska OCS Region), "Alaska Outer Continental Shelf - Beaufort Sea Planning Area Oil and Gas Lease Sale 170 - Final Environmental Impact Statement", OCS EIS/EA MMS 98-0007, February 1998.
38. MMS (US Department of the Interior, Minerals Management Service, Alaska OCS Region), "Alaska Outer Continental Shelf - Chukchi Sea Oil & Gas Lease Sale 126 - Final Environmental Impact Statement", Vol. II, OCS EIS/EA MMS 90-0095, Anchorage, AK, January 1991.
39. MMS (US Department of the Interior, Minerals Management Service, Alaska OCS Region), "Undiscovered Oil and Gas Resources, Alaska Federal Offshore", OCS Monograph MMS 98-0054, Anchorage, AK, 1998.
40. MMS (US Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Region), "Investigation of Shell Offshore Inc., Hobbit Pipeline Leak Ship Shoal Block 281, January 24, 1990, Gulf of Mexico, Offshore Louisiana", OCS Report MMS 91-0025, New Orleans, March 1991.
41. MMS (US Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Region), "Investigation of the Exxon Company USA Pipeline Leak /Eugene Island Block 314, May 6, 1990, Gulf of Mexico, Offshore Louisiana", OCS Report MMS 91-0066, New

Orleans, November 1991.

42. MMS (US Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Regional Office), "Investigation of Chevron Pipe Line Company Pipeline Leak, South Pass Block 38, September 29, 1998, Gulf of Mexico Off the Louisiana Coast", OCS Report MMS 99-0053, New Orleans, September 1999.
43. MMS (US Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Regional Office), "Investigation of Shell Offshore Inc., Hobbit Pipeline Leak, Ship Shoal Block 281, November 16, 1994, Gulf of Mexico, Off the Louisiana Coast", OCS Report MMS 97-0031, New Orleans, August 1997.
44. MMS (US Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Regional Office), "Investigation of Shell Pipe Line Corporation Pipeline Leak South Pass Block 65 December 30, 1986, Gulf of Mexico off the Louisiana Coast", OCS Report MMS 87-0114, December 1987.
45. Modarres, M., M. Kaminsky, and V. Krisvtsov, "Reliability Engineering and Risk Analysis", Marcel Deker Inc., 1999.
46. O'Connor, M.J, and Associates Ltd., Preliminary Ice Keel/Seabed Interaction Study", Final Report to GCRI, March 1984.
47. Offshore Technology Research Center, "Comparative Risk Analysis for Deepwater Production Systems", Final Project Report for Minerals Management Service, January 2001.
48. OPL, “Field Development Concepts of the World”, 1990.
49. Owen, L., D. Blanchet, and P. Flones, "The Northstar Project - Year-Round Production in the Alaskan Beaufort Sea", in Proceedings, Volume 1, 16th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC), Ottawa, ON, August 12-17, 2001.
50. Paulin, M.J., D. Nixon, G.A. Lanan, and B. McShane, "Environmental Loadings & Geotechnical Considerations for the Northstar Offshore Pipelines", in Proceedings, Volume 1, 16th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC), Ottawa, ON, August 12-17, 2001.
51. Roberts, N.H., W.E. Veseley, D.F. Haasl, and F.F. Goldberg, “Fault Tree Handbook”, NUREG-0492, US Nuclear Regulatory Commission, Washington, DC, 1985.
52. S.L. Ross Environmental Research Ltd., "Blowout and Spill Probability Assessment for the Northstar and Liberty Oil Development Projects in the Alaska North Slope", Report to BP Exploration (Alaska), Inc., November 1998.
53. Ross, S.L., c.W. Ross, F. Lepine, and K.E. Langtry, “*Ixtoc I* Oil Blowout”, Environment Canada E.P.S. Spill Technology Newsletter, pp. 245-256, July-August 1979.
54. S.L. Ross Environmental Research Ltd., "Blowout and Spill Probability Assessment for the Sable Offshore Energy Project", Report to Mobil Oil Canada Properties, November 1995.
55. S.L. Ross Environmental Research Ltd., "Contingency Plans to Monitor and Clean Up Large Spills from SOEP Offshore Facilities", Prepared for Sable Offshore Energy Project,

Halifax, NS, March 31, 1998.

56. S.L. Ross Environmental Research Ltd., "Large Oil Spills and Blowouts from Exploration Drilling on Georges Bank: An Analysis of their Probability, Behaviour, Control and Environmental Effects", Chevron Canada Resources and Texaco Canada Petroleum Inc., submitted to the Georges Bank Review Panel, January 1999.
57. S.L. Ross Environmental Research Ltd., "Oil Spills Associated with the Terra Nova Development Project off Newfoundland: Risk Assessment; Spill Fate, Behaviour and Impact; Countermeasures; and Contingency Planning", Report to Petro-Canada Inc., December 1996.
58. S.L. Ross Environmental Research Ltd., "Panuke/Cohasset Field Development Project: Risk, Behaviour and Effects of Oil Spills", Report to IONA Resources Ltd. and Nova Scotia Resources Ltd., July 1989.
59. ScanPower A.S., "Blowout Frequency Assessment of Northstar", Report to BP Exploration (Alaska), Report No. 27.83.01/R1, Kjeller, Norway, July 2, 2001.
60. Sefton, A.D., "The Development of the U.K. Safety Case Regime: A Shift in Responsibility from Government to Industry", Offshore Technology Conference, Houston, USA, 1994.
61. Shared Services Drilling, "A Review of Alaska North Slope Blowouts, 1974-1997", June 30, 1998.
62. Sharples, B.P.M., J.J. Stiff, D.W. Kalinowski and W.G. Tidmarsh, "Statistical Risk Methodology: Application for Pollution Risks from Canadian Georges Bank Drilling Program", 21st Annual Offshore Technology Conference, Houston, TX, May 1-4, 1989.
63. Southwest Research Institute, "New Methods for Rapid Leak Detection in Offshore Pipelines", Final Report to Minerals management Service, US Department of the Interior, SwRI Project No. 04-4558, April 1992.
64. System Safety and Reliability Committee, Santa Barbara County, Energy Division, "Risk Matrix Guidelines", 1998.
65. U.S. Nuclear Regulatory Commission, "Reactor Safety Study", WASH-1400, NUREG-75/014, Appendix I – IV, October 1975.
66. Upstream Technology Group, "Analysis of Strudel Scours and Ice Gouges for the Liberty Development Pipeline", Final Draft, *no date.*
67. Weeks, W.F., P.W. Barnes, D.M. Rearic, and E. Reimnitz, "Some Probabilistic Aspects of Ice Gouging on the Alaskan Shelf of the Beaufort Sea", US Army Cold Regions Research and Engineering Laboratory, June 7, 1983.
68. Weeks, W.F., P.W. Barnes, D.M. Rearic, and E. Reimnitz, "Statistical Aspects of Ice Gouging on the Alaskan Shelf of the Beaufort Sea", US Army Cold Regions Research and Engineering Laboratory, 1982.
69. Wylie, W.W., and A.B. Visram, "Drilling Kick Statistics", Proceedings, IADC/SPE Drilling Conference, Houston, TX, February 27-March 2, 1980.

The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

The Minerals Management Service Mission

As a bureau of the Department of the Interior, the Minerals Management Service's (MMS) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS), collect revenue from the Federal OCS and onshore Federal and Indian lands, and distribute those revenues.

Moreover, in working to meet its responsibilities, the **Offshore Minerals Management Program** administers the OCS competitive leasing program and oversees the safe and environmentally sound exploration and production of our Nation's offshore natural gas, oil and other mineral resources. The MMS **Royalty Management Program** meets its responsibilities by ensuring the efficient, timely and accurate collection and disbursement of revenue from mineral leasing and production due to Indian tribes and allottees, States and the U.S. Treasury.

The MMS strives to fulfill its responsibilities through the general guiding principles of: (1) being responsive to the public's concerns and interests by maintaining a dialogue with all potentially affected parties and (2) carrying out its programs with an emphasis on working to enhance the quality of life for all Americans by lending MMS assistance and expertise to economic development and environmental protection.