

FINAL TASK 4A.2 REPORT

VOLUME I

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

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March 2008

By



Bercha International Inc.
Calgary, Alberta, Canada



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

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ABSTRACT

Oil spill occurrence estimates were generated for high and low case estimated future oil and gas development scenarios (including exploration, production, and abandonment) in the Chukchi 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): $\geq 10,000$ bbl
- Significant (SG): $\geq 1,000$ bbl

Quantification was carried out for each future year for a high and low principal Chukchi Sea development scenario, with a range of development parameters, in duration up to 28 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.

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- Dr. James Craig, Resource Evaluation Section
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- 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 Chukchi 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 Chukchi 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
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These indicators were quantified for the following spill sizes:

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- Significant (SG): $\geq 1,000$ 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 Chukchi Sea exploration and development scenarios, extending up to 30 years from 2011 to 2040. 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 deep water offshore development scenarios in the Chukchi 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 and Source

How do spill indicators for the Chukchi scenario and for its non-Arctic counterpart vary by spill size and location? Table 1 and Figure 1 and 2 summarize the Life of Field average spill indicator values by spill size and source. 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. High Case non-Arctic spill indicators are approximately 35% greater than Arctic High Case counterparts.

How do the spill indicators vary by facility type for representative scenarios? The contributions of spill indicators by facility have been summarized by representative scenario years, again, 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 Table 1:

- Pipelines contribute the most (57%) to the two Arctic spill frequency indicators.
- Platforms are next in relative contribution to spill frequencies (33%) and least in contribution to spill index (4%).
- Wells are by far (at 80%) the highest contributors to spill index, while platforms and wells together are responsible for an 84% contribution to the spill index.

Table 1
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	12.499	1.350	5	22.491	1.349	9	34.237	2.054	12
	73%	73%	4%	74%	74%	4%	72%	72%	3%
Large Spills 1000-9999 bbl	2.631	0.284	18	4.715	0.283	31	8.155	0.489	52
	15%	15%	12%	15%	15%	12%	17%	17%	14%
Huge Spills =>10000 bbl	1.899	0.205	121	3.385	0.203	213	5.239	0.314	302
	11%	11%	84%	11%	11%	84%	11%	11%	83%
Significant Spills =>1000 bbl	4.529	0.489	138	8.100	0.486	245	13.394	0.804	353
	27%	27%	96%	26%	26%	96%	28%	28%	97%
All Spills	17.028	1.839	143	30.592	1.835	254	47.631	2.858	365
	100%	100%	100%	100%	100%	100%	100%	100%	100%
Pipeline Spills	9.725	1.050	23	17.506	1.050	42	31.452	1.887	78
	57%	57%	16%	57%	57%	16%	66%	66%	21%
Platform Spills	5.702	0.616	6	10.263	0.616	10	12.331	0.740	12
	33%	33%	4%	34%	34%	4%	26%	26%	3%
Well Spills	1.601	0.173	114	2.823	0.169	202	3.848	0.231	275
	9%	9%	80%	9%	9%	80%	8%	8%	75%
Platform and Well Spills	7.303	0.789	120	13.086	0.785	212	16.179	0.971	287
	43%	43%	84%	43%	43%	84%	34%	34%	79%
All Spills	17.028	1.839	143	30.592	1.835	254	47.631	2.858	365
	100%	100%	100%	100%	100%	100%	100%	100%	100%

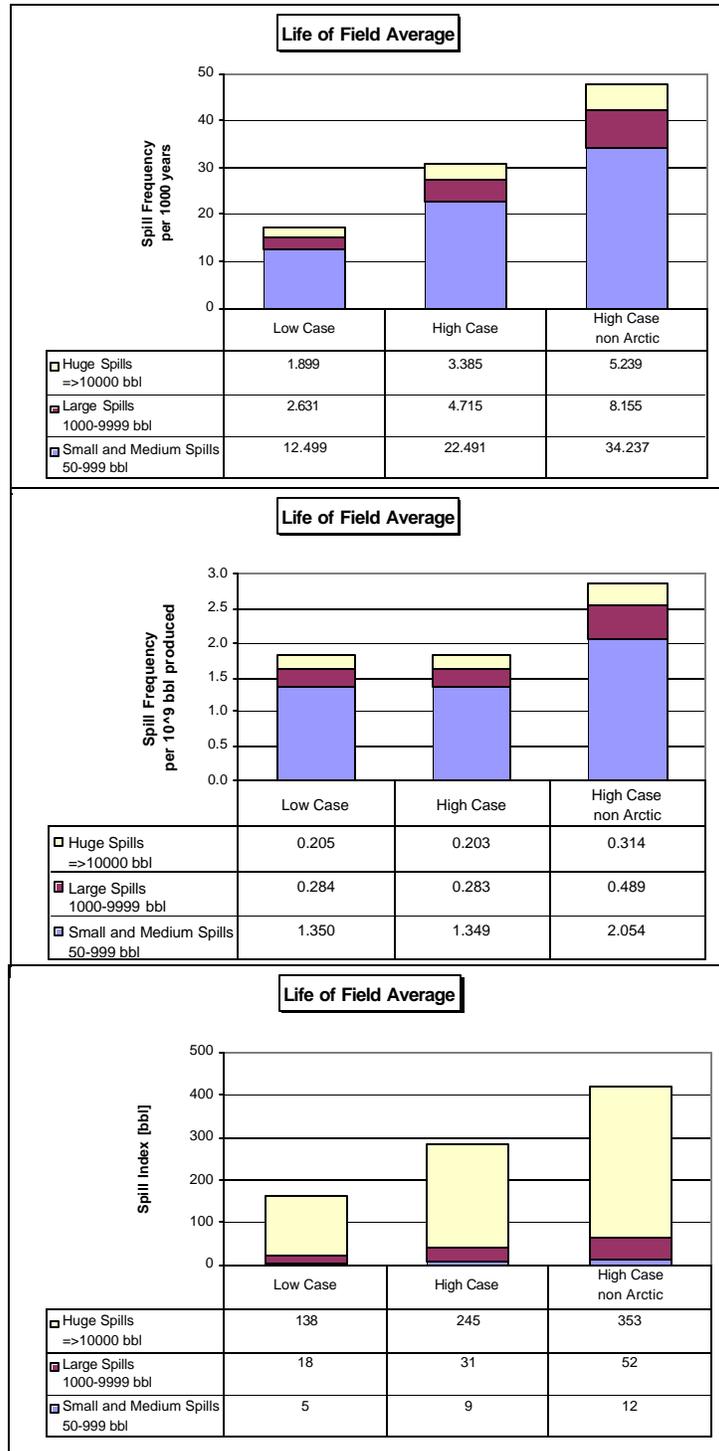


Figure 1
Chukchi Sea Life of Field Spill Indicators – By Spill Size
(Appendix Figure 5.1)

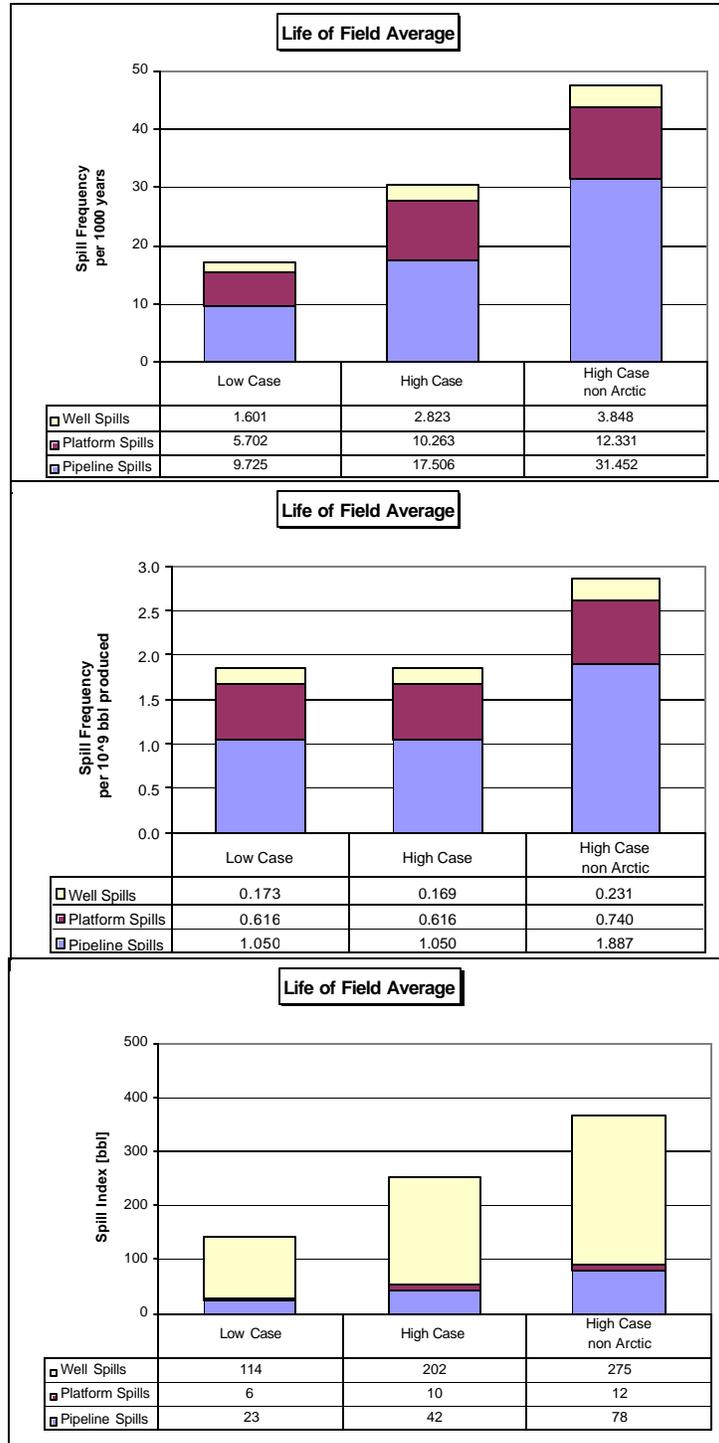


Figure 2
Chukchi Sea Life of Field Spill Indicators – By Source Composition
(Appendix Figure 5.2)

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. Platforms will be in between, with more spills than wells.

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.

B.3 The Variance of Oil Spill Occurrence Indicators

Figures 5, 6, and 7 show the Cumulative Distribution Functions (CDF) for each of the three Chukchi Sea High Case Life of Field average spill indicators. The variability of these indicators is fairly representative of the trends in variability for spill indicators for all sales and locations studied. Generally, the following can be observed from the figures:

- The variance of the frequency spill indicators (Figures 5 and 6) decreases as spill size increases for pipelines and platforms. For example, in the top right-hand graph of Figure 5, the significant spills plot has a much steeper (and hence less variable) slope than that of all spills. Similarly, in the top left-hand graph, small and medium spills illustrate the largest variability; huge spills show the least variability for these facilities.
- The opposite occurs for wells, where large spills show greater variance than small ones.
- The variability of the spill index (Figure 7) shows variance trends opposite to those of the frequency spill indicators.

The Cumulative Distribution Functions contain extensive information on the statistical properties of the spill indicators. For example, from Figure 5, it can be seen, for all significant spills, that the Life of Field average mean (50%) value of 8 (spills per 1,000 years) ranges between about 15 and 3 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 6. The spill index variability shown in Figure 7 is proportionally higher. For example, in Figure 7, the mean value of the significant spills index of 240 per billion barrels produced ranges from 150 to 400.

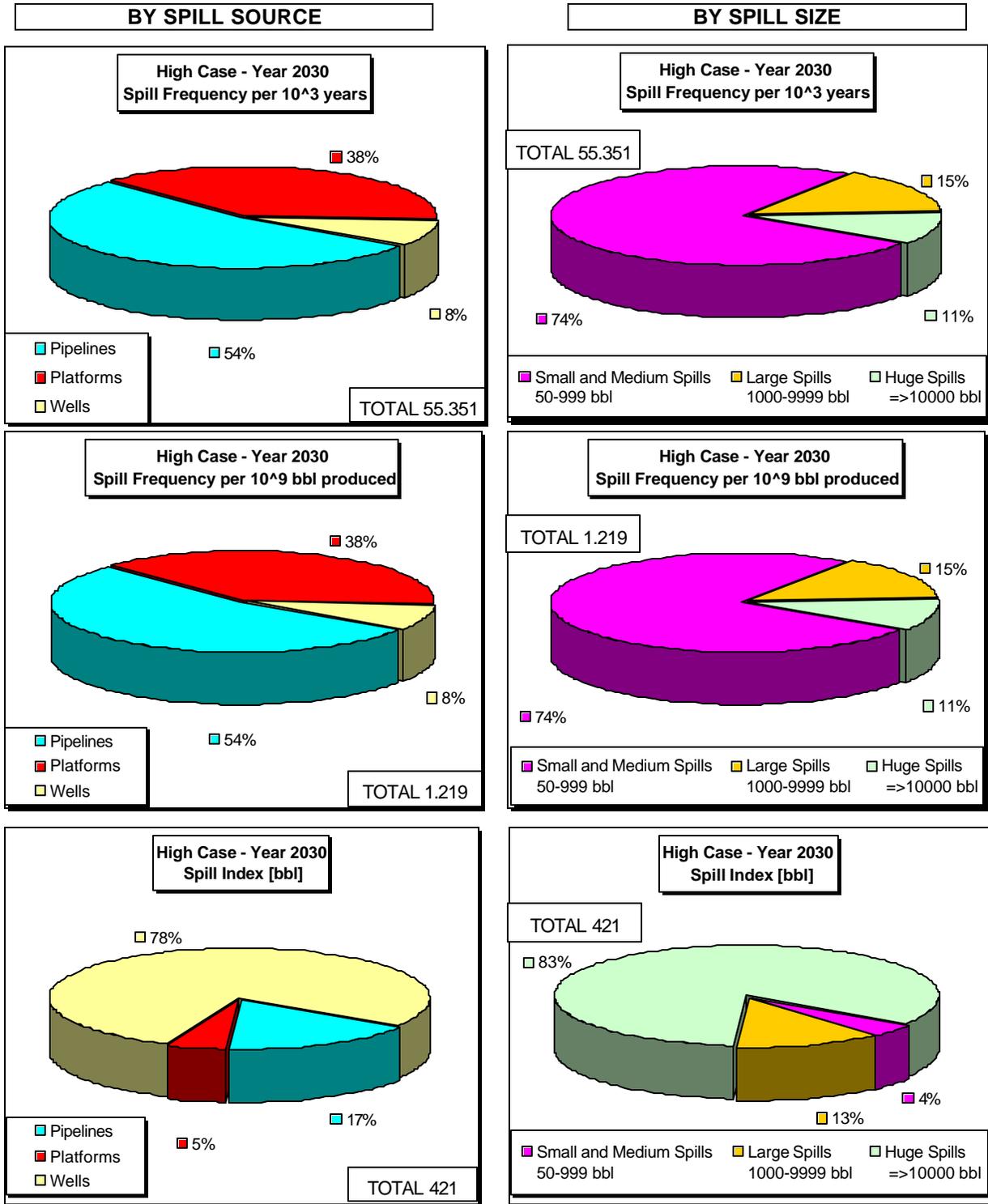


Figure 3
Chukchi Sea High Case – Year 2030 –
Spill Indicator Composition by Source and Spill Size
(Appendix Figure 4.2.17)

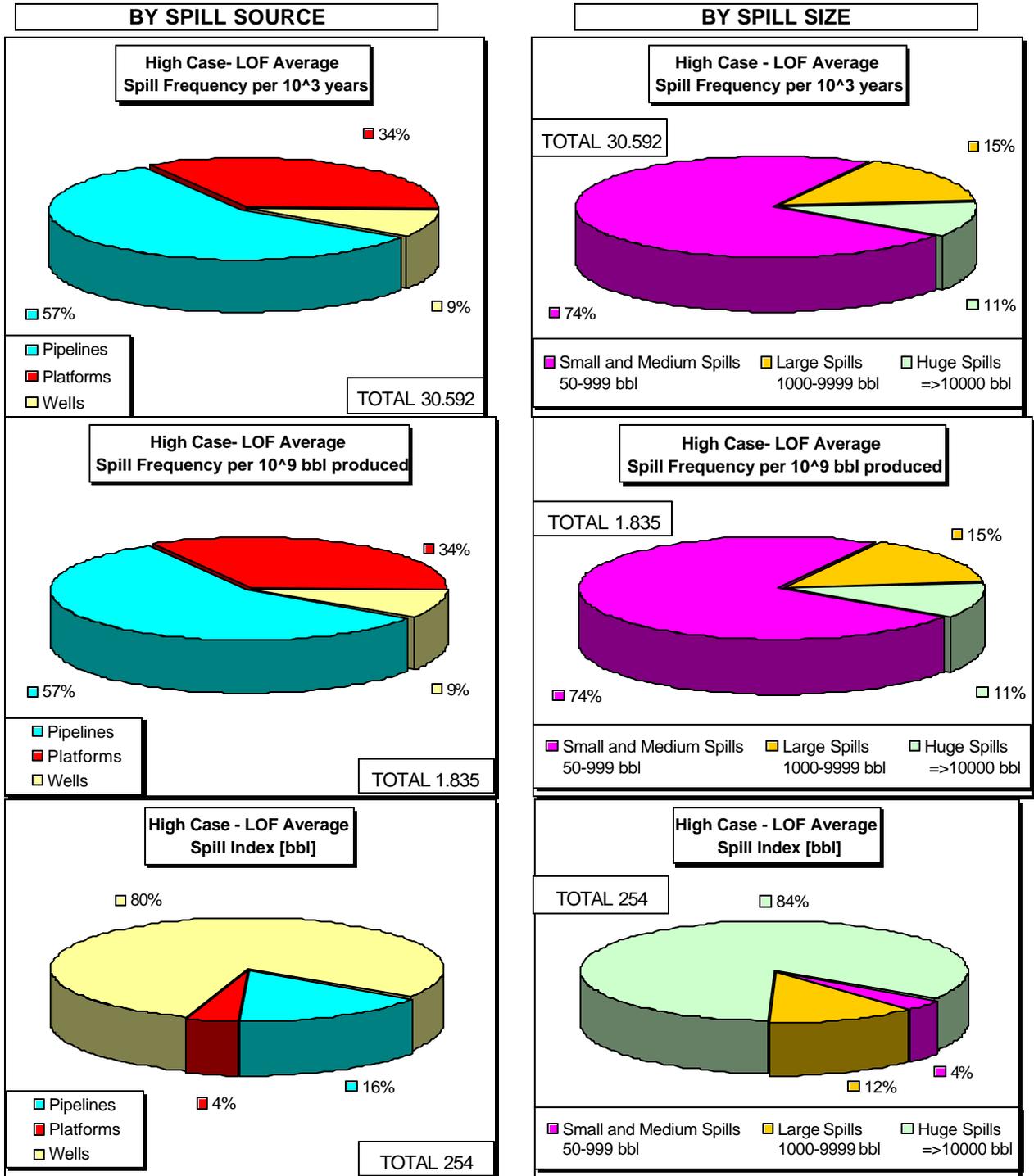


Figure 4
Chukchi Sea High Case – Life of Field Average Spill Indicator
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(Appendix Figure 4.2.18)

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

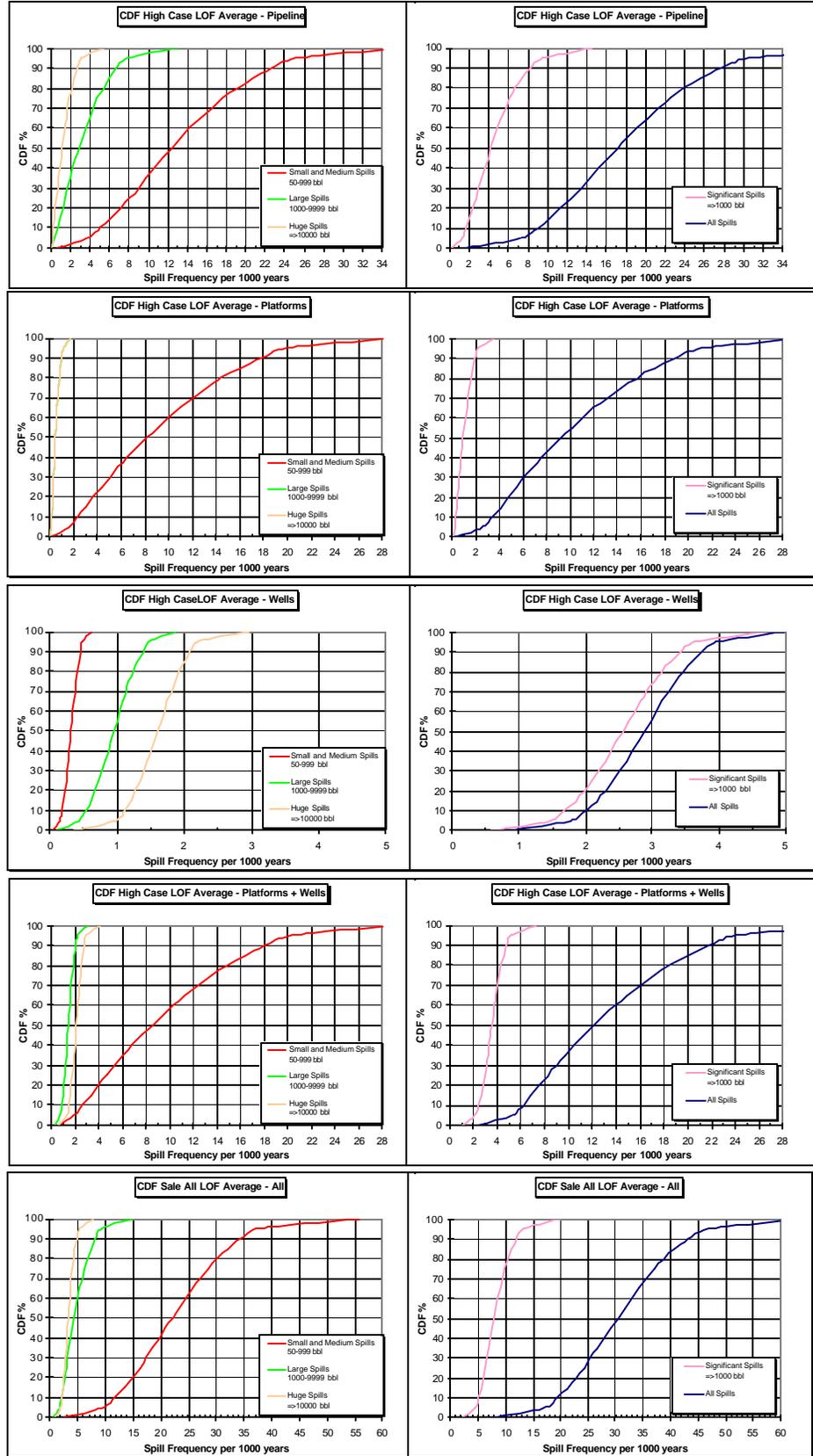


Figure 6
Chukchi Sea
High Case
Life of Field
Average Spills
per Barrel Produced
(Appendix
Figure 4.2.15)

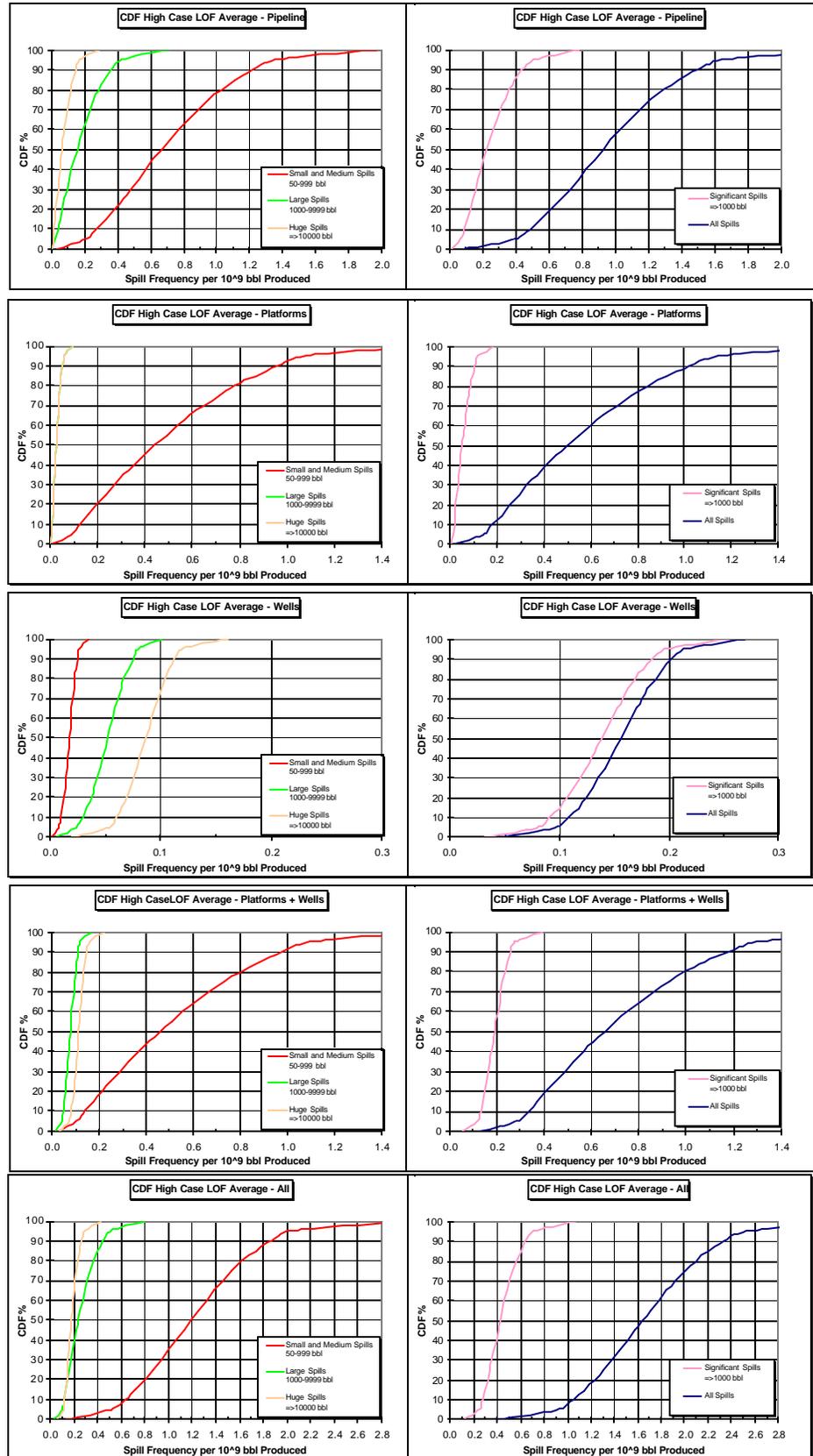
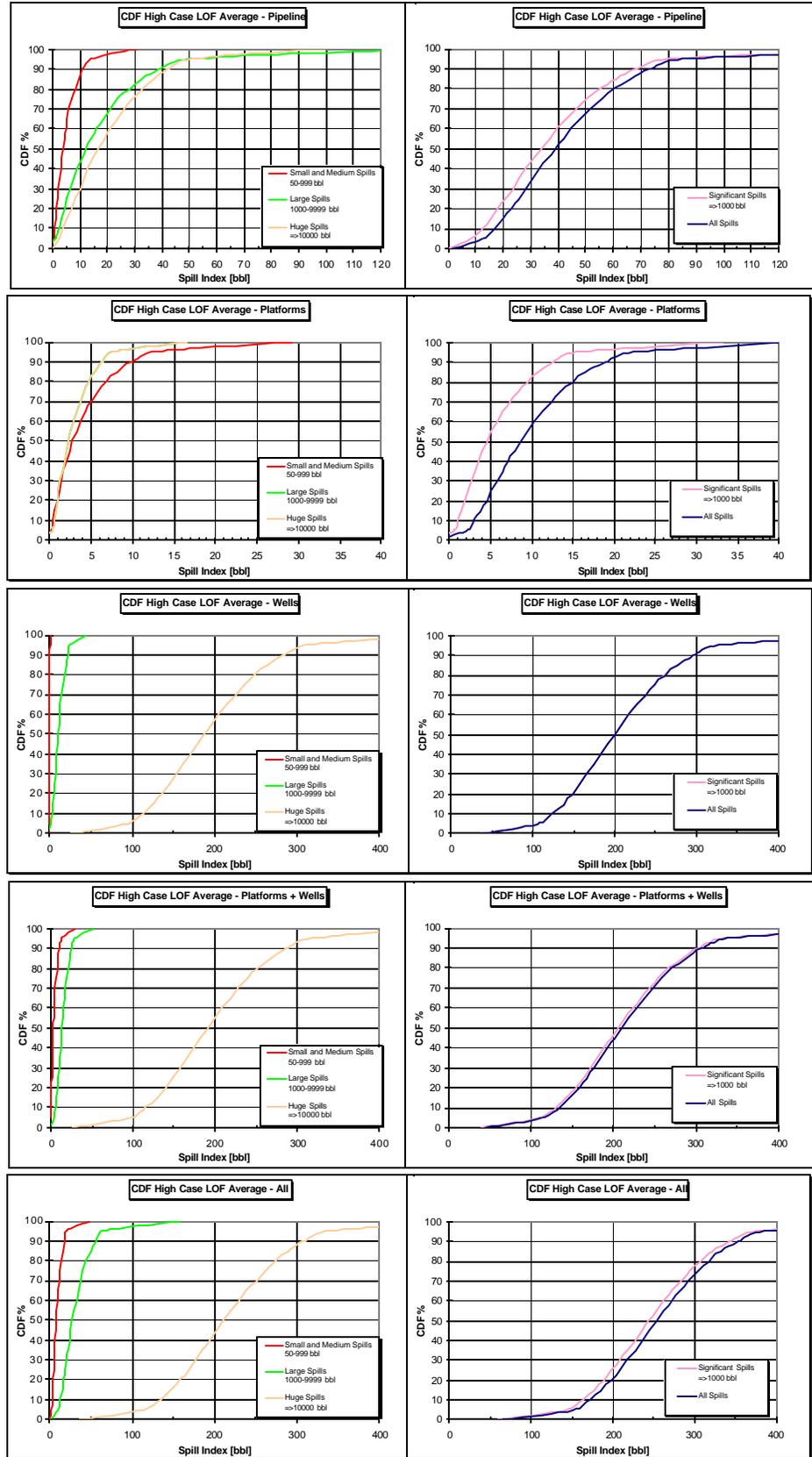


Figure 7
Chukchi Sea
High Case
Life of Field
Average
Spill Index (bbl)
– CDF
(Appendix
Figure 4.2.16)



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 Chukchi 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 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 relative cursory way restricted to engineering judgment.
- Upheaval buckling effect assessments were included on the basis of an educated guess used in previous studies; no engineering analysis was carried out for the assessment of frequencies to be expected for these effects.

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 the oil spill occurrence indicator model to generate additional model validation information, including direct application to specific non-Arctic scenarios, such as GOM projects, which have an oil spill statistical history.
- Utilize the oil spill occurrence indicator model in a sensitivity mode to identify the importance of different Arctic effect variables introduced to provide a prioritized list of those items having the highest potential impact on Arctic oil spills.
- 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.

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GLOSSARY OF TERMS AND ACRONYMS

Bbbl	Billion Barrels
CDF	Cumulative D istribution F unction
Consequence	The direct effect of an accidental event.
GOM	G ulf of 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): $\geq 10,000$ bbl Significant (SG): $\geq 1,000$ 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 deeper waters in the Chukchi and Beaufort Seas.

The prediction of the reliability (or failure) of systems without history can be approached through a variety of mathematical techniques, 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], fault tree methodology was applied to the prediction of oil spill rates for oil and gas developments such as those now operational or contemplated for the Beaufort and Chukchi Seas in the Alaska OCS, and used to generate predictions of oil spill occurrence indicators.

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. In the present study, as well as in the preceding Chukchi Sea study [13], 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:

- 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 Chukchi Sea sales.

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

- Develop the fault tree method for estimating oil spill occurrences from Chukchi 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. Chukchi 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 Year 2011 to 2040. Within the Chukchi study area, the present development is located in deep water; earlier studies [14] dealt with medium and shallow developments. It is assumed that the development in this study is limited to the deep water location while connecting to land through previously studied developments [13].

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 [12], 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) Chukchi 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 Chukchi 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) - $\geq 10,000$ bbl
- Significant (SG) - $\geq 1,000$ 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.

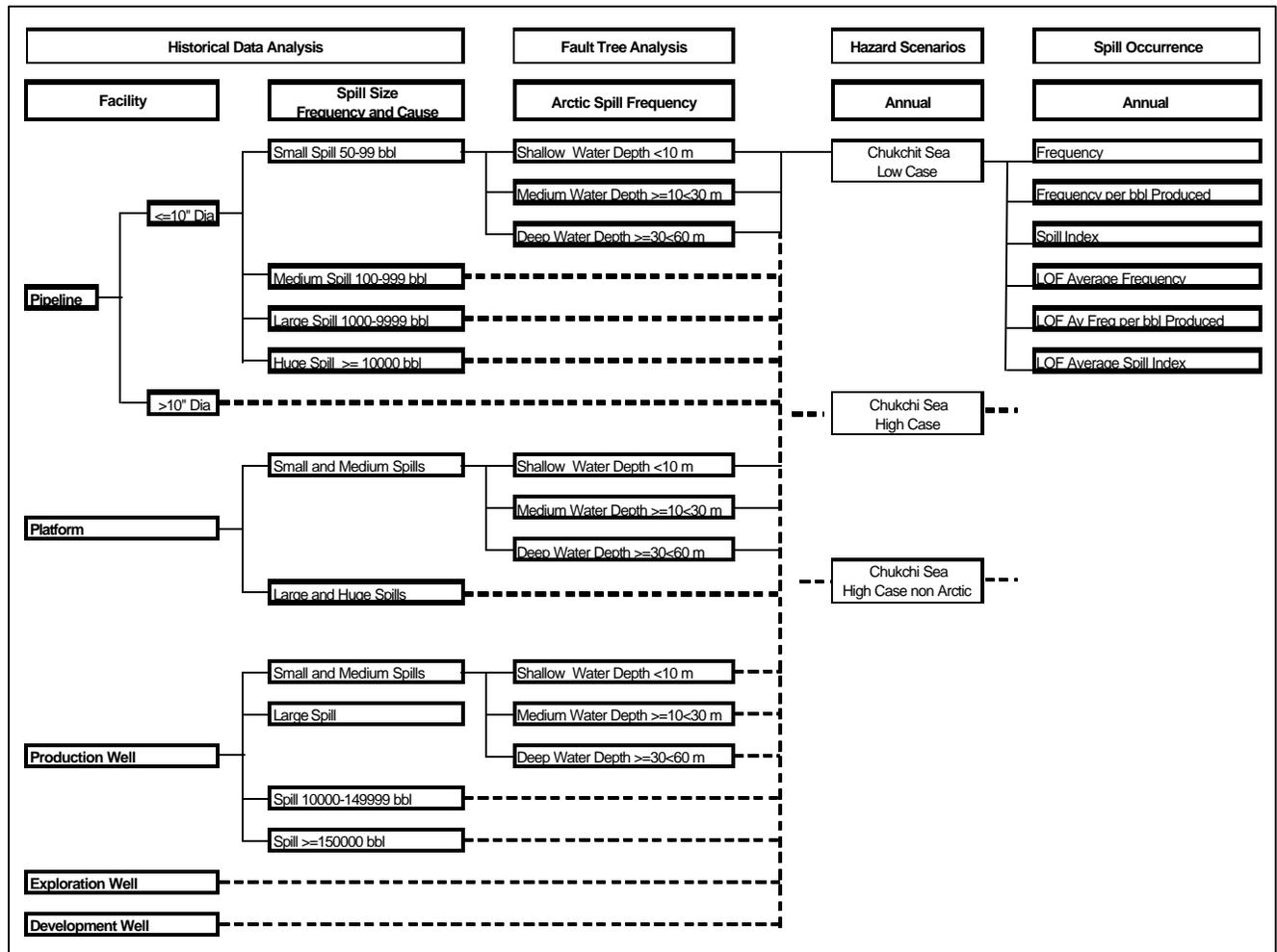


Figure 1.2
Calculation Flow Chart

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 Chukchi Sea extended beyond the 60-meter isobath.

Two principal future development scenarios were defined for the Chukchi Sea, as well as a compatible non-Arctic (hypothetical) scenario. The two Arctic scenarios represent a High and Low production volume case. Each scenario was described for each year in its development history, from the year 2011 to the year 2040. 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 DISTRIBUTION %	NUMBER OF SPILLS	EXPOSURE [km-years]	FREQUENCY spill per 10 ⁵ km-year	HISTORICAL DISTRIBUTION %	NUMBER OF SPILLS	EXPOSURE [km-years]	FREQUENCY spill per 10 ⁵ km-year	
CORROSION	8.57	3	273847	1.0955	6.67	1	273847	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		0.3652					
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:

$$\text{Mode} = 3 \times \text{Historical} - \text{High} - \text{Low} \quad (2.1)$$

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	Exposure	Frequency	
		Number of Spills	km-years	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. DISTRIBUTION %	NUMBER OF SPILLS	EXPOSURE [well-years]	FREQUENCY spill per 10 ⁴ well-year	HIST. DISTRIBUTION %	NUMBER OF SPILLS	EXPOSURE [well-years]	FREQUENCY spill per 10 ⁴ well-year
EQUIPMENT FAILURE	52.24	35	212971	1.6434		212971		
Process Equipment	20.90	14		0.6574			0.0470	
Transfer Hose	17.91	12		0.5635			0.0470	
Incorrect Operation	13.43	9		0.4226			0.0939	
HUMAN ERROR	17.91	12		0.5635			0.1409	
TANK FAILURE	2.99	2		0.0939	14.29		1	0.3287
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

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.

2.5 Arctic Effects Historical Data

2.5.1 General Approaches to the Quantification of Arctic Effects

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

Table 2.8
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		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

2.5.2 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:

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

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 present deep water location in the Chukchi, ice gouging does not occur.

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 – so that for the present study, they do not apply.

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 quantified in previous work [12, 13]. Assuming that a upheaval buckling occurs 20% as often as strudel scour [13], 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. Other Arctic effects have been incorporated on the basis of values used in preceding studies [12, 13].

2.5.5 Thaw Settlement

Thaw settlement occurs when a permafrost lens or formation over which the pipeline was installed melts as a result of the heat generated by the pipeline and ceases to support the pipeline so that the pipeline overburden loads the pipeline and causes it to deflect downwards. As there are no permafrost strata in the Chukchi study area, no thaw settlement is expected.

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.

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

CAUSE CLASSIFICATION	Spill Size	Deep		
		Frequency Increment per 10 ⁵ km-year		
		Min	Mode	Max
Upheaval Buckling	S	0.00221	0.00469	0.02761
	M	0.00221	0.00469	0.02761
	L	0.00552	0.01174	0.06904
	H	0.00110	0.00235	0.01381
Other Arctic	S	0.00033	0.00070	0.00414
	M	0.00033	0.00070	0.00414
	L	0.00083	0.00176	0.01036
	H	0.00017	0.00035	0.00207

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

CAUSE	SPILL SIZE	Water Depth	REASON
		Deep	
		Frequency Increment per 10 ⁴ well-year	
		Expected	
		Mode	
Ice Force	SM	0.3256 <i>0.0765</i>	Assumed 10,000 year return period ice force causes spill 4% of occurrences (96% reliability). 85% of the spills are SM.
	LH	0.0575 <i>0.0135</i>	
Facility Low Temperature	SM	0.0986 <i>0.0986</i>	Assumed fraction of Historical Equipment Failure release frequency with 6% for SM and 1% for LH spill sizes.
	LH	0.0164 <i>0.0164</i>	
Other Arctic	SM	0.0212 <i>0.0088</i>	5% of sum of above.
	LH	0.0037 <i>0.0015</i>	

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 [14].

Table 2.13
Summary of Historical Spill Size Distribution Parameters

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
	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

The subject development is assumed to be entirely in deep water; pipelines connecting the current estimated location to shore were considered in previous studies [13]. For the purposes of the fault tree analysis utilized in this study, future Chukchi 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 (deep water only)
- 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. As indicated above, the subject development is located entirely in deep water.

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 is the Chukchi Sea lease deep water location.

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	<ul style="list-style-type: none"> ▪ Artificial island ▪ Drill barge ▪ Ice island 	<ul style="list-style-type: none"> ▪ Artificial island ▪ Drill ship (summer) ▪ Caisson 	<ul style="list-style-type: none"> ▪ Drill ship (summer) ▪ Semisubmersible (summer) 	<ul style="list-style-type: none"> ▪ Drill ship (summer) ▪ Semisubmersible (summer)
PRODUCTION	<ul style="list-style-type: none"> ▪ Artificial island ▪ Caisson island 	<ul style="list-style-type: none"> ▪ Caisson island ▪ Gravity Base Structure (GBS) 	<ul style="list-style-type: none"> ▪ Caisson island ▪ Gravity Base Structure (GBS) 	<ul style="list-style-type: none"> ▪ New design structure ▪ Submarine habitat
TRANSPORT	<ul style="list-style-type: none"> ▪ Subsea pipeline 	<ul style="list-style-type: none"> ▪ Subsea pipeline 	<ul style="list-style-type: none"> ▪ Subsea pipeline ▪ Storage & tankers 	<ul style="list-style-type: none"> ▪ Subsea pipeline ▪ Submarine storage ▪ Icebreaking tankers ▪ Submarine tankers

3.2 Chukchi Sea Development Scenarios

As a basis for the current analysis, the geographic 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. Table 3.2 summarizes the key quantity parameters of a possible High and Low production Chukchi scenario. The facility quantities are hypothetical, and not based on any operator's plan. No facilities are assumed in the very deep region; all are in the deep region. Onshore facilities are mentioned in Table 3.2 for completeness, but excluded in the analysis.

Table 3.3 summarizes the High Case development scenario including its temporal development from 2011 to Year 2040, after which time it is forecast to cease production. For items such as exploration and field delineation well drilling, the actual number of wells drilled in a given year were needed, since the statistics of well spill (blowouts) are on a per well drilled exposure unit. For items that continue from year to year, such as production wells or subsea pipelines, both the annual incremental and the cumulative total are needed. Specifically, the following facility quantities were estimated and distributed as shown in Table 3.3:

- Exploration wells drilled – annual
- Delineation wells drilled – annual
- Production platforms – annual and cumulative
- 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.

Table 3.4 summarizes the Low Case Chukchi development scenario.

The high and low values given in Tables 3.3 and 3.4, respectively, were used in the balance of the calculations.

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

Scenario Element	Range		Comments
	High	Low	
Maximum oil production (Bbbl/year)	54	30	-
Natural gas production	0	0	Delayed for North Slope gas line; reinjected
Exploration wells	7	4	-
Delineation wells	8	4	Confirm and define the commercial discovery
Production platforms	2	1	Central platform with processing facility; supports 20-100 wells.
Production wells	50	25	On platform
Service wells	-	-	All service wells are on platform
In-field flowlines (mi)	0	0	None
Offshore pipeline (mi)	80	40	Additional pipelines to shore were included in the previous study [13]
Onshore sales pipeline (mi)	300	300	Connecting to existing/future North Slope pipelines (n/a)
Years of activity	30	28	Period from lease sale to end of oil production

Table 3.3
Chukchi Sea High Case Development Data (2011-2040)
(App. Table 3.3)

Year	Water Depth	Exploration Wells	Delineation Wells	Expl./Del. Rigs	Production Platforms						In-use Pipeline Length [miles]						Production MMbbl	
					Platforms		Platform Wells		Subsea Wells		Rigs	Sum <=10"		Sum >10"		Sum All		
					Incr.	Cum.	Incr.	Cum.	Incr.	Cum.		Incr.	Cum.	Incr.	Cum.	Incr.		Cum.
2011	Shallow																	
	Medium																	
	Deep	1		1														
	Total	1		1														
2012	Shallow																	
	Medium																	
	Deep	1	1	1														
	Total	1	1	1														
2013	Shallow																	
	Medium																	
	Deep		2	1														
	Total		2	1														
2014	Shallow																	
	Medium																	
	Deep	1	1	1														
	Total	1	1	1														
2015	Shallow																	
	Medium																	
	Deep	2	1	2														
	Total	2	1	2														
2016	Shallow																	
	Medium																	
	Deep	1	2	2														
	Total	1	2	2														
2017	Shallow																	
	Medium																	
	Deep	1	1	1														
	Total	1	1	1														
2018	Shallow																	
	Medium																	
	Deep																	
	Total																	
2019	Shallow																	
	Medium																	
	Deep										10	10	10	10				
	Total										10	10	10	10				
2020	Shallow																	
	Medium																	
	Deep										10	20	10	20				
	Total										10	20	10	20				

Table 3.3 ~ Continued ~

Year	Water Depth	Exploration Wells	Delineation Wells	Expl./Del. Rigs	Production Platforms						In-use Pipeline Length [miles]						Production MMbbl	
					Platforms		Platform Wells		Subsea Wells		Rigs	Sum ≤ 10"		Sum > 10"		Sum All		
					Incr.	Cum.	Incr.	Cum.	Incr.	Cum.		Incr.	Cum.	Incr.	Cum.	Incr.		Cum.
2021	Shallow																	
	Medium																	
	Deep										20	40	20	40				
	Total										20	40	20	40				
2022	Shallow																	
	Medium																	
	Deep				1	1	6	6		1		10	50	10	50		13.5	
	Total				1	1	6	6		1		10	50	10	50		13.5	
2023	Shallow																	
	Medium																	
	Deep					1	7	13		1		10	60	10	60		16.9	
	Total					1	7	13		1		10	60	10	60		16.9	
2024	Shallow																	
	Medium																	
	Deep					1	7	20		1		20	80	20	80		22.5	
	Total					1	7	20		1		20	80	20	80		22.5	
2025	Shallow																	
	Medium																	
	Deep				1	2	11	31		2		80		80		43.5		
	Total				1	2	11	31		2		80		80		43.5		
2026	Shallow																	
	Medium																	
	Deep					2	7	38		1		80		80		46.9		
	Total					2	7	38		1		80		80		46.9		
2027	Shallow																	
	Medium																	
	Deep					2	7	45		1		80		80		52.5		
	Total					2	7	45		1		80		80		52.5		
2028	Shallow																	
	Medium																	
	Deep					2	5	50		1		80		80		54.0		
	Total					2	5	50		1		80		80		54.0		
2029	Shallow																	
	Medium																	
	Deep					2		50				80		80		49.2		
	Total					2		50				80		80		49.2		
2030	Shallow																	
	Medium																	
	Deep					2		50				80		80		45.4		
	Total					2		50				80		80		45.4		

Table 3.3 ~ Continued ~

Year	Water Depth	Exploration Wells	Delineation Wells	Expl./Del. Rigs	Production Platforms						In-use Pipeline Length [miles]						Production MMbbl	
					Platforms		Platform Wells		Subsea Wells		Rigs	Sum <=10"		Sum >10"		Sum All		
					Incr.	Cum.	Incr.	Cum.	Incr.	Cum.		Incr.	Cum.	Incr.	Cum.	Incr.		Cum.
2031	Shallow																	
	Medium																	
	Deep					2	50					80		80			36.3	
	Total					2	50					80		80			36.3	
2032	Shallow																	
	Medium																	
	Deep					2	50					80		80			29.0	
	Total					2	50					80		80			29.0	
2033	Shallow																	
	Medium																	
	Deep					2	50					80		80			23.3	
	Total					2	50					80		80			23.3	
2034	Shallow																	
	Medium																	
	Deep					2	50					80		80			18.6	
	Total					2	50					80		80			18.6	
2035	Shallow																	
	Medium																	
	Deep					2	50					80		80			14.8	
	Total					2	50					80		80			14.8	
2036	Shallow																	
	Medium																	
	Deep					2	50					80		80			11.9	
	Total					2	50					80		80			11.9	
2037	Shallow																	
	Medium																	
	Deep					2	50					80		80			9.5	
	Total					2	50					80		80			9.5	
2038	Shallow																	
	Medium																	
	Deep					-1	1	-25	25			-40	40	-40	40		5.0	
	Total					-1	1	-25	25			-40	40	-40	40		5.0	
2039	Shallow																	
	Medium																	
	Deep					1	25					40		40			4.0	
	Total					1	25					40		40			4.0	
2040	Shallow																	
	Medium																	
	Deep					1	25					40		40			3.2	
	Total					1	25					40		40			3.2	

**Table 3.4
Chukchi Sea Low Case Development Data (2011-2038)**

Year	Water Depth	Exploration Wells	Delineation Wells	Expl./Del. Rigs	Production Platforms						In-use Pipeline Length [miles]						Production MMbbl	
					Platforms		Platform Wells		Subsea Wells		Rigs	Sum <=10"		Sum >10"		Sum All		
					Incr.	Cum.	Incr.	Cum.	Incr.	Cum.		Incr.	Cum.	Incr.	Cum.	Incr.		Cum.
2011	Shallow																	
	Medium																	
	Deep	1		1														
	Total	1		1														
2012	Shallow																	
	Medium																	
	Deep	1	1	1														
	Total	1	1	1														
2013	Shallow																	
	Medium																	
	Deep		2	1														
	Total		2	1														
2014	Shallow																	
	Medium																	
	Deep	1	1	1														
	Total	1	1	1														
2015	Shallow																	
	Medium																	
	Deep	1		1														
	Total	1		1														
2016	Shallow																	
	Medium																	
	Deep																	
	Total																	
2017	Shallow																	
	Medium																	
	Deep																	
	Total																	
2018	Shallow																	
	Medium																	
	Deep																	
	Total																	
2019	Shallow																	
	Medium																	
	Deep										10	10	10	10				
	Total										10	10	10	10				
2020	Shallow																	
	Medium																	
	Deep										10	20	10	20				
	Total										10	20	10	20				

Table 3.4 ~ Continued ~

Year	Water Depth	Exploration Wells	Delineation Wells	Expl./Del. Rigs	Production Platforms						In-use Pipeline Length [miles]						Production MMbbl	
					Platforms		Platform Wells		Subsea Wells		Rigs	Sum <=10"		Sum >10"		Sum All		
					Incr.	Cum.	Incr.	Cum.	Incr.	Cum.		Incr.	Cum.	Incr.	Cum.	Incr.		Cum.
2021	Shallow																	
	Medium																	
	Deep										20	40	20	40				
	Total										20	40	20	40				
2022	Shallow																	
	Medium																	
	Deep				1	1	6	6		1		40		40			13.5	
	Total				1	1	6	6		1		40		40			13.5	
2023	Shallow																	
	Medium																	
	Deep					1	7	13		1		40		40			16.9	
	Total					1	7	13		1		40		40			16.9	
2024	Shallow																	
	Medium																	
	Deep					1	7	20		1		40		40			22.5	
	Total					1	7	20		1		40		40			22.5	
2025	Shallow																	
	Medium																	
	Deep					1	5	25		1		40		40			30.0	
	Total					1	5	25		1		40		40			30.0	
2026	Shallow																	
	Medium																	
	Deep					1		25				40		40			30.0	
	Total					1		25				40		40			30.0	
2027	Shallow																	
	Medium																	
	Deep					1		25				40		40			30.0	
	Total					1		25				40		40			30.0	
2028	Shallow																	
	Medium																	
	Deep					1		25				40		40			24.0	
	Total					1		25				40		40			24.0	
2029	Shallow																	
	Medium																	
	Deep					1		25				40		40			19.2	
	Total					1		25				40		40			19.2	
2030	Shallow																	
	Medium																	
	Deep					1		25				40		40			15.4	
	Total					1		25				40		40			15.4	

Table 3.4 ~ Continued ~

Year	Water Depth	Exploration Wells	Delineation Wells	Expl./Del. Rigs	Production Platforms						In-use Pipeline Length [miles]						Production MMbbl	
					Platforms		Platform Wells		Subsea Wells		Rigs	Sum <=10"		Sum >10"		Sum All		
					Incr.	Cum.	Incr.	Cum.	Incr.	Cum.		Incr.	Cum.	Incr.	Cum.	Incr.		Cum.
2031	Shallow																	
	Medium																	
	Deep					1	25					40		40			12.3	
	Total					1	25					40		40			12.3	
2032	Shallow																	
	Medium																	
	Deep					1	25					40		40			9.8	
	Total					1	25					40		40			9.8	
2033	Shallow																	
	Medium																	
	Deep					1	25					40		40			7.9	
	Total					1	25					40		40			7.9	
2034	Shallow																	
	Medium																	
	Deep					1	25					40		40			6.3	
	Total					1	25					40		40			6.3	
2035	Shallow																	
	Medium																	
	Deep					1	25					40		40			5.0	
	Total					1	25					40		40			5.0	
2036	Shallow																	
	Medium																	
	Deep					1	25					40		40			4.0	
	Total					1	25					40		40			4.0	
2037	Shallow																	
	Medium																	
	Deep					1	25					40		40			3.2	
	Total					1	25					40		40			3.2	
2038	Shallow																	
	Medium																	
	Deep					-1	-25					-40		-40				
	Total					-1	-25					-40		-40				

CHAPTER 4

FAULT TREE ANALYSIS FOR ARCTIC OIL SPILL FREQUENCIES

4.1 General Description of Fault Tree Analysis

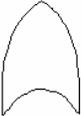
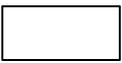
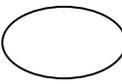
Fault trees are a method for modeling the occurrence of failures. They are used when an adequate history to provide failure statistics is not available. Developed initially by Rasmussen for the US Nuclear Regulatory Commission in the early 1970s [65, 51], fault trees have become a popular risk analytic 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

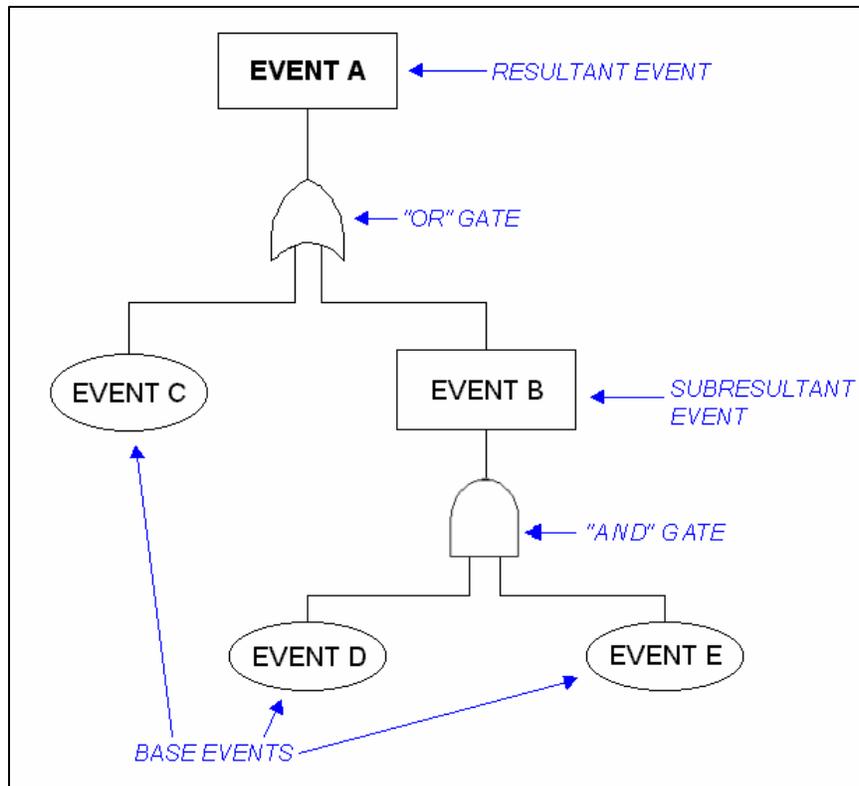
4.2.1 *Fault Tree Analysis Basics*

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, 14, 18, 23, 51]. For the present application, a simple system connected through OR gates only will be 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:

$$\text{For AND Gate: } P = \prod_n^{i=1} P_i \quad (4.1a)$$

Example: Output Event Probability = P_x
Input Events failure probabilities, P_1, P_2, \dots

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

$$\text{For OR Gate: } P = 1 - \prod_n^{i=1} (1 - P_i) \quad (4.2a)$$

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

$$P_y = 1 - \prod_n (1 - P_1)(1 - P_2)(1 - P_3)$$

$$P_y = P_1 + P_2 + P_3; \text{ for } P_i \leq 0.1 \quad (4.2b)$$

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.

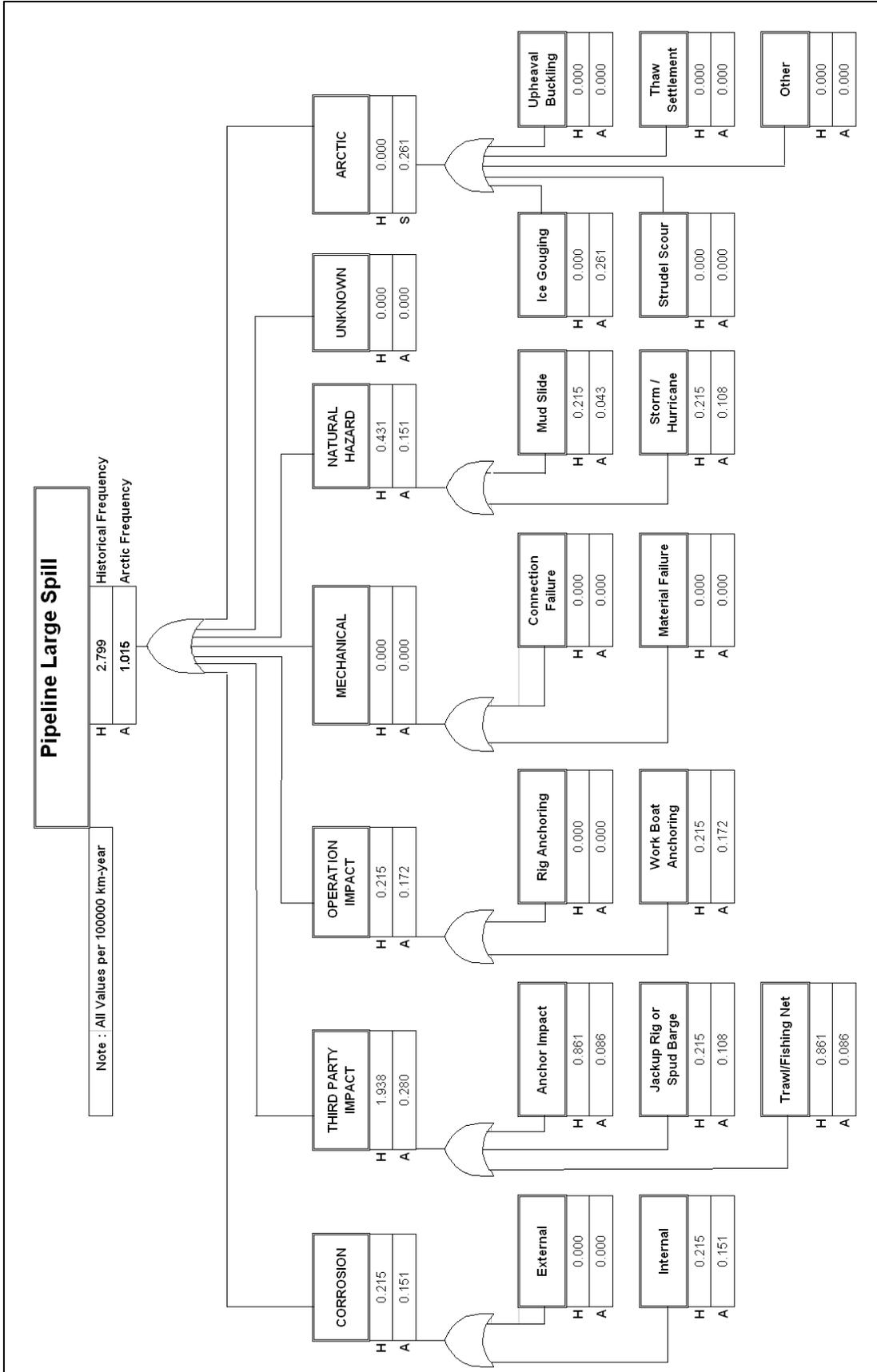


Figure 4.2
Example of Fault Tree to Transform Historical (GOM) to Arctic Spill Frequencies¹
¹ The input data used here are only illustrative and do not represent the inputs used later in this study.

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 1.015×10^{-5} /km-yr. The non-Arctic historical frequency for this spill size, by comparison, is 2.799×10^{-5} /km-yr, or approximately 2.8 times higher. Both frequencies are for illustrative purposes only.

4.2.3 Monte Carlo Simulation

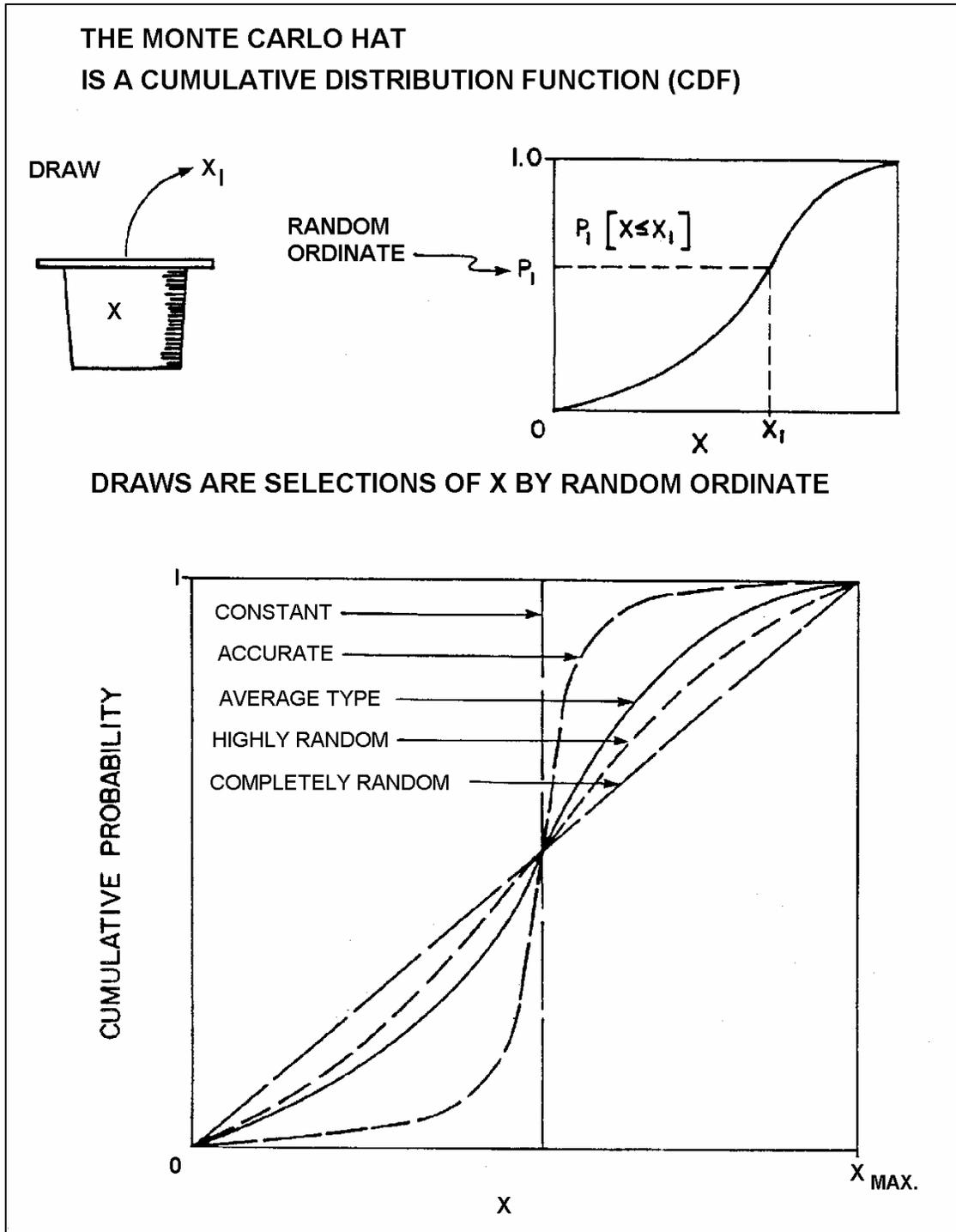
A type of numerical simulation, called Monte Carlo simulation [9] can be used to obtain the outcome of a set of interactions for equations in which the independent variables are described by distributions of any arbitrary form. The Monte Carlo simulation is a systematic method for selecting values from 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:

$$X = X_1 + X_2 \quad (4.3)$$

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 study [12], a Triangular Distribution was selected.

According to [13], 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				
				Historical	Low	Mode	High	Expected
By Diameter	By Spill Size							
<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 10⁵ 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	Deep		Reason	
		Historical	Expected Frequency Change %		
CORROSION					
External	All		(30)	Low temperature and bio effects. Extra smart pigging.	
Internal	All		(30)	Extra smart pigging.	
THIRD PARTY IMPACT					
Anchor Impact	All		(50)	Low traffic.	
Jackup Rig or Spud Barge	All		(50)	Low facility density.	
Trawl/Fishing Net	All		(50)	Low fishing activity. Less bottom fishing in deeper water.	
OPERATION IMPACT					
Rig Anchoring	All		(20)	Low marine traffic during ice season (8 months).	
Work Boat Anchoring	All		(20)	Low work boat traffic during ice season (8 months).	
MECHANICAL					
Connection Failure	All				
Material Failure	All				
NATURAL HAZARD					
Mud Slide	All		(80)	Gradient low. Mud slide potential (gradient) increases with water depth.	
Storm/ Hurricane	All		(60)	Fewer severe storms.	
		Freq. Increment per 10 ⁵ km ² -year			
		Expected			
		Mode			
ARCTIC					
Upheaval Buckling	S		0.0129	The failure frequency is 20% of that of Strudel Scour [13].	
			0.0047		
	M		0.0129		
			0.0047		
	L		0.0323		
		0.0117			
H		0.0065			
		0.0023			
Other Arctic	S		0.0019		Assessed as 10% of all Arctic effects [13].
			0.0007		
	M		0.0019		
			0.0007		
	L		0.0048		
			0.0018		
	H		0.0010		
			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 $1/10$ of the modal value.

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

CAUSE CLASSIFICATION	Spill Size	Deep		
		Frequency Change %		
		Min	Mode	Max
CORROSION				
External	All	(90)	(30)	(10)
Internal	All	(90)	(30)	(10)
THIRD PARTY IMPACT				
Anchor Impact	All	(90)	(50)	(10)
Jackup Rig or Spud Barge	All	(90)	(50)	(10)
Trawl/Fishing Net	All	(90)	(50)	(10)
OPERATION IMPACT				
Rig Anchoring	All	(50)	(20)	(10)
Work Boat Anchoring	All	(50)	(20)	(10)
MECHANICAL				
Connection Failure	All			
Material Failure	All			
NATURAL HAZARD				
Mud Slide	All	(90)	(80)	(10)
Storm/ Hurricane	All	(90)	(60)	(10)
		Frequency Increment per 10⁵ km-year		
ARCTIC UNIQUE				
Upheaval Buckling	S	0.00221	0.00469	0.02761
	M	0.00221	0.00469	0.02761
	L	0.00552	0.01174	0.06904
	H	0.00110	0.00235	0.01381
Other Arctic	S	0.00033	0.00070	0.00414
	M	0.00033	0.00070	0.00414
	L	0.00083	0.00176	0.01036
	H	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. Although only deep water is applicable for this development, frequencies derived for shallow and medium depth categories are shown, but not used later. 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 10⁵ km-yr) historically. With the first and second order frequency changes attributable to Arctic effects, this frequency is reduced to 2.750 for deep water. A similar reduction of failure frequencies 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.

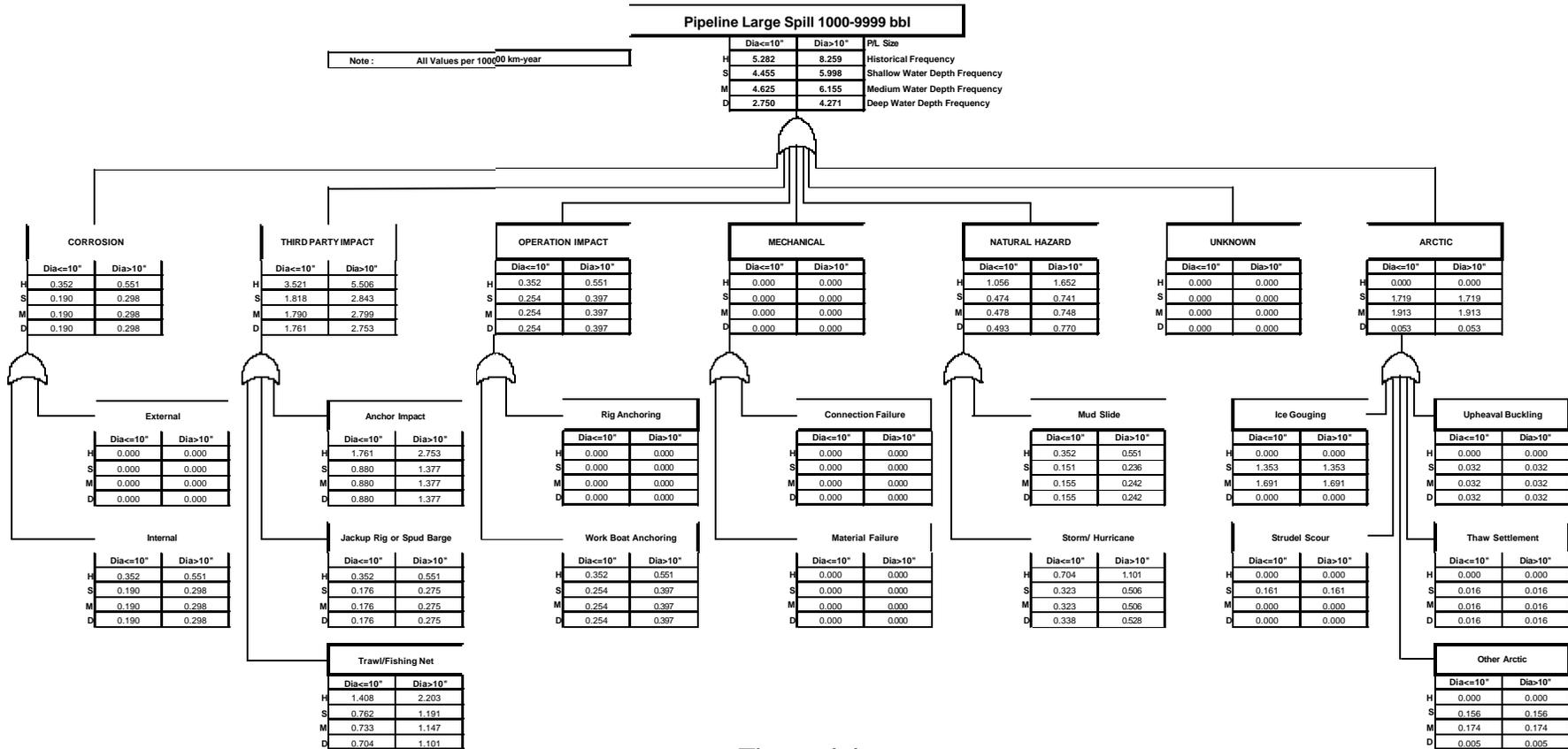


Figure 4.4
Large Spill Frequencies for Pipeline
(Appendix Figure 2.3)

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

CAUSE CLASSIFICATION	HISTORICAL DISTRIBUTION %	SMALL SPILLS 50-99 bbl							
		Pipeline Diameter <=10"				Pipeline Diameter >10"			
		FREQUENCY spills per 10 ⁵ km-year	Deep			FREQUENCY spills per 10 ⁵ km-year	Deep		
			Frequency Change	New Frequency	New Distribution %		Frequency Change	New Frequency	New Distribution %
CORROSION	8.57	0.517	(0.238)	0.280	5.84	0.566	(0.260)	0.306	5.84
External	2.86	0.172	(0.079)	0.093	1.95	0.189	(0.087)	0.102	1.95
Internal	5.71	0.345	(0.158)	0.187	3.89	0.378	(0.173)	0.204	3.89
THIRD PARTY IMPACT	22.86	1.380	(0.690)	0.690	14.39	1.510	(0.755)	0.755	14.40
Anchor Impact	20.00	1.207	(0.604)	0.604	12.60	1.322	(0.661)	0.661	12.60
Jackup Rig or Spud Barge									
Trawl/Fishing Net	2.86	0.172	(0.086)	0.086	1.80	0.189	(0.094)	0.094	1.80
OPERATION IMPACT	8.57	0.517	(0.145)	0.373	7.78	0.566	(0.158)	0.408	7.78
Rig Anchoring	2.86	0.172	(0.048)	0.124	2.59	0.189	(0.053)	0.136	2.59
Work Boat Anchoring	5.71	0.345	(0.096)	0.249	5.19	0.378	(0.106)	0.272	5.19
MECHANICAL	5.71	0.345		0.345	7.20	0.378		0.378	7.20
Connection Failure	2.86	0.172		0.172	3.60	0.189		0.189	3.60
Material Failure	2.86	0.172		0.172	3.60	0.189		0.189	3.60
NATURAL HAZARD	48.57	2.932	(0.193)	2.739	57.15	3.209	(0.211)	2.998	57.17
Mud Slide	5.71	0.345	(0.193)	0.152	3.17	0.378	(0.211)	0.166	3.17
Storm/ Hurricane	42.86	2.587		2.587	53.98	2.832		2.832	54.00
ARCTIC			0.021	0.021	0.44		0.021	0.021	0.41
Ice Gouging									
Strudel Scour									
Upheaval Buckling			0.0129	0.0129	0.27		0.0129	0.0129	0.25
Thaw Settlement			0.0065	0.0065	0.13		0.0065	0.0065	0.12
Other Arctic			0.0019	0.0019	0.04		0.0019	0.0019	0.04
UNKNOWN	5.71	0.345		0.345	7.20	0.378		0.378	7.20
TOTALS	100.00	6.036	(1.244)	4.792	100.00	6.608	(1.363)	5.244	100.00

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

(App. Table 2.4)

CAUSE CLASSIFICATION	HISTORICAL DISTRIBUTION %	MEDIUM SPILLS 100-999 bbl							
		Pipeline Diameter <=10"				Pipeline Diameter >10"			
		FREQUENCY spills per 10 ⁵ km-year	Deep			FREQUENCY spills per 10 ⁵ km-year	Deep		
			Frequency Change	New Frequency	New Distribution %		Frequency Change	New Frequency	New Distribution %
CORROSION	8.57	0.905	(0.416)	0.490	5.85	1.274	(0.585)	0.689	5.86
External	2.86	0.302	(0.139)	0.163	1.95	0.425	(0.195)	0.230	1.95
Internal	5.71	0.604	(0.277)	0.327	3.90	0.850	(0.390)	0.460	3.90
THIRD PARTY IMPACT	22.86	2.414	(1.207)	1.207	14.42	3.398	(1.699)	1.699	14.43
Anchor Impact	20.00	2.113	(1.056)	1.056	12.62	2.973	(1.487)	1.487	12.63
Jackup Rig or Spud Barge									
Trawl/Fishing Net	2.86	0.302	(0.151)	0.151	1.80	0.425	(0.212)	0.212	1.80
OPERATION IMPACT	8.57	0.905	(0.253)	0.652	7.79	1.274	(0.356)	0.918	7.80
Rig Anchoring	2.86	0.302	(0.084)	0.217	2.60	0.425	(0.119)	0.306	2.60
Work Boat Anchoring	5.71	0.604	(0.169)	0.435	5.20	0.850	(0.237)	0.612	5.20
MECHANICAL	5.71	0.604		0.604	7.21	0.850		0.850	7.22
Connection Failure	2.86	0.302		0.302	3.61	0.425		0.425	3.61
Material Failure	2.86	0.302		0.302	3.61	0.425		0.425	3.61
NATURAL HAZARD	48.57	5.131	(0.338)	4.793	57.26	7.221	(0.475)	6.746	57.30
Mud Slide	5.71	0.604	(0.338)	0.266	3.18	0.850	(0.475)	0.374	3.18
Storm/ Hurricane	42.86	4.527		4.527	54.08	6.372		6.372	54.12
ARCTIC			0.021	0.021	0.25		0.021	0.021	0.18
Ice Gouging									
Strudel Scour									
Upheaval Buckling			0.0129	0.0129	0.15		0.0129	0.0129	0.11
Thaw Settlement			0.0065	0.0065	0.08		0.0065	0.0065	0.05
Other Arctic			0.0019	0.0019	0.02		0.0019	0.0019	0.02
UNKNOWN	5.71	0.604		0.604	7.21	0.850		0.850	7.22
TOTALS	100.00	10.563	(2.192)	8.371	100.00	14.867	(3.094)	11.773	100.00

Table 4.8
Arctic Pipeline Large Spill (1,000-9,999 bbl) Frequencies
(App. Table 2.5)

CAUSE CLASSIFICATION	HISTORICAL DISTRIBUTION %	LARGE SPILLS 1000-9999 bbl							
		Pipeline Diameter <=10"				Pipeline Diameter >10"			
		FREQUENCY spills per 10 ³ km-year	Deep			FREQUENCY spills per 10 ³ km-year	Deep		
			Frequency Change	New Frequency	New Distribution %		Frequency Change	New Frequency	New Distribution %
CORROSION	6.67	0.352	(0.162)	0.190	6.92	0.551	(0.253)	0.298	6.97
External									
Internal	6.67	0.352	(0.162)	0.190	6.92	0.551	(0.253)	0.298	6.97
THIRD PARTY IMPACT	66.67	3.521	(1.761)	1.761	64.01	5.506	(2.753)	2.753	64.46
Anchor Impact	33.33	1.761	(0.880)	0.880	32.00	2.753	(1.377)	1.377	32.23
Jackup Rig or Spud Barge	6.67	0.352	(0.176)	0.176	6.40	0.551	(0.275)	0.275	6.45
Trawl/Fishing Net	26.67	1.408	(0.704)	0.704	25.60	2.203	(1.101)	1.101	25.78
OPERATION IMPACT	6.67	0.352	(0.098)	0.254	9.22	0.551	(0.154)	0.397	9.29
Rig Anchoring									
Work Boat Anchoring	6.67	0.352	(0.098)	0.254	9.22	0.551	(0.154)	0.397	9.29
MECHANICAL									
Connection Failure									
Material Failure									
NATURAL HAZARD	20.00	1.056	(0.564)	0.493	17.91	1.652	(0.882)	0.770	18.03
Mud Slide	6.67	0.352	(0.197)	0.155	5.64	0.551	(0.308)	0.242	5.68
Storm/ Hurricane	13.33	0.704	(0.367)	0.338	12.27	1.101	(0.573)	0.528	12.36
ARCTIC			0.053	0.053	1.93		0.053	0.053	1.25
Ice Gouging									
Strudel Scour									
Upheaval Buckling			0.0323	0.0323	1.17		0.0323	0.0323	0.76
Thaw Settlement			0.0161	0.0161	0.59		0.0161	0.0161	0.38
Other Arctic			0.0048	0.0048	0.18		0.0048	0.0048	0.11
UNKNOWN									
TOTALS	100.00	5.282	(2.531)	2.750	100.00	8.259	(3.988)	4.271	100.00

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

CAUSE CLASSIFICATION	HISTORICAL DISTRIBUTION %	HUGE SPILLS =>10000 bbl							
		Pipeline Diameter <=10"				Pipeline Diameter >10"			
		FREQUENCY spills per 10 ⁵ km-year	Deep			FREQUENCY spills per 10 ⁵ km-year	Deep		
			Frequency Change	New Frequency	New Distribution %		Frequency Change	New Frequency	New Distribution %
CORROSION	6.67	0.050	(0.023)	0.027	6.87	0.220	(0.101)	0.119	7.02
External									
Internal	6.67	0.050	(0.023)	0.027	6.87	0.220	(0.101)	0.119	7.02
THIRD PARTY IMPACT	66.67	0.503	(0.252)	0.252	63.52	2.203	(1.101)	1.101	64.86
Anchor Impact	33.33	0.252	(0.126)	0.126	31.76	1.101	(0.551)	0.551	32.43
Jackup Rig or Spud Barge	6.67	0.050	(0.025)	0.025	6.35	0.220	(0.110)	0.110	6.49
Trawl/Fishing Net	26.67	0.201	(0.101)	0.101	25.41	0.881	(0.441)	0.441	25.95
OPERATION IMPACT	6.67	0.050	(0.014)	0.036	9.15	0.220	(0.062)	0.159	9.35
Rig Anchoring									
Work Boat Anchoring	6.67	0.050	(0.014)	0.036	9.15	0.220	(0.062)	0.159	9.35
MECHANICAL									
Connection Failure									
Material Failure									
NATURAL HAZARD	20.00	0.151	(0.081)	0.070	17.77	0.661	(0.353)	0.308	18.15
Mud Slide	6.67	0.050	(0.028)	0.022	5.59	0.220	(0.123)	0.097	5.71
Storm/ Hurricane	13.33	0.101	(0.052)	0.048	12.18	0.441	(0.229)	0.211	12.43
ARCTIC			0.011	0.011	2.69		0.011	0.011	0.63
Ice Gouging									
Strudel Scour									
Upheaval Buckling			0.0065	0.0065	1.63		0.0065	0.0065	0.38
Thaw Settlement			0.0032	0.0032	0.81		0.0032	0.0032	0.19
Other Arctic			0.0010	0.0010	0.24		0.0010	0.0010	0.06
UNKNOWN									
TOTALS	100.00	0.755	(0.359)	0.396	100.00	3.304	(1.606)	1.698	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 ⁵ km-year	Arctic Frequency	Historical Frequency spills per 10 ⁵ km-year	Arctic Frequency
		Deep		Deep
SMALL SPILLS 50-99 bbl	6.036	4.792	6.608	5.244
MEDIUM SPILLS 100-999 bbl	10.563	8.371	14.867	11.773
LARGE SPILLS 1000-9999 bbl	5.282	2.750	8.259	4.271
HUGE SPILLS =>10000 bbl	0.755	0.396	3.304	1.698

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, the process facility release, storage tank release, and structural 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. As before, storms tend to be less severe in the Arctic, and certainly during the ice season would have limited impact on the facility. Due to the extremely low traffic density, as for the case of pipelines, the ship collision cause has been reduced by 50%.

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
		Deep	
EQUIPMENT FAILURE	All		
Process Equipment	All	(30)	State of the art now, High QC, High Inspection and Maintenance Requirements
Transfer Hose	All	(30)	State of the art now, High QC, High Inspection and Maintenance Requirements
Incorrect Operation	All	(30)	State of the art now, High QC, High Inspection and Maintenance Requirements
HUMAN ERROR	All	(20)	More qualified personnel - training, education, but colder
TANK FAILURE	All	(30)	State of the art now, High QC, High Inspection and Maintenance Requirements
SHIP COLLISION	All	(40)	Very low traffic density.
WEATHER	All	20	Cold Temperatures, cycling
HURRICANE	All	(60)	Less severe storms. More intensity in deep water.
OTHER	All		
		Freq. Increment per 10 ⁴ well-year	
		Expected	
		Mode	
ARCTIC UNIQUE			
Ice Force	SM	0.3256	Assumed 10,000 year return period ice force causes spill 4% of occurrences (96% reliability). 85% of the spills are SM.
		0.0765	
LH		0.0575	
		0.0135	
Facility Low Temperature	SM	0.0986	Assumed fraction of Historical Equipment Failure release frequency with 6% for SM and 1% for LH spill sizes.
		0.0986	
LH		0.0164	
		0.0164	
Other Arctic	SM	0.0212	5% of sum of above.
		0.0088	
LH		0.0037	
		0.0015	

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

CAUSE CLASSIFICATION	Spill Size	Deep		
		Frequency Change %		
		Min	Mode	Max
EQUIPMENT FAILURE	All			
Process Equipment	All	(60)	(30)	(10)
Transfer Hose	All	(60)	(30)	(10)
Incorrect Operation	All	(60)	(30)	(10)
HUMAN ERROR	All	(60)	(20)	(10)
TANK FAILURE	All	(60)	(30)	(10)
SHIP COLLISION	All	(60)	(40)	(10)
WEATHER	All	10	20	30
HURRICANE	All	(90)	(60)	(10)
OTHER	All			
		Frequency Increment per 10⁴ well-year		
ARCTIC UNIQUE				
Ice Force	SM	0.008	0.077	0.765
	LH	0.001	0.014	0.135
Facility Low Temperature	SM	0.049	0.099	0.148
	LH	0.008	0.016	0.025
Other Arctic	SM	0.0028	0.0088	0.0456
	LH	0.0005	0.0015	0.0080

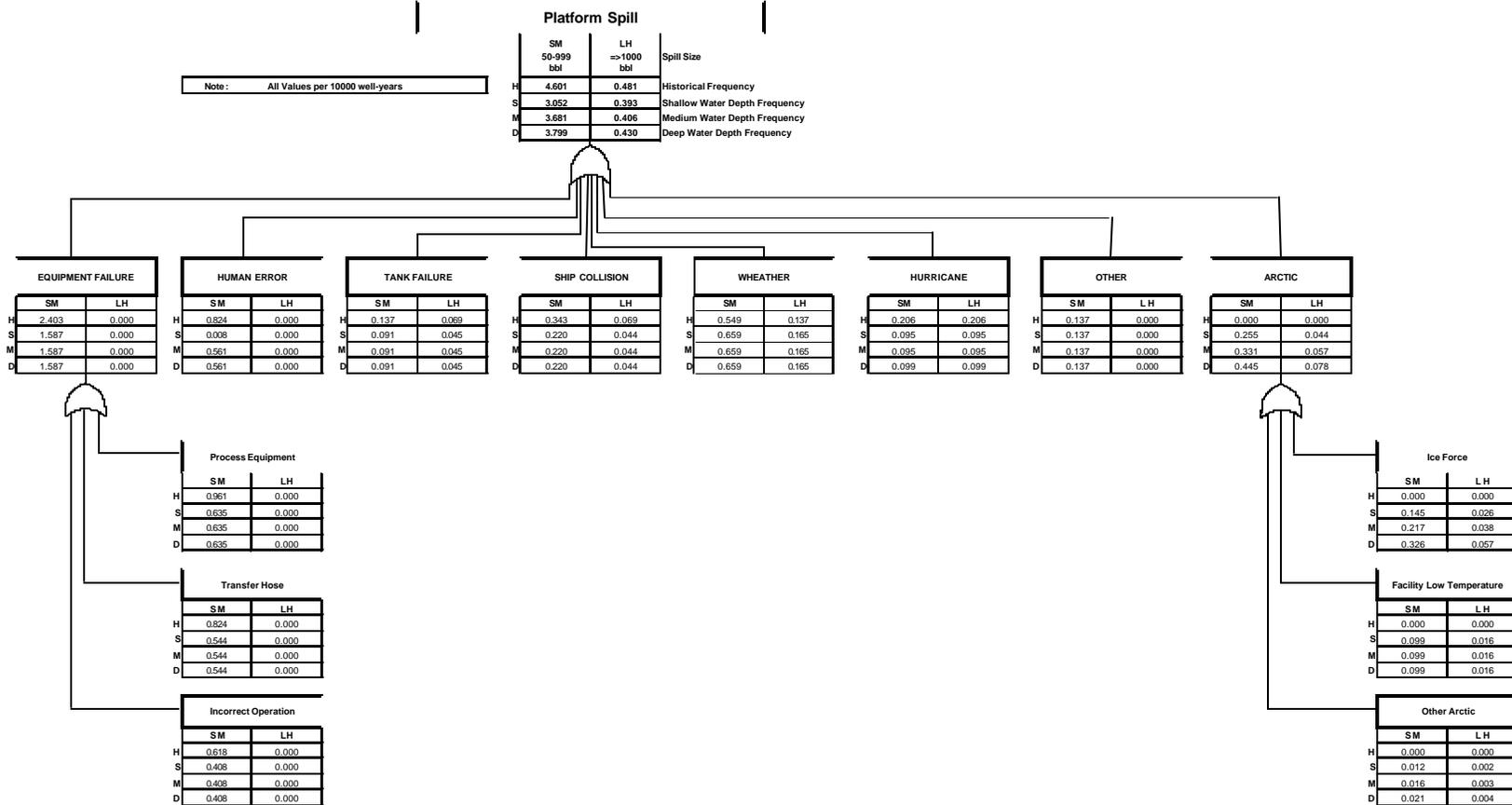


Figure 4.5
Spill Frequencies Platform Fault Tree
(Appendix Figure 2.5)

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

CAUSE CLASSIFICATION	HISTORICAL DISTRIBUTION %	SMALL AND MEDIUM SPILLS 50-999 bbl			
		FREQUENCY spills per 10 ⁴ well-year	Deep		
			Frequency Change	New Frequency	New Distribution %
EQUIPMENT FAILURE	52.24	2.403	(0.816)	1.587	41.78
Process Equipment	20.90	0.961	(0.327)	0.635	16.71
Transfer Hose	17.91	0.824	(0.280)	0.544	14.32
Incorrect Operation	13.43	0.618	(0.210)	0.408	10.74
HUMAN ERROR	17.91	0.824	(0.263)	0.561	14.76
TANK FAILURE	2.99	0.137	(0.047)	0.091	2.39
SHIP COLLISION	7.46	0.343	(0.124)	0.220	5.78
WEATHER	11.94	0.549	0.110	0.659	17.35
HURRICANE	4.48	0.206	(0.107)	0.099	2.60
OTHER	2.99	0.137		0.137	3.62
ARCTIC			0.445	0.445	11.72
Ice Force			0.326	0.326	8.57
Facility Low Temperature			0.099	0.099	2.60
Other Arctic			0.021	0.021	0.56
TOTALS	100.00	4.601	(0.802)	3.799	100.00

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

CAUSE CLASSIFICATION	HISTORICAL DISTRIBUTION %	LARGE AND HUGE SPILLS =>1000 bbl			
		FREQUENCY spills per 10 ⁴ well-year	Deep		
			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	10.54
SHIP COLLISION	14.29	0.069	(0.025)	0.044	10.21
WEATHER	28.57	0.137	0.027	0.165	38.29
HURRICANE	42.86	0.206	(0.107)	0.099	22.94
OTHER					
ARCTIC			0.078	0.078	18.02
Ice Force			0.057	0.057	13.35
Facility Low Temperature			0.016	0.016	3.82
Other Arctic			0.004	0.004	0.86
TOTALS	100.00	0.481	(0.050)	0.430	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 km-year	Arctic Frequency
		Deep
SMALL AND MEDIUM SPILLS 50-999 bbl	4.601	3.799
LARGE AND HUGE SPILLS =>1000 bbl	0.481	0.430

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)

EVENT	FREQUENCY UNIT	Historical Expected Frequency Change %	Reason
		Deep	
		Small and Medium Spills: 50-999 bbl	
PRODUCTION WELL	spill per 10 ⁴ well-year	(30)	State of the art now, High QC, High Inspection and Maintenance Requirements
EXPLORATION WELL DRILLING	spill per 10 ⁴ wells	(10)	Highly qualified drilling contractor. Better logistics support in shallow water.
DEVELOPMENT WELL DRILLING	spill per 10 ⁴ wells	(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)	State of the art now, High QC, High Inspection and Maintenance Requirements
EXPLORATION WELL DRILLING	spill per 10 ⁴ wells	(10)	Highly qualified drilling contractor. Better logistics support in shallow water.
DEVELOPMENT WELL DRILLING	spill per 10 ⁴ wells	(10)	Highly qualified drilling contractor. Better logistics support in shallow water.
		Spill: 10000-149999 bbl	
PRODUCTION WELL	spill per 10 ⁴ well-year	(30)	State of the art now, High QC, High Inspection and Maintenance Requirements
EXPLORATION WELL DRILLING	spill per 10 ⁴ wells	(10)	Highly qualified drilling contractor. Better logistics support in shallow water.
DEVELOPMENT WELL DRILLING	spill per 10 ⁴ wells	(10)	Highly qualified drilling contractor. Better logistics support in shallow water.
		Spill: >=150000 bbl	
PRODUCTION WELL	spill per 10 ⁴ well-year	(30)	State of the art now, High QC, High Inspection and Maintenance Requirements
EXPLORATION WELL DRILLING	spill per 10 ⁴ wells	(10)	Highly qualified drilling contractor. Better logistics support in shallow water.
DEVELOPMENT WELL DRILLING	spill per 10 ⁴ wells	(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	Deep	
			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
EXPLORATION WELL DRILLING	spill per 10 ⁴ wells	2.262	-0.226	2.035
DEVELOPMENT WELL DRILLING	spill per 10 ⁴ wells	0.692	-0.069	0.623
Large Spills 1000-9999 bbl				
PRODUCTION WELL	spill per 10 ⁴ well-year	1.026	-0.308	0.718
EXPLORATION WELL DRILLING	spill per 10 ⁴ wells	15.824	-1.582	14.242
DEVELOPMENT WELL DRILLING	spill per 10 ⁴ wells	4.833	-0.483	4.350
Spills 10000-149999 bbl				
PRODUCTION WELL	spill per 10 ⁴ well-year	0.440	-0.132	0.308
EXPLORATION WELL DRILLING	spill per 10 ⁴ wells	6.799	-0.680	6.119
DEVELOPMENT WELL DRILLING	spill per 10 ⁴ wells	2.076	-0.208	1.868
Spills >=150000 bbl				
PRODUCTION WELL	spill per 10 ⁴ well-year	0.293	-0.088	0.205
EXPLORATION WELL DRILLING	spill per 10 ⁴ wells	3.936	-0.394	3.543
DEVELOPMENT WELL DRILLING	spill per 10 ⁴ wells	2.076	-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			
	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											
	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			
	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).
 - High Case
 - Low Case
 - High Case Non-Arctic
- By water depth (deep only).
- By facility type (six types).
- By spill size (four sizes).
- By year (2011 to 2040 which is 30 years inclusive).

The above combinations translate into 72 sets of spill indicators per year. Given that these are calculated for each year, with the scenario lasting for 30 years, gives 2,160 sets of indicators. In this chapter, we will try to summarize only the salient results of the indicators; the Appendix 4 gives the full calculation printouts for the Monte Carlo results used in the body of this report.

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 2,200), 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 2,200 combinations needs to be sampled, in this case a sampling of 2,200 iterations was carried out for each combination studied. This translates into roughly 10 million arithmetic operations to generate the Monte Carlo results.

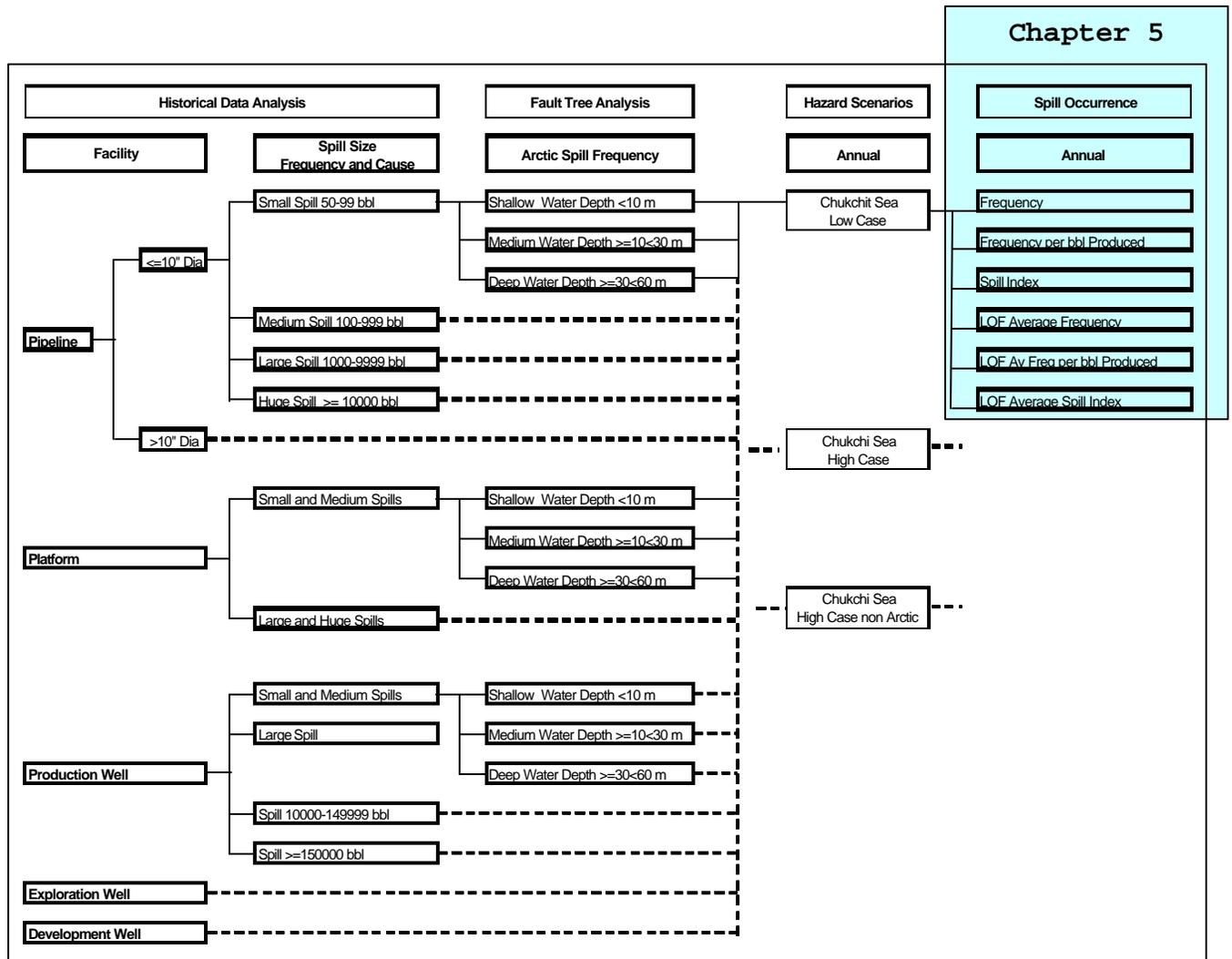


Figure 5.1
Calculation Flow Chart

5.3 Summary of Chukchi Sea Oil Spill Occurrence Indicators

5.3.1 Chukchi Sea High Case Oil Spill Occurrence Indicators

Each of the principal oil spill occurrence indicators calculated for the pipelines, platforms, and wells under 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 2040 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 $\geq 10,000$ 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 41.0 per thousand years. Next, in that year, large spills are approximately 8.0 per thousand years, as shown in the second bar increment (i.e., $49.0 - 41.0 = 8.0$). Finally, the top increment corresponds to huge spills, and is approximately 6.0 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. The spills per barrel produced continue to rise to the final production year (2043), because the facility quantities (and hence spill rate) remain relatively high, while production volumes decrease significantly each year. Clearly, the spill index (Figure 5.4) is dominated by the huge spills. 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 pipelines (Figure 5.6). In earlier studies [12], platforms caused the most spills. The largest of the facility spill expectations, as represented by spill index, are the wells (Figure 5.7), simply because they have the potential to release the largest amounts of oil in blowouts.

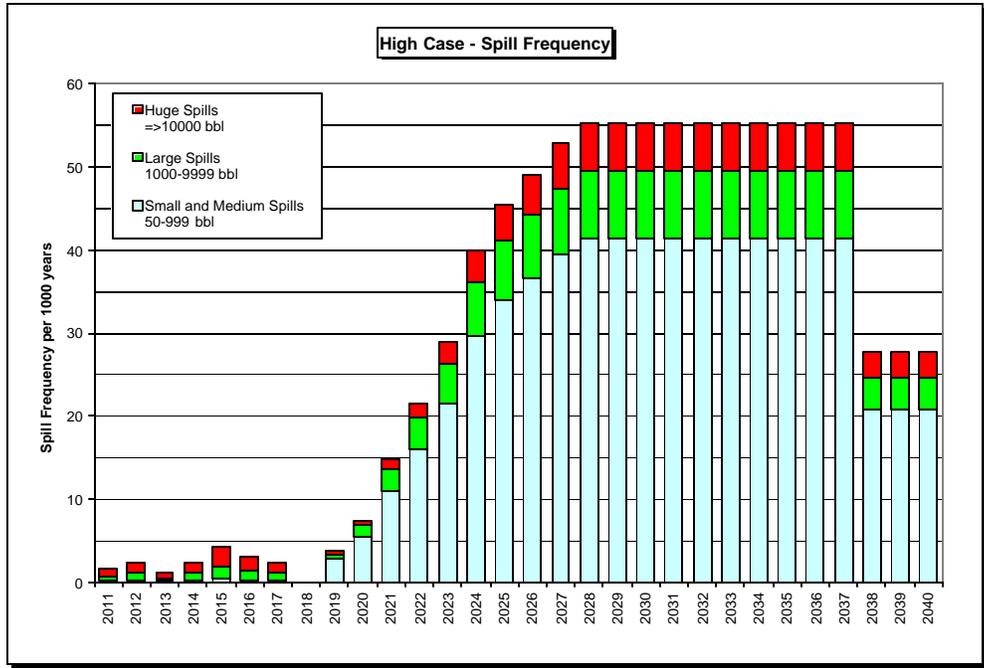


Figure 5.2
Chukchi Sea High Case Spill Frequency per 1,000 Years
(Appendix Figure 4.2.01)

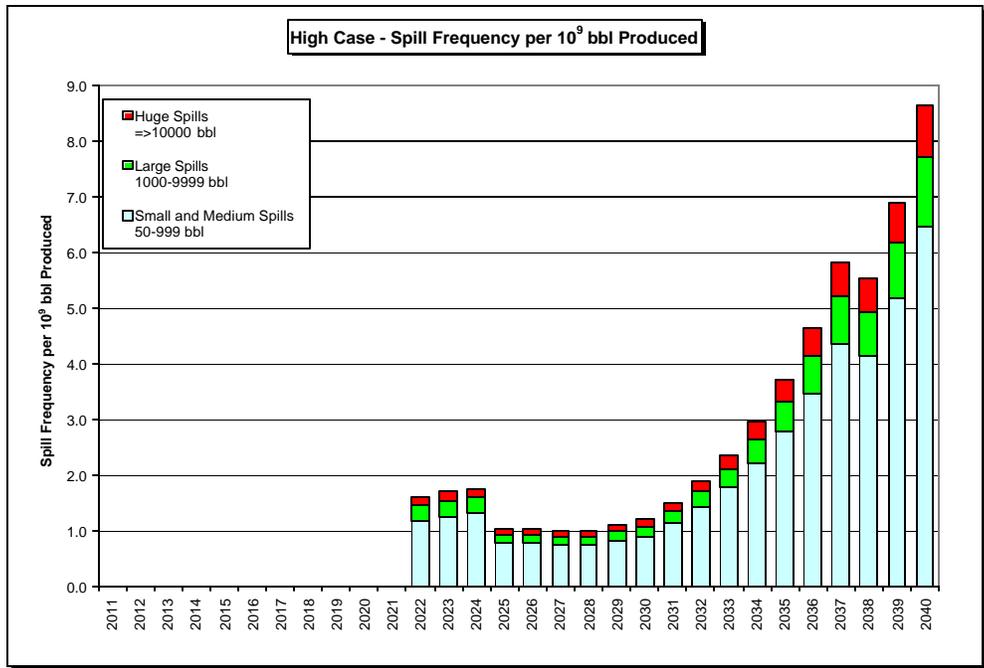


Figure 5.3
Chukchi Sea High Case Spill Frequency per 10⁹ Barrels Produced
(Appendix Figure 4.2.02)

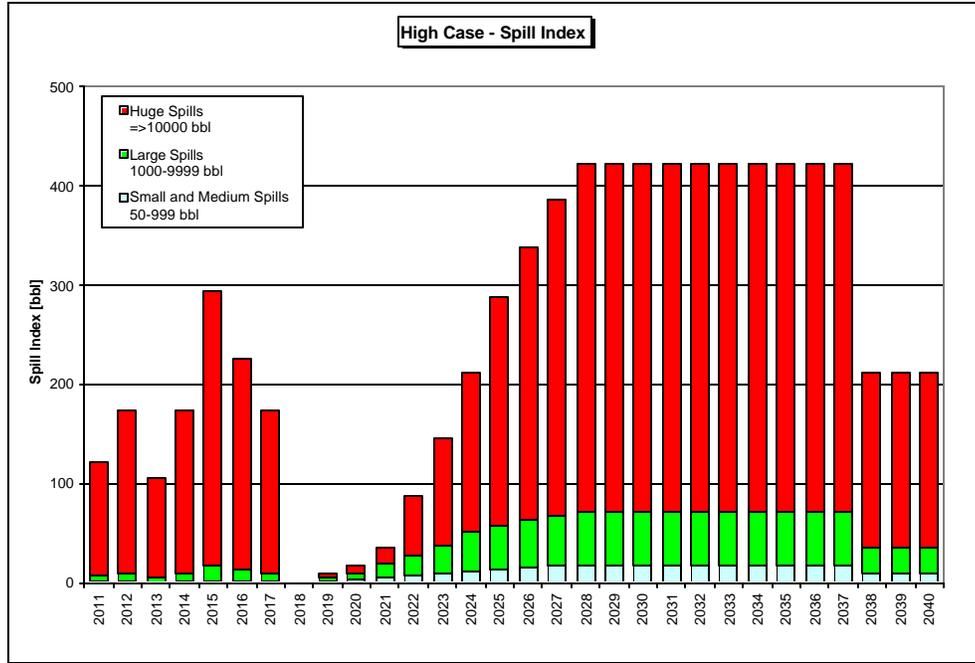


Figure 5.4
Chukchi Sea High Case Spill Index
(Appendix Figure 4.2.03)

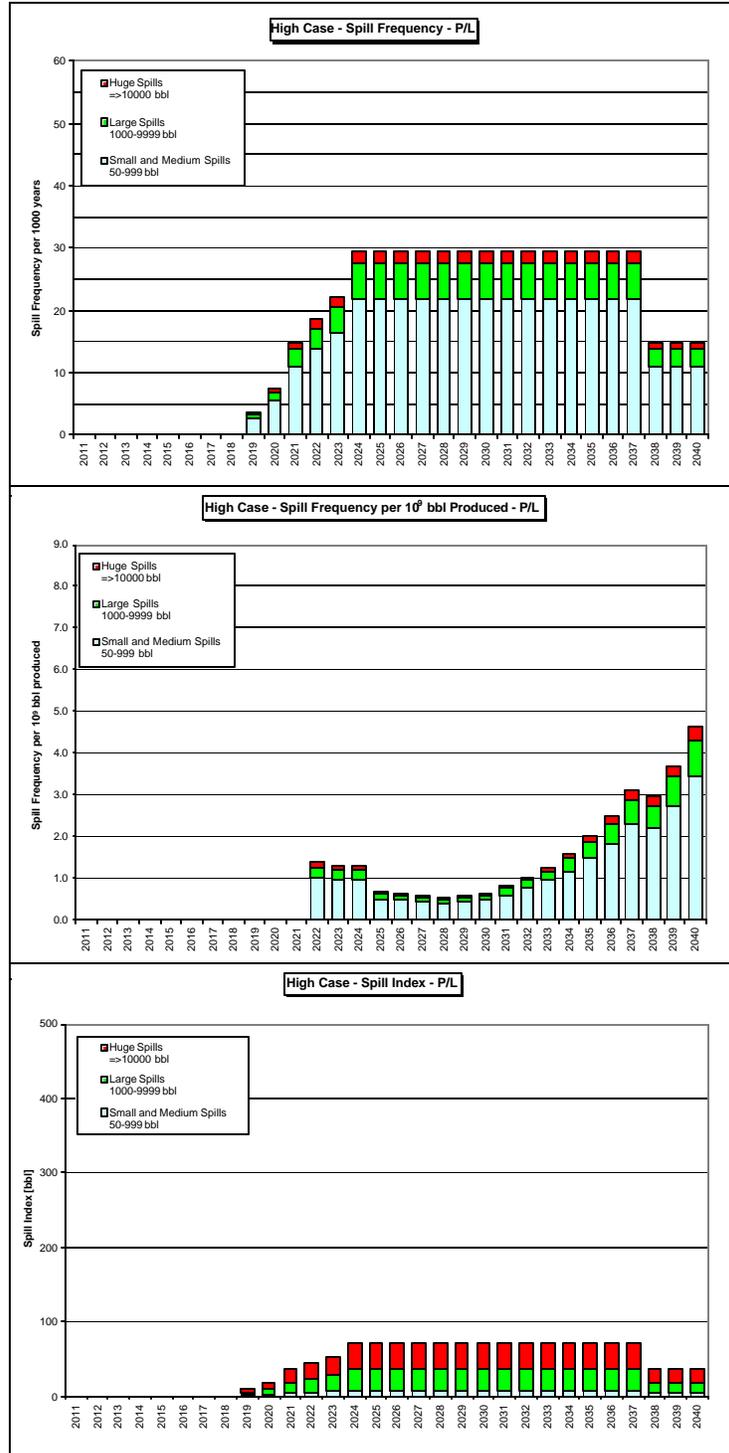


Figure 5.5
Chukchi Sea High Case Spill Indicators – Pipeline
 (Appendix Figures 4.2.04, 4.2.05, 4.2.06)

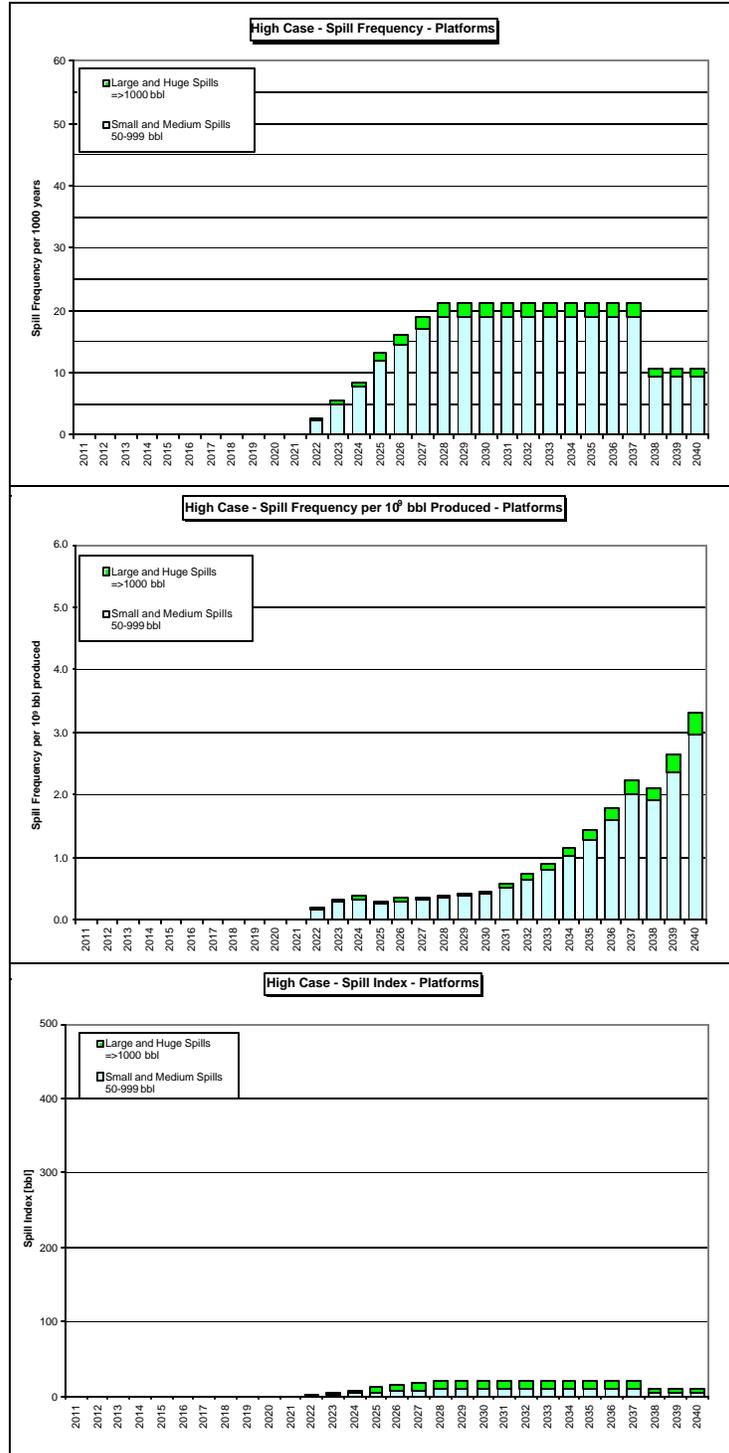


Figure 5.6
Chukchi Sea High Case Spill Indicators – Platforms
(Appendix Figures 4.2.07, 4.2.08, 4.2.09)

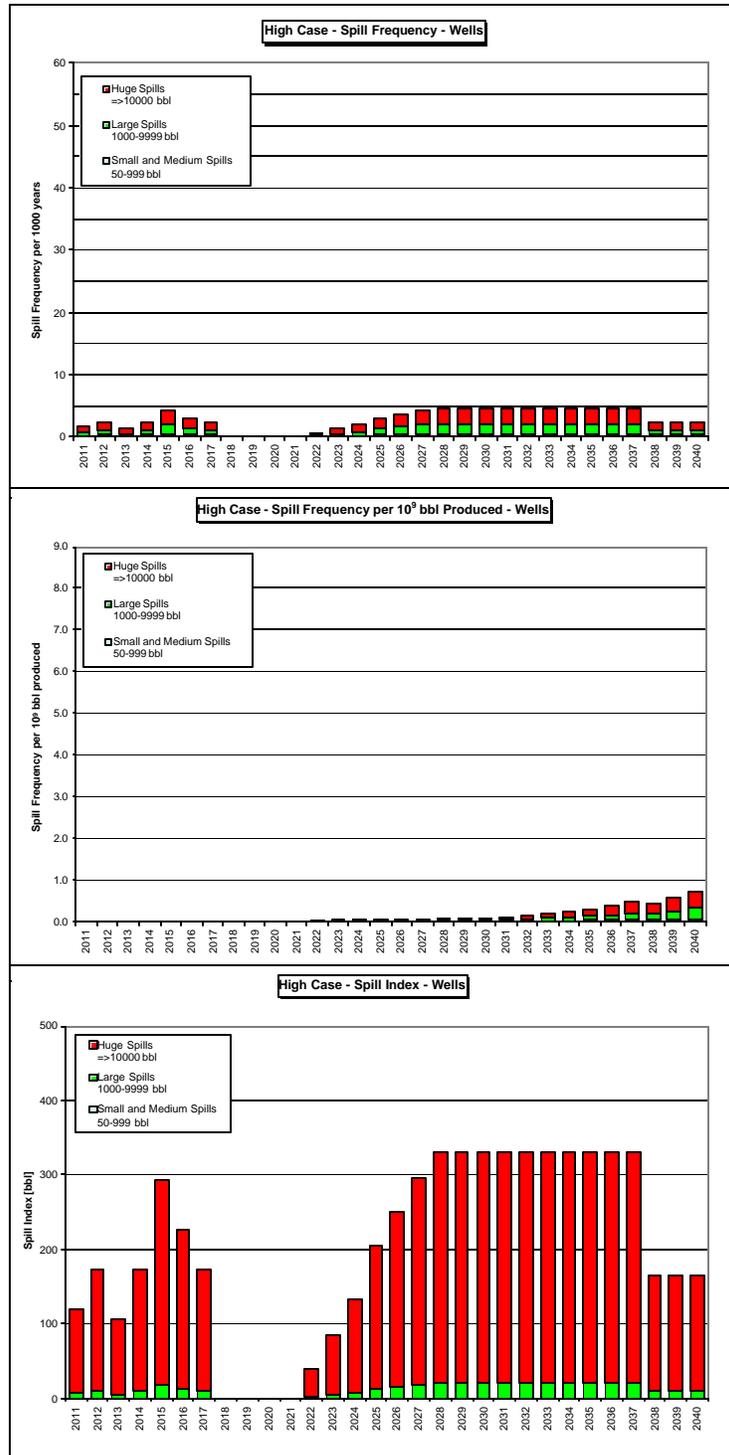


Figure 5.7
Chukchi Sea High Case Spill Indicators – Wells
 (Appendix Figures 4.2.10, 4.2.11, 4.2.12)

Finally, as part of the assessment of the Chukchi 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-hand central graph, for significant spills $\geq 1,000$ bbl (large and huge), there is a 50% probability that a spill frequency will be no more than 0.25 per billion barrels produced in year 2030. In other words, there is a 50% chance that large and huge spills will occur at a rate of 0.25 per billion bbl or less.

The frequency spill indicator variability can be estimated from the upper (95%) and lower (5%) bound values. For example, for large spill frequency (from Table 5.1), the lower bound (3.040) is 41% of the mean (7.363); the upper bound (15.75), 213% of the mean. 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 ($\pm 10\%$) 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 Sale 1 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 Chukchi 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 36%. The spills per barrel produced are also significantly reduced, as can be seen in Figures 5.14 and 5.15. The spill index (Figure 5.13), because of the disproportionate effect of large spills, shows a reduction of approximately 34%. 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 5.1
Chukchi 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 =	41.42	8.12	5.82	13.94	55.36	0.91	0.18	0.13	0.31	1.22	17.18	53.65	350.17	403.81	420.99
Std Deviation =	16.25	3.97	1.84	4.55	16.88	0.36	0.09	0.04	0.10	0.37	11.24	30.54	126.17	130.07	130.55
Variance =	263.985	15.778	3.377	20.739	284.882	0.128	0.008	0.002	0.010	0.138	126.420	932.414	15919.700	16919.380	17044.490
Skewness =	0.39	0.81	0.53	0.58	0.34	0.39	0.81	0.53	0.58	0.34	1.19	1.30	0.48	0.44	0.43
Kurtosis =	2.76	3.28	3.04	3.18	2.77	2.76	3.28	3.04	3.18	2.77	4.72	5.49	3.23	3.19	3.19
Mode =	36.28	4.27	4.07	8.34	50.08	0.80	0.09	0.11	0.23	1.09	2.95	44.19	230.87	282.47	272.68
Minimum =	3.871	0.885	1.303	2.996	14.957	0.085	0.019	0.029	0.066	0.329	-1.173	0.253	43.711	79.588	93.237
5% Perc =	17.034	3.040	3.176	7.436	29.511	0.375	0.067	0.070	0.164	0.650	3.679	16.317	159.178	205.605	221.727
10% Perc =	21.054	3.645	3.612	8.444	34.279	0.464	0.080	0.080	0.186	0.755	5.191	21.417	194.466	243.633	260.638
15% Perc =	24.068	4.115	3.947	9.286	37.378	0.530	0.091	0.087	0.205	0.823	6.355	25.454	219.726	268.809	285.557
20% Perc =	26.904	4.575	4.223	9.964	40.346	0.593	0.101	0.093	0.219	0.889	7.585	28.830	239.049	291.201	306.962
25% Perc =	29.216	5.008	4.477	10.588	42.868	0.644	0.110	0.099	0.233	0.944	8.732	31.836	259.937	309.981	327.689
30% Perc =	31.429	5.417	4.721	11.167	45.296	0.692	0.119	0.104	0.246	0.998	9.872	34.897	277.879	329.193	346.124
35% Perc =	33.596	5.867	4.952	11.726	47.465	0.740	0.129	0.109	0.258	1.045	10.996	37.873	294.988	346.155	362.699
40% Perc =	35.695	6.353	5.175	12.255	49.766	0.786	0.140	0.114	0.270	1.096	12.223	40.687	310.034	362.745	379.059
45% Perc =	37.950	6.837	5.393	12.813	51.987	0.836	0.151	0.119	0.282	1.145	13.438	43.947	325.413	378.929	396.493
50% Perc =	40.180	7.363	5.613	13.408	54.255	0.885	0.162	0.124	0.295	1.195	14.731	47.283	339.752	394.991	411.829
55% Perc =	42.498	7.941	5.839	13.978	56.461	0.936	0.175	0.129	0.308	1.244	16.111	50.527	355.949	410.934	428.056
60% Perc =	44.645	8.494	6.091	14.632	58.829	0.983	0.187	0.134	0.322	1.296	17.586	54.382	372.612	428.474	445.263
65% Perc =	46.986	9.157	6.374	15.321	61.082	1.035	0.202	0.140	0.337	1.345	19.165	58.910	389.375	446.661	463.237
70% Perc =	49.541	9.795	6.658	16.012	63.987	1.091	0.216	0.147	0.353	1.409	20.976	63.721	408.942	466.399	484.155
75% Perc =	52.349	10.609	6.975	16.800	66.969	1.153	0.234	0.154	0.370	1.475	23.159	68.874	428.273	487.342	504.280
80% Perc =	55.702	11.429	7.348	17.690	69.996	1.227	0.252	0.162	0.390	1.542	25.567	74.766	452.753	509.295	528.176
85% Perc =	59.070	12.412	7.784	18.796	73.424	1.301	0.273	0.171	0.414	1.617	28.416	82.896	480.314	536.438	554.049
90% Perc =	63.486	13.724	8.388	20.245	78.263	1.398	0.302	0.185	0.446	1.724	32.541	94.300	516.986	574.305	593.308
95% Perc =	69.929	15.750	9.181	22.229	84.766	1.540	0.347	0.202	0.490	1.867	38.906	112.703	576.375	635.191	653.137
Maximum =	103.278	26.645	13.348	34.536	123.456	2.275	0.587	0.294	0.761	2.719	81.979	249.893	945.258	983.543	1003.756

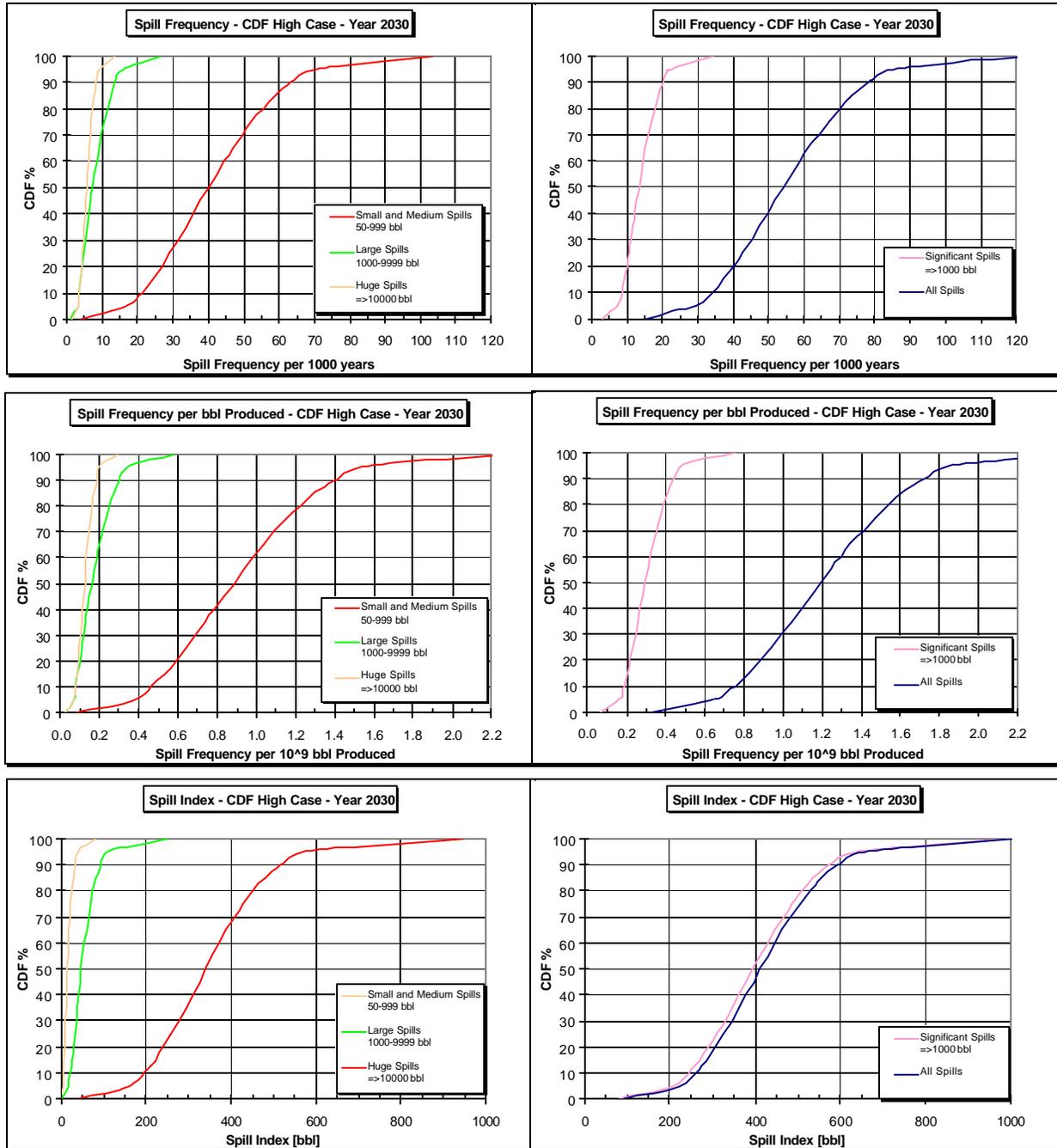


Figure 5.8
Chuckchi Sea High Case Spill Indicator Distributions – Year 2030
(Appendix Figure 4.2.13)

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

Spill Size	Spill Source									
	Pipelines		Platforms		Wells		Platforms and Wells		All	
	LOF Average - Spill Frequency per 10 ³ years									
Small and Medium Spills 50-999 bbl	12.960	74%	9.219	90%	0.313	11%	9.532	73%	22.491	74%
Large Spills 1000-9999 bbl	3.253	19%	0.522	5%	0.940	33%	1.462	11%	4.715	15%
Huge Spills =>10000 bbl	1.293	7%	0.522	5%	1.570	56%	2.092	16%	3.385	11%
Significant Spills =>1000 bbl	4.546	26%	1.044	10%	2.510	89%	3.554	27%	8.100	26%
All Spills	17.506	100%	10.263	100%	2.823	100%	13.086	100%	30.592	100%
LOF Average - Spill Frequency per 10 ⁹ bbl produced										
Small and Medium Spills 50-999 bbl	0.778	74%	0.553	90%	0.019	11%	0.572	73%	1.349	74%
Large Spills 1000-9999 bbl	0.195	19%	0.031	5%	0.056	33%	0.088	11%	0.283	15%
Huge Spills =>10000 bbl	0.078	7%	0.031	5%	0.094	56%	0.126	16%	0.203	11%
Significant Spills =>1000 bbl	0.273	26%	0.063	10%	0.151	89%	0.213	27%	0.486	26%
All Spills	1.050	100%	0.616	100%	0.169	100%	0.785	100%	1.835	100%
LOF Average - Spill Index [bbl]										
Small and Medium Spills 50-999 bbl	5	12%	4	41%	0	0%	4	2%	9	4%
Large Spills 1000-9999 bbl	17	40%	3	29%	12	6%	15	7%	31	12%
Huge Spills =>10000 bbl	20	48%	3	29%	190	94%	193	91%	213	84%
Significant Spills =>1000 bbl	37	88%	6	59%	202	100%	208	98%	245	96%
All Spills	42	100%	10	100%	202	100%	212	100%	254	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	12.960	58%	3.253	69%	1.293	38%	4.546	56%	17.506	57%
Platforms	9.219	41%	0.522	11%	0.522	15%	1.044	13%	10.263	34%
Wells	0.313	1%	0.940	20%	1.570	46%	2.510	31%	2.823	9%
Platforms and Wells	9.532	42%	1.462	31%	2.092	62%	3.554	44%	13.086	43%
All	22.491	100%	4.715	100%	3.385	100%	8.100	100%	30.592	100%
LOF Average - Spill Frequency per 10 ⁹ bbl produced										
Pipelines	0.778	58%	0.195	69%	0.078	38%	0.273	56%	1.050	57%
Platforms	0.553	41%	0.031	11%	0.031	15%	0.063	13%	0.616	34%
Wells	0.019	1%	0.056	20%	0.094	46%	0.151	31%	0.169	9%
Platforms and Wells	0.572	42%	0.088	31%	0.126	62%	0.213	44%	0.785	43%
All	1.349	100%	0.283	100%	0.203	100%	0.486	100%	1.835	100%
LOF Average - Spill Index [bbl]										
Pipelines	5	53%	17	54%	20	9%	37	15%	42	16%
Platforms	4	45%	3	9%	3	1%	6	2%	10	4%
Wells	0	2%	12	37%	190	89%	202	83%	202	80%
Platforms and Wells	4	47%	15	46%	193	91%	208	85%	212	84%
All	9	100%	31	100%	213	100%	245	100%	254	100%

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

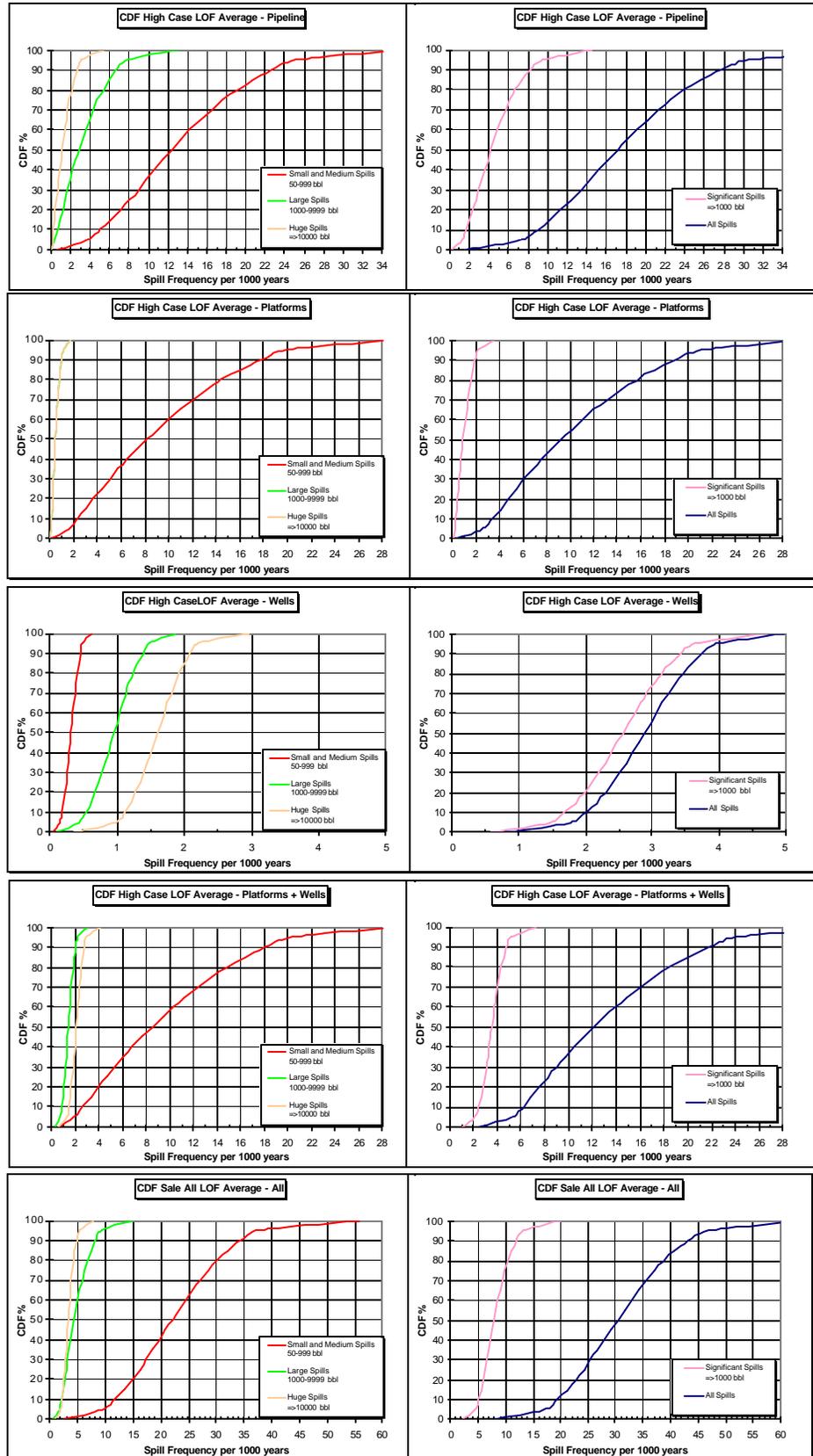
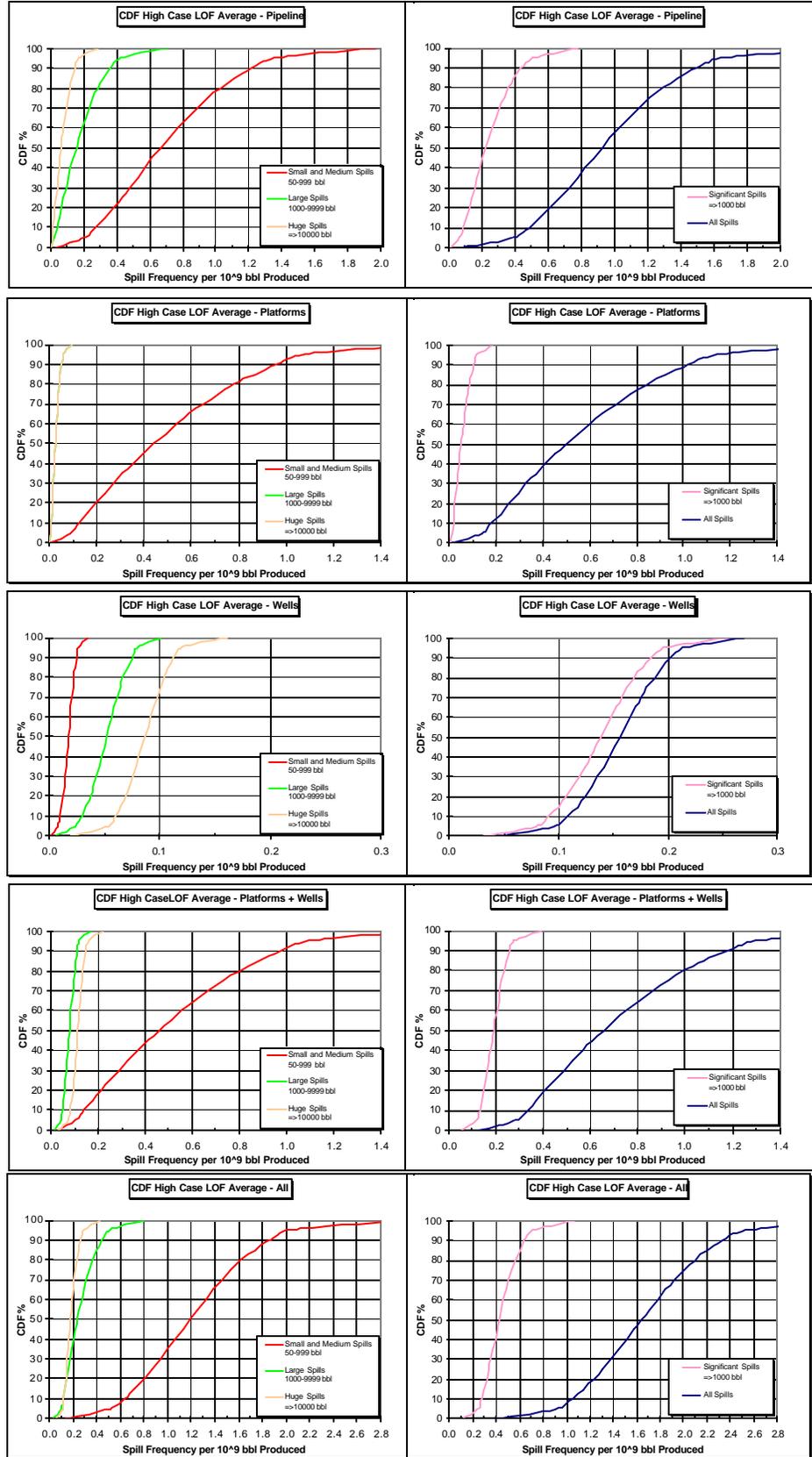


Figure 5.10
Chukchi Sea
High Case
Life of Field
Average Spills
per Barrel Produced
(Appendix
Figure 4.2.15)



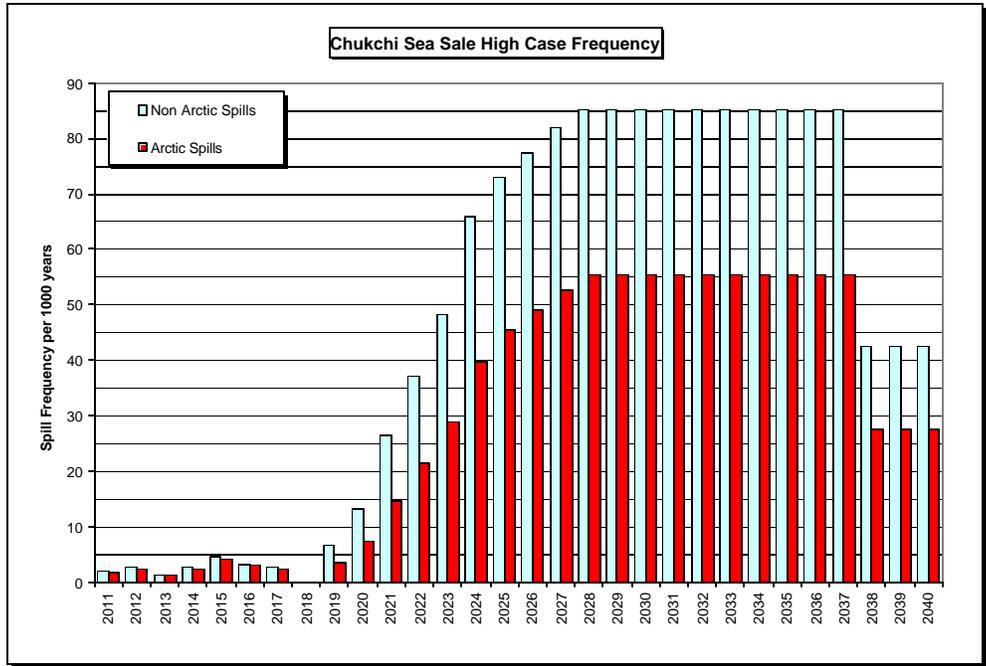


Figure 5.11
Chukchi Sea High Case Spill Frequency – Arctic and Non-Arctic
(Appendix Figure 5.3)

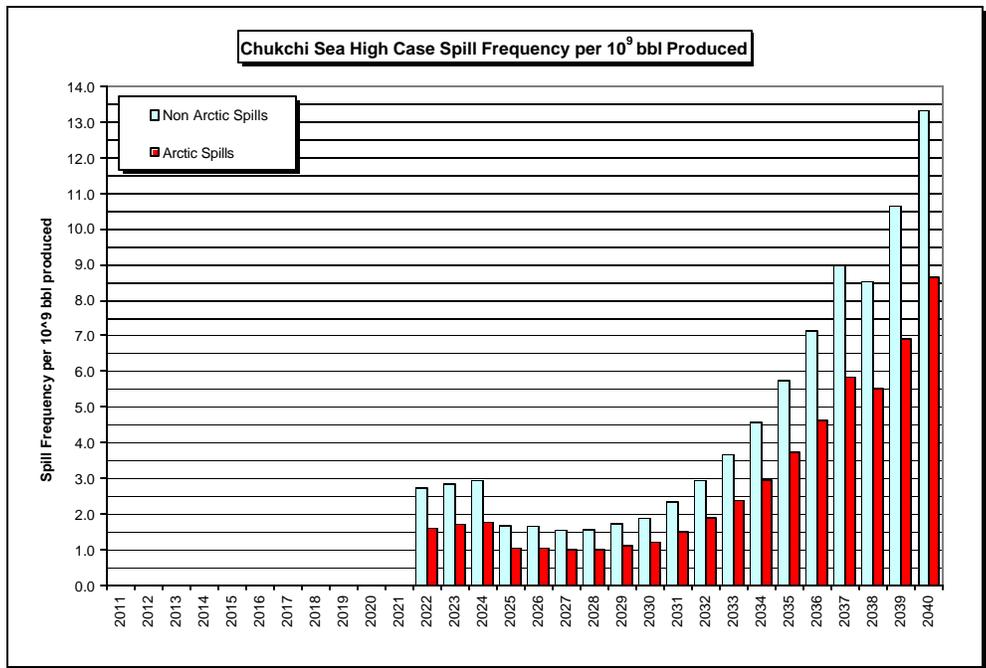


Figure 5.12
Chukchi Sea High Case Spill Frequency per 10⁹ Barrels Produced – Arctic and Non-Arctic
(Appendix Figure 5.4)

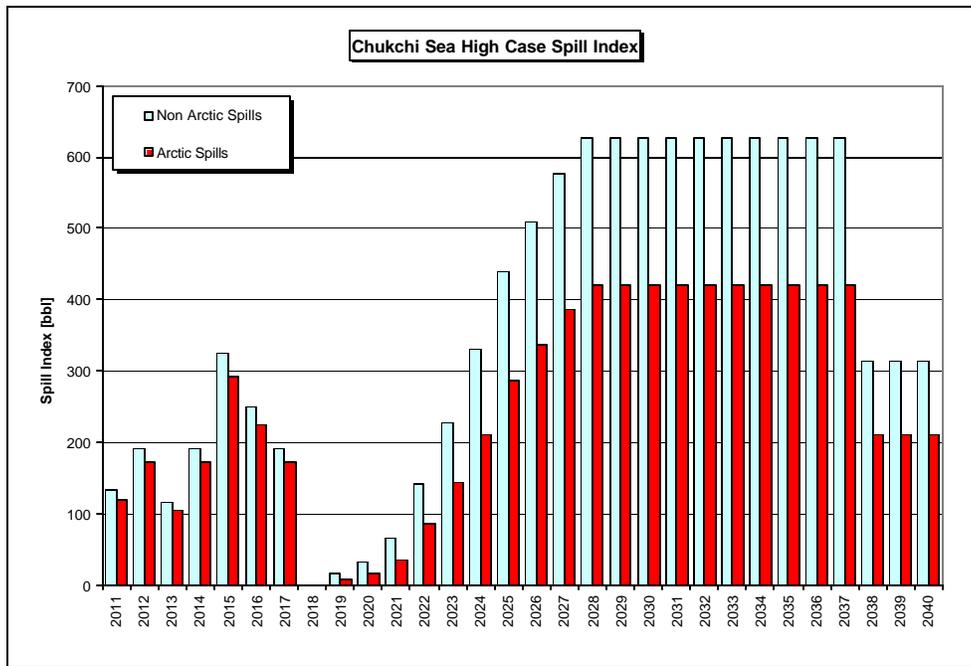


Figure 5.13
Chukchi Sea High Case Spill Index – Arctic and Non-Arctic
(Appendix Figure 5.5)

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	12.499	1.350	5	22.491	1.349	9	34.237	2.054	12
	73%	73%	4%	74%	74%	4%	72%	72%	3%
Large Spills 1000-9999 bbl	2.631	0.284	18	4.715	0.283	31	8.155	0.489	52
	15%	15%	12%	15%	15%	12%	17%	17%	14%
Huge Spills =>10000 bbl	1.899	0.205	121	3.385	0.203	213	5.239	0.314	302
	11%	11%	84%	11%	11%	84%	11%	11%	83%
Significant Spills =>1000 bbl	4.529	0.489	138	8.100	0.486	245	13.394	0.804	353
	27%	27%	96%	26%	26%	96%	28%	28%	97%
All Spills	17.028	1.839	143	30.592	1.835	254	47.631	2.858	365
	100%	100%	100%	100%	100%	100%	100%	100%	100%
Pipeline Spills	9.725	1.050	23	17.506	1.050	42	31.452	1.887	78
	57%	57%	16%	57%	57%	16%	66%	66%	21%
Platform Spills	5.702	0.616	6	10.263	0.616	10	12.331	0.740	12
	33%	33%	4%	34%	34%	4%	26%	26%	3%
Well Spills	1.601	0.173	114	2.823	0.169	202	3.848	0.231	275
	9%	9%	80%	9%	9%	80%	8%	8%	75%
Platform and Well Spills	7.303	0.789	120	13.086	0.785	212	16.179	0.971	287
	43%	43%	84%	43%	43%	84%	34%	34%	79%
All Spills	17.028	1.839	143	30.592	1.835	254	47.631	2.858	365
	100%	100%	100%	100%	100%	100%	100%	100%	100%

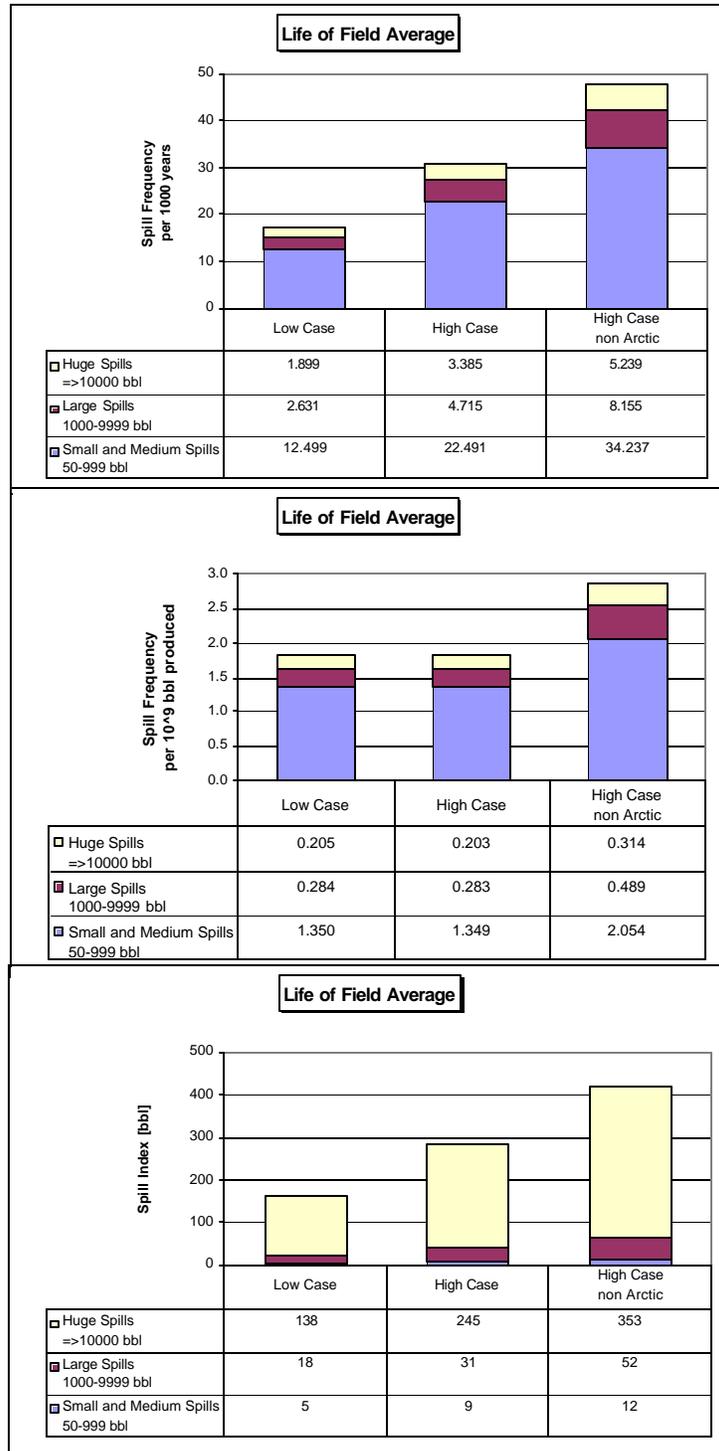


Figure 5.14
Chukchi Sea Life of Field Spill Indicators – By Spill Size
(Appendix Figure 5.1)

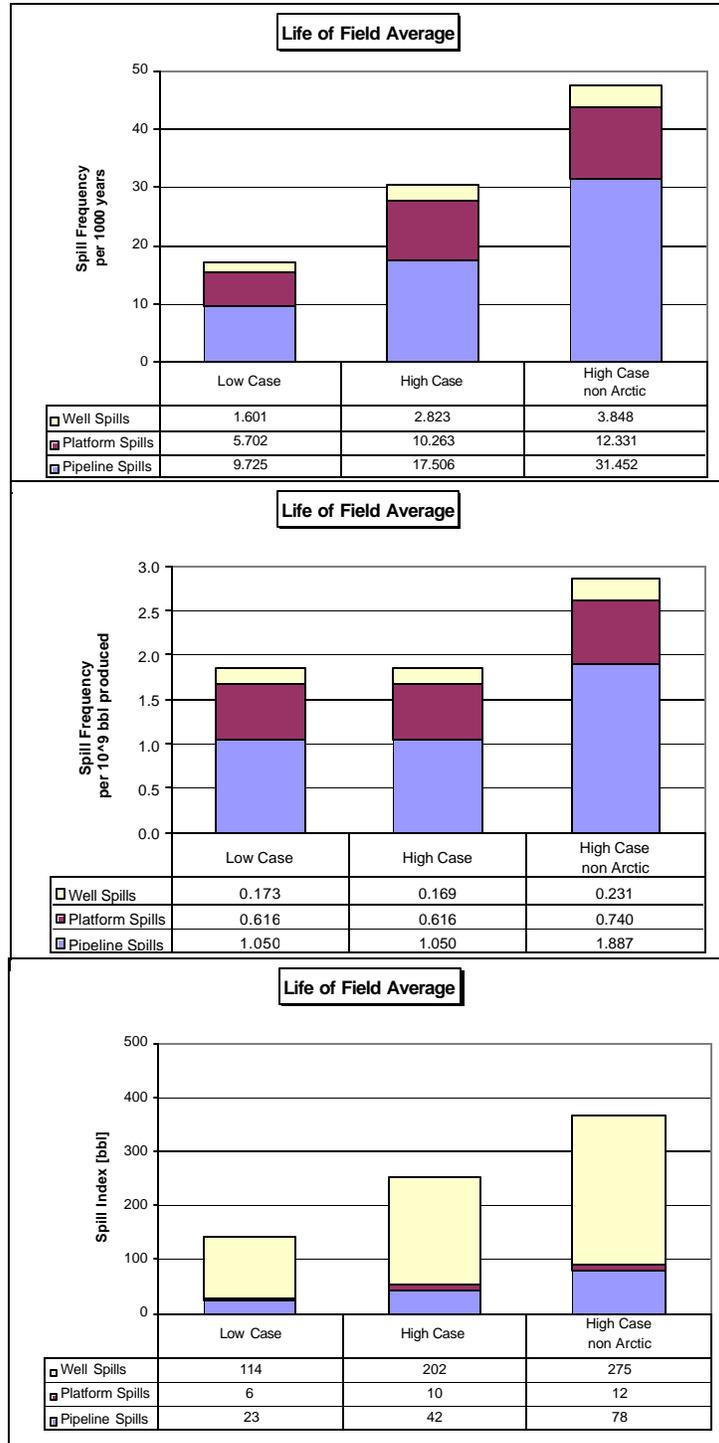


Figure 5.15
Chukchi Sea Life of Field Spill Indicators – By Source Composition
(Appendix Figure 5.2)

5.4 Summary of Representative Oil Spill Occurrence Indicator Results

How do spill indicators for the Chukchi scenario and for its non-Arctic counterpart vary by spill size and location? Table 5.3 and Figure 5.14 and 5.15 summarize the Life of Field average spill indicator values by spill size and source. 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 scenarios.
- The spill index increases significantly with spill size for all scenarios.
- All non-Arctic scenario spill indicators are greater than their Arctic counterparts. High Case non-Arctic spill indicators are approximately 35% greater than Arctic High Case counterparts.

How do the spill indicators vary by facility type for representative scenarios? The contributions of spill indicators by facility have been summarized by representative scenario years, again, 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 Table 5.3:

- Pipelines contribute the most (57%) to the two spill frequency indicators.
- Platforms are next in relative contribution to spill frequencies (33%) and least in contribution to spill index (4%).
- Wells are by far (at 80%) the highest contributors to spill index, while platforms and wells together are responsible for a 84% contribution to the 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. Platforms will be in between, with more spills than wells.

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.

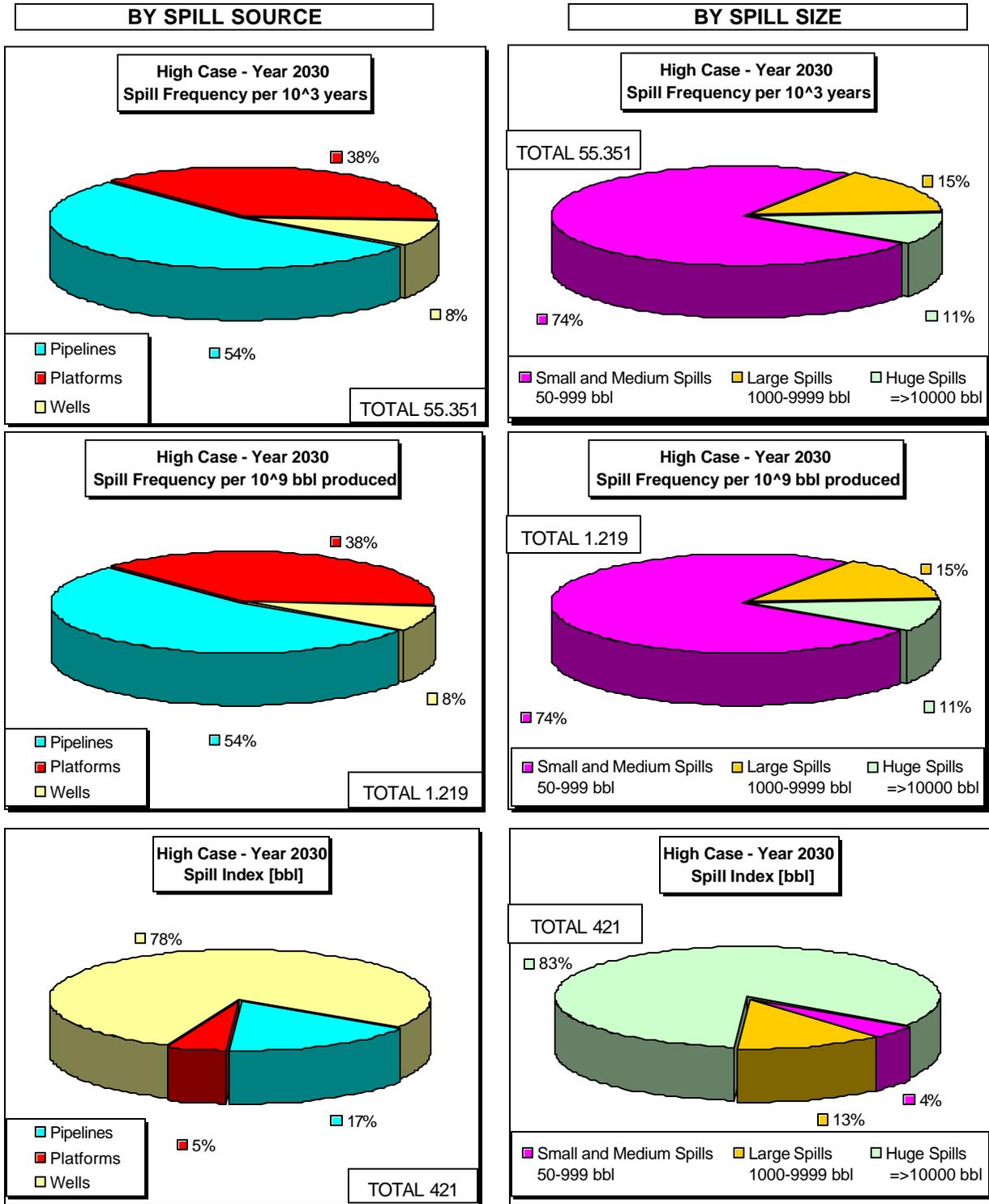


Figure 5.16
Chukchi Sea High Case – Year 2030 –
Spill Indicator Composition by Source and Spill Size
(Appendix Figure 4.2.17)

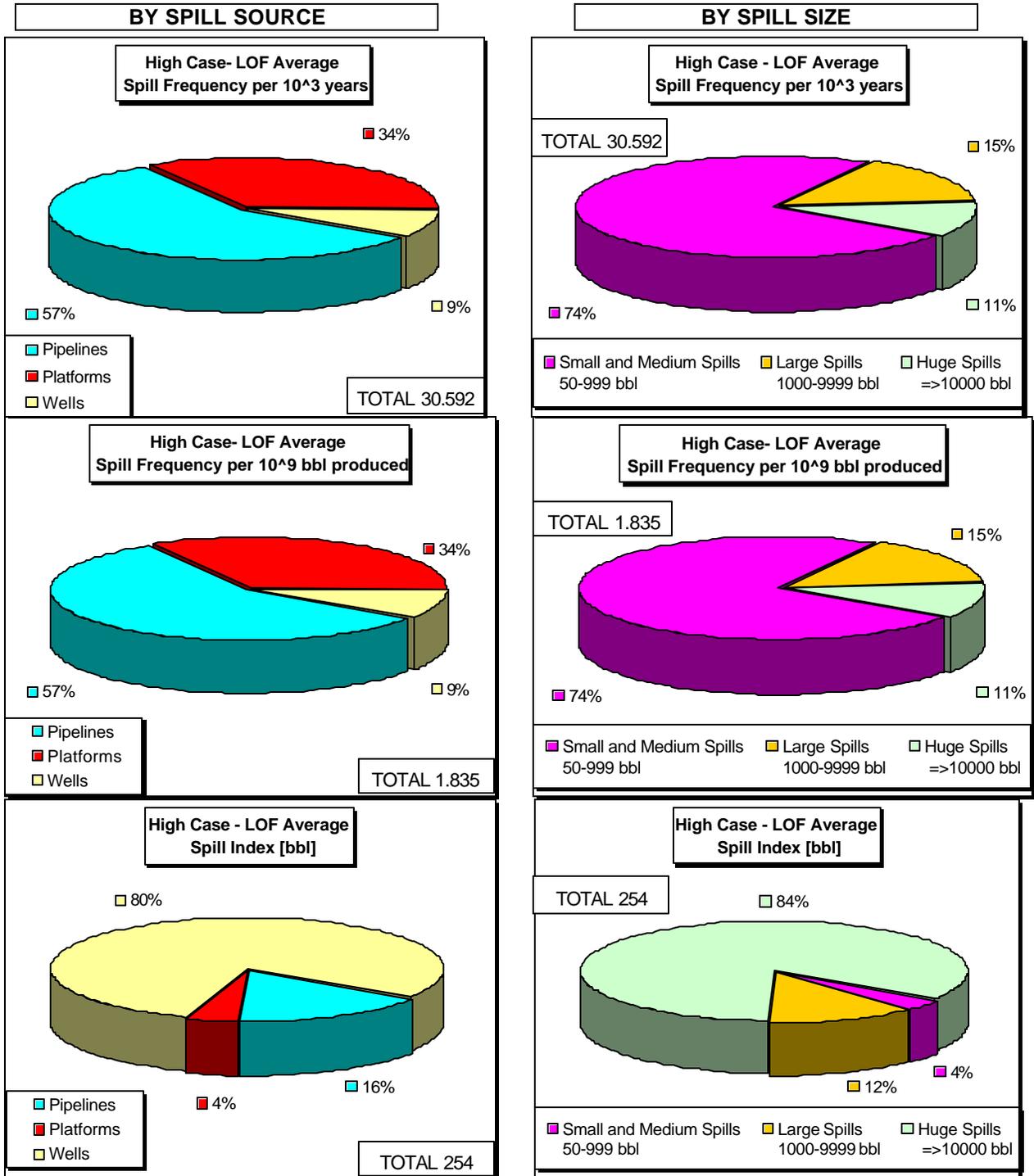


Figure 5.17
Chukchi Sea High Case – Life of Field Average Spill Indicator
Composition by Source and Spill Size
(Appendix Figure 4.2.18)

Figures¹ 5.18, 5.19, and 5.20 show the Cumulative Distribution Functions (CDF) for each of the three Chukchi Sea High Case Life of Field average spill indicators. The variability of these indicators is fairly representative of the trends in variability for spill indicators for all sales and locations studied. Generally, the following can be observed from the figures:

- The variance of the frequency spill indicators (Figures 5.18 and 5.19) decreases as spill size increases for pipelines and platforms. For example, in the top right-hand graph of Figure 5.18, the significant spills plot has a much steeper (and hence less variable) slope than that of all spills. Similarly, in the top left-hand graph, small and medium spills illustrate the largest variability; huge spills show the least variability for these facilities.
- The opposite occurs for wells, where large spills show greater variance than small ones.
- The variability of the spill index (Figure 5.20) shows variance trends opposite to those of the frequency spill indicators.

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 8 (spills per 1,000 years) ranges between about 15 and 3 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 240 per billion barrels produced ranges from 150 to 400.

¹ Note: Figures 5.18 and 5.19 are duplicated here, from Figures 5.9 and 5.10, for convenience.

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

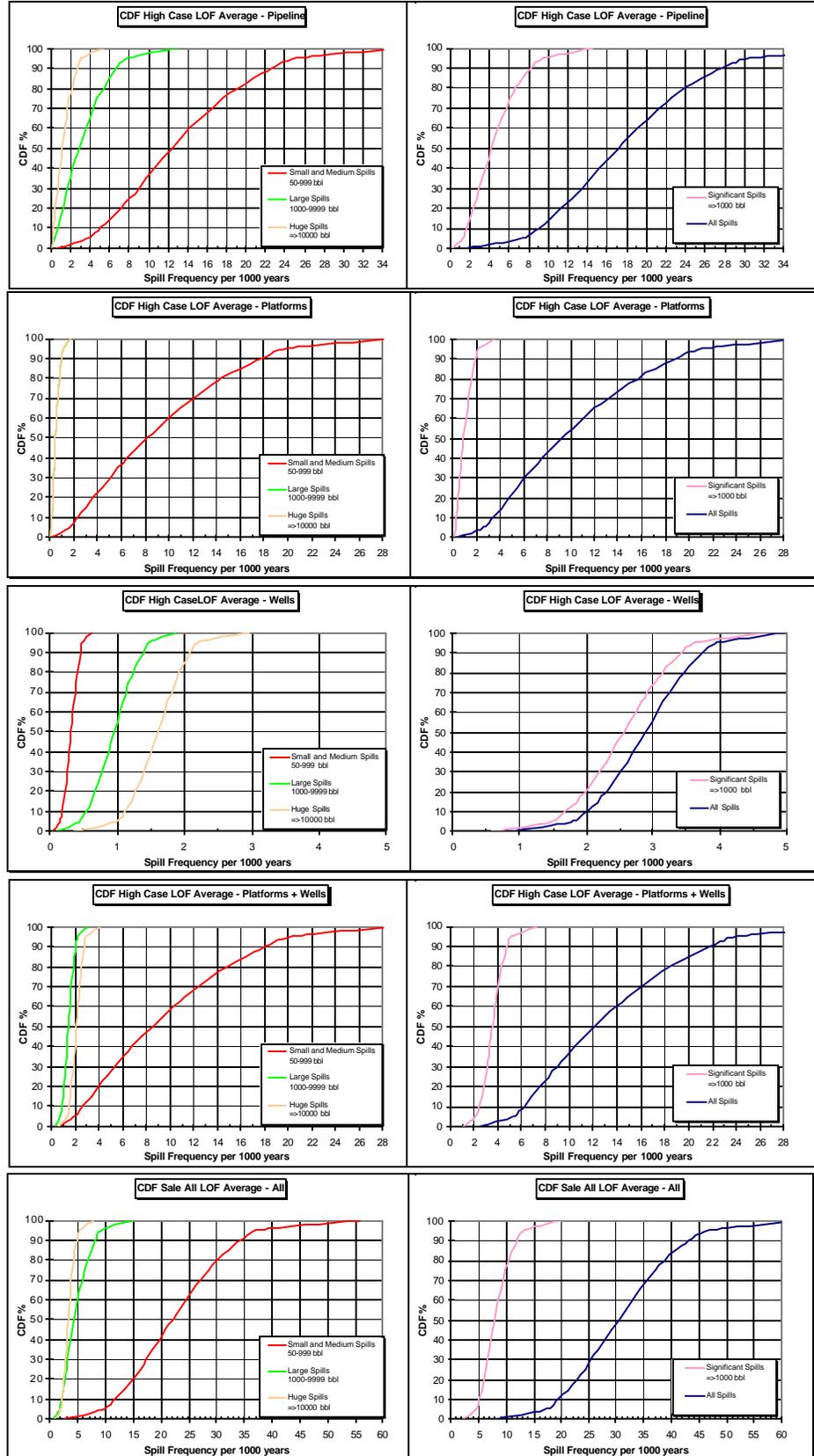


Figure 5.19
Chukchi Sea
High Case
Life of Field
Average Spills
per Barrel Produced
(Appendix
Figure 4.2.15)

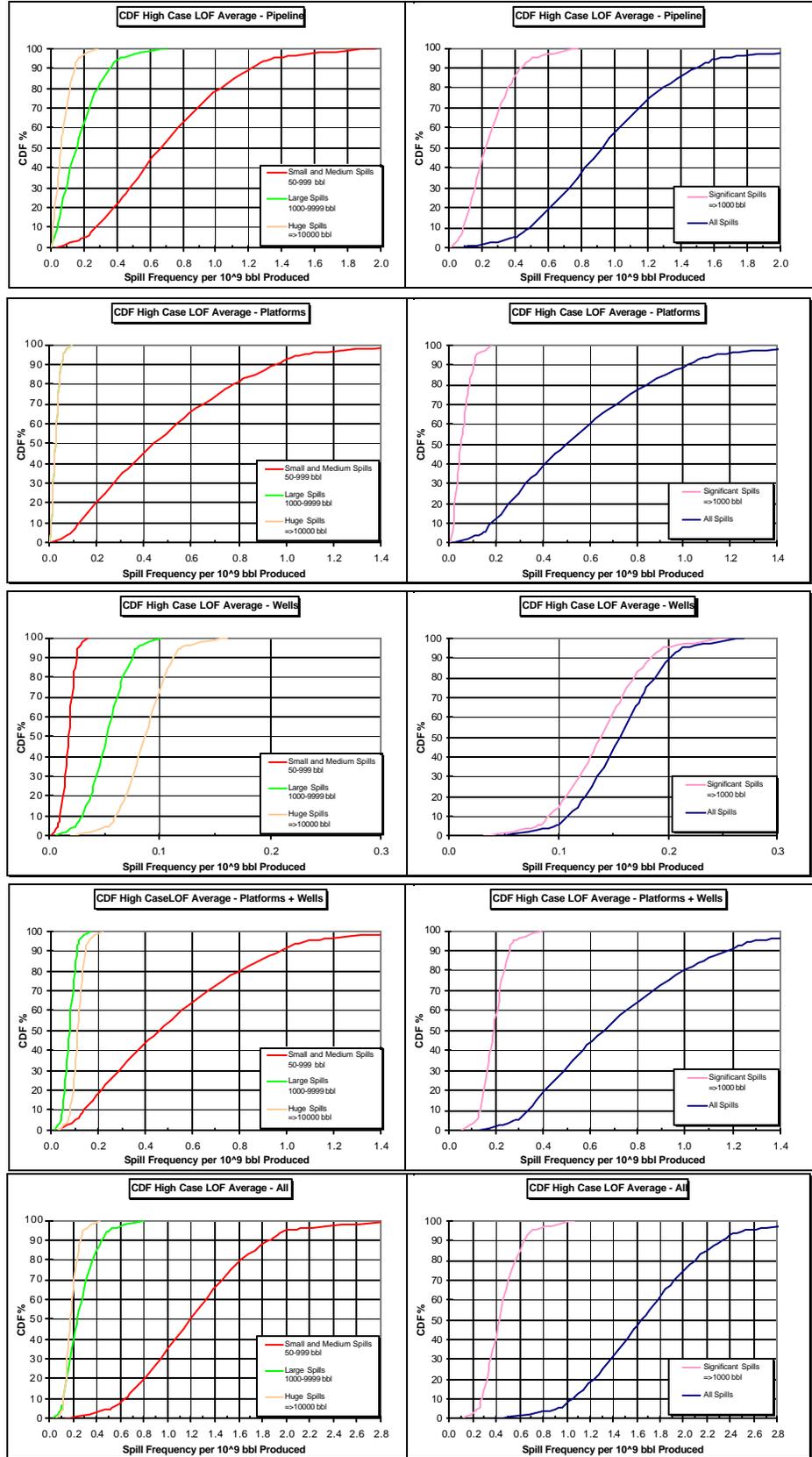
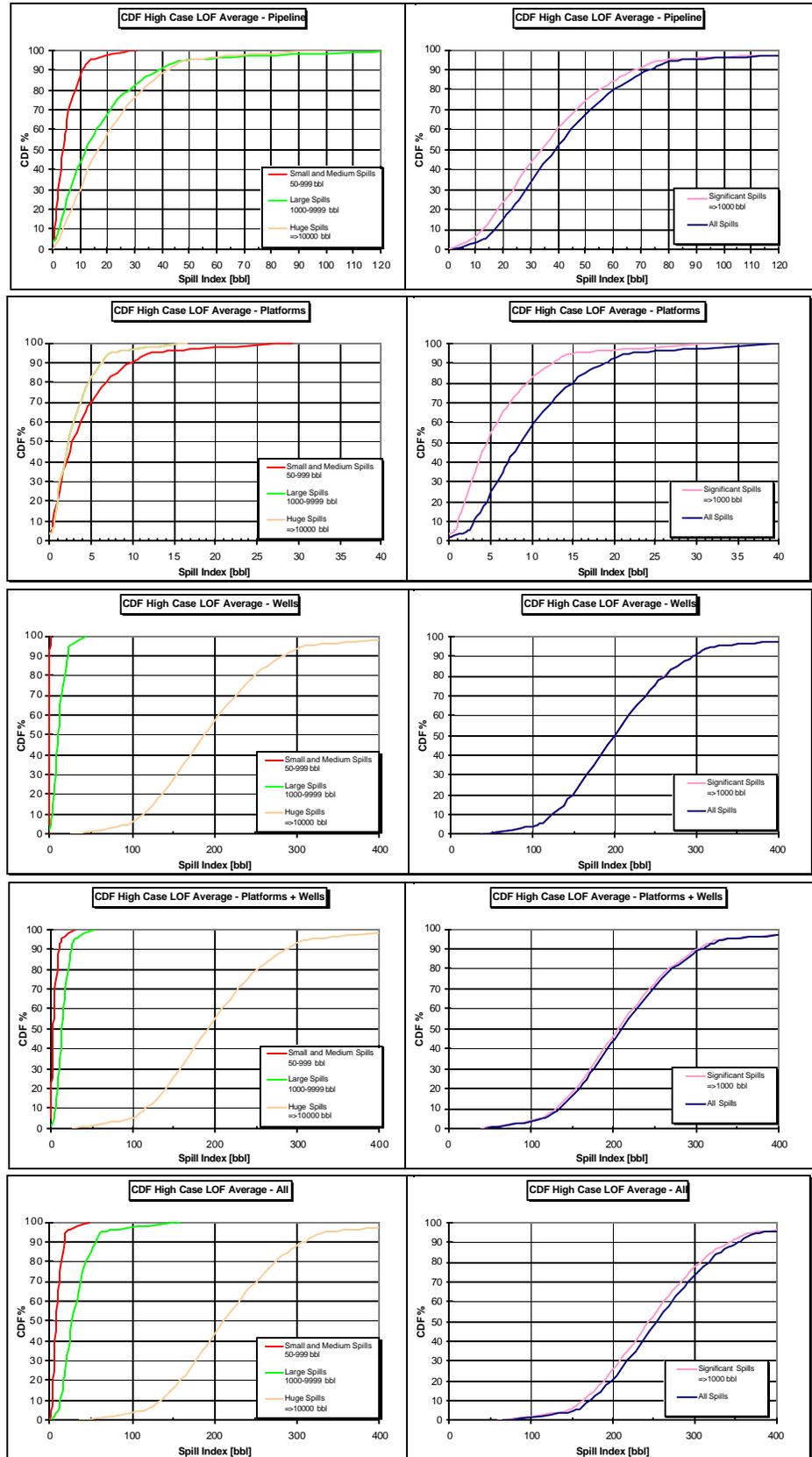


Figure 5.20
Chukchi Sea
High Case
Life of Field
Average
Spill Index (bbl)
– CDF
(Appendix
Figure 4.2.16)



CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

6.1.1 General Conclusions

Oil spill occurrence indicators were quantified for future deep water offshore development scenarios in the Chukchi 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 and Source

How do spill indicators for the Chukchi scenario and for its non-Arctic counterpart vary by spill size and location? Table 6.1 and Figure 6.1 and 6.2 summarize the Life of Field average spill indicator values by spill size and source. 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. High Case non-Arctic spill indicators are approximately 35% greater than Arctic High Case counterparts.

How do the spill indicators vary by facility type for representative scenarios? The contributions of spill indicators by facility have been summarized by representative scenario years, again, 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 Table 6.1:

- Pipelines contribute the most (57%) to the two Arctic spill frequency indicators.
- Platforms are next in relative contribution to spill frequencies (33%) and least in contribution to spill index (4%).
- Wells are by far (at 80%) the highest contributors to spill index, while platforms and wells together are responsible for an 84% contribution to the 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. Platforms will be in between, with more spills than wells.

Table 6.1
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	12.499	1.350	5	22.491	1.349	9	34.237	2.054	12
	73%	73%	4%	74%	74%	4%	72%	72%	3%
Large Spills 1000-9999 bbl	2.631	0.284	18	4.715	0.283	31	8.155	0.489	52
	15%	15%	12%	15%	15%	12%	17%	17%	14%
Huge Spills =>10000 bbl	1.899	0.205	121	3.385	0.203	213	5.239	0.314	302
	11%	11%	84%	11%	11%	84%	11%	11%	83%
Significant Spills =>1000 bbl	4.529	0.489	138	8.100	0.486	245	13.394	0.804	353
	27%	27%	96%	26%	26%	96%	28%	28%	97%
All Spills	17.028	1.839	143	30.592	1.835	254	47.631	2.858	365
	100%	100%	100%	100%	100%	100%	100%	100%	100%
Pipeline Spills	9.725	1.050	23	17.506	1.050	42	31.452	1.887	78
	57%	57%	16%	57%	57%	16%	66%	66%	21%
Platform Spills	5.702	0.616	6	10.263	0.616	10	12.331	0.740	12
	33%	33%	4%	34%	34%	4%	26%	26%	3%
Well Spills	1.601	0.173	114	2.823	0.169	202	3.848	0.231	275
	9%	9%	80%	9%	9%	80%	8%	8%	75%
Platform and Well Spills	7.303	0.789	120	13.086	0.785	212	16.179	0.971	287
	43%	43%	84%	43%	43%	84%	34%	34%	79%
All Spills	17.028	1.839	143	30.592	1.835	254	47.631	2.858	365
	100%	100%	100%	100%	100%	100%	100%	100%	100%

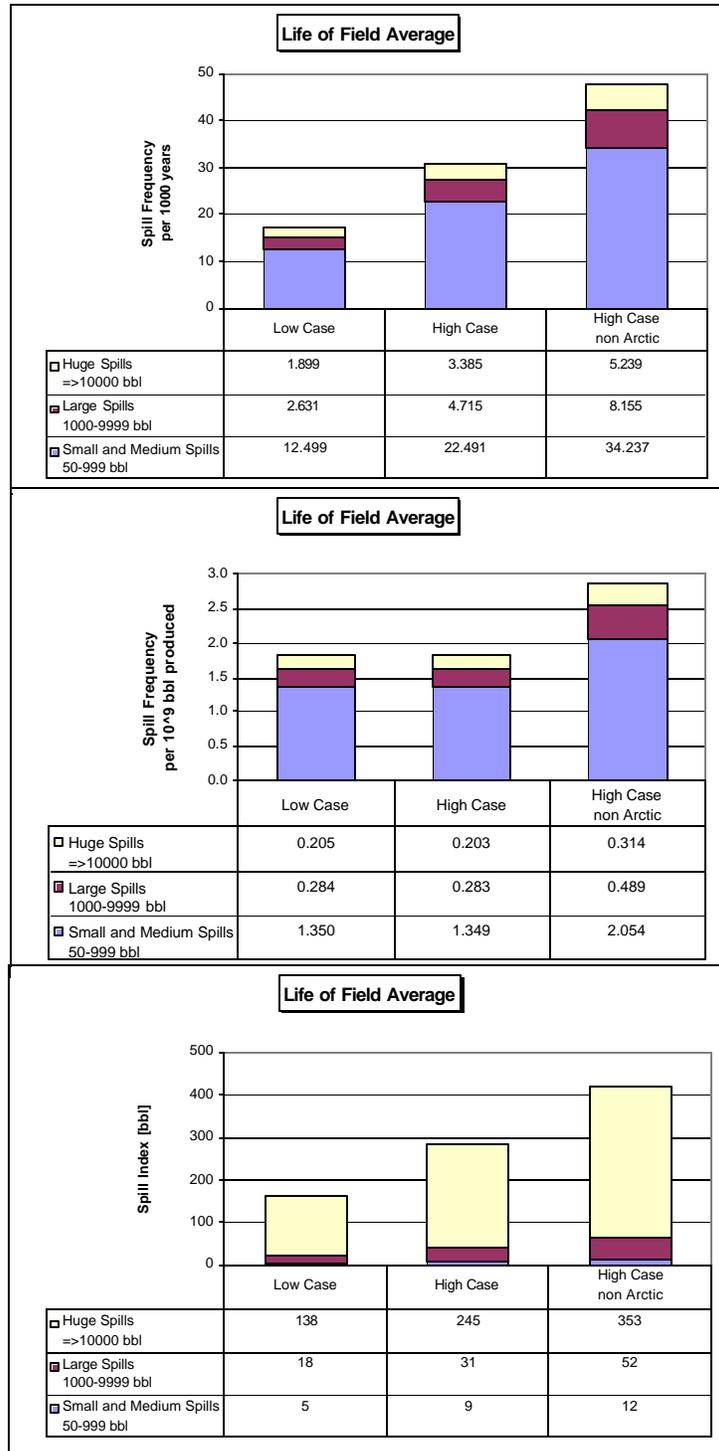


Figure 6.1
Chukchi Sea Life of Field Spill Indicators – By Spill Size
(Appendix Figure 5.1)

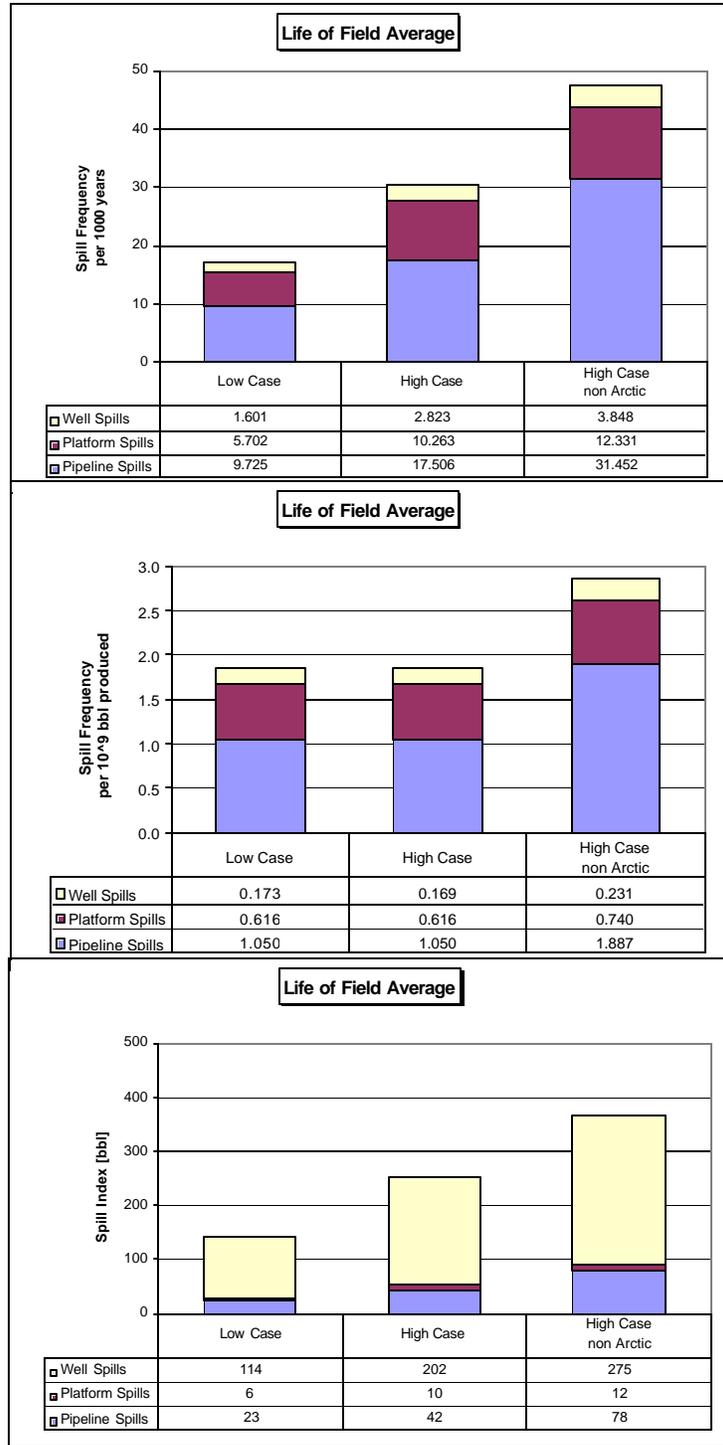


Figure 6.2
Chukchi Sea Life of Field Spill Indicators – By Source Composition
(Appendix Figure 5.2)

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.

6.1.3 The Variance of Oil Spill Occurrence Indicators

Figures 6.5, 6.6, and 6.7 show the Cumulative Distribution Functions (CDF) for each of the three Chukchi Sea High Case Life of Field average spill indicators. The variability of these indicators is fairly representative of the trends in variability for spill indicators for all sales and locations studied. Generally, the following can be observed from the figures:

- The variance of the frequency spill indicators (Figures 6.5 and 6.6) decreases as spill size increases for pipelines and platforms. For example, in the top right-hand graph of Figure 6.5, the significant spills plot has a much steeper (and hence less variable) slope than that of all spills. Similarly, in the top left-hand graph, small and medium spills illustrate the largest variability; huge spills show the least variability for these facilities.
- The opposite occurs for wells, where large spills show greater variance than small ones.
- The variability of the spill index (Figure 6.7) shows variance trends opposite to those of the frequency spill indicators.

The Cumulative Distribution Functions contain extensive information on the statistical properties of the spill indicators. For example, from Figure 6.5, it can be seen, for all significant spills, that the Life of Field average mean (50%) value of 8 (spills per 1,000 years) ranges between about 15 and 3 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 6.6. The spill index variability shown in Figure 6.7 is proportionally higher. For example, in Figure 6.7, the mean value of the significant spills index of 240 per billion barrels produced ranges from 150 to 400.

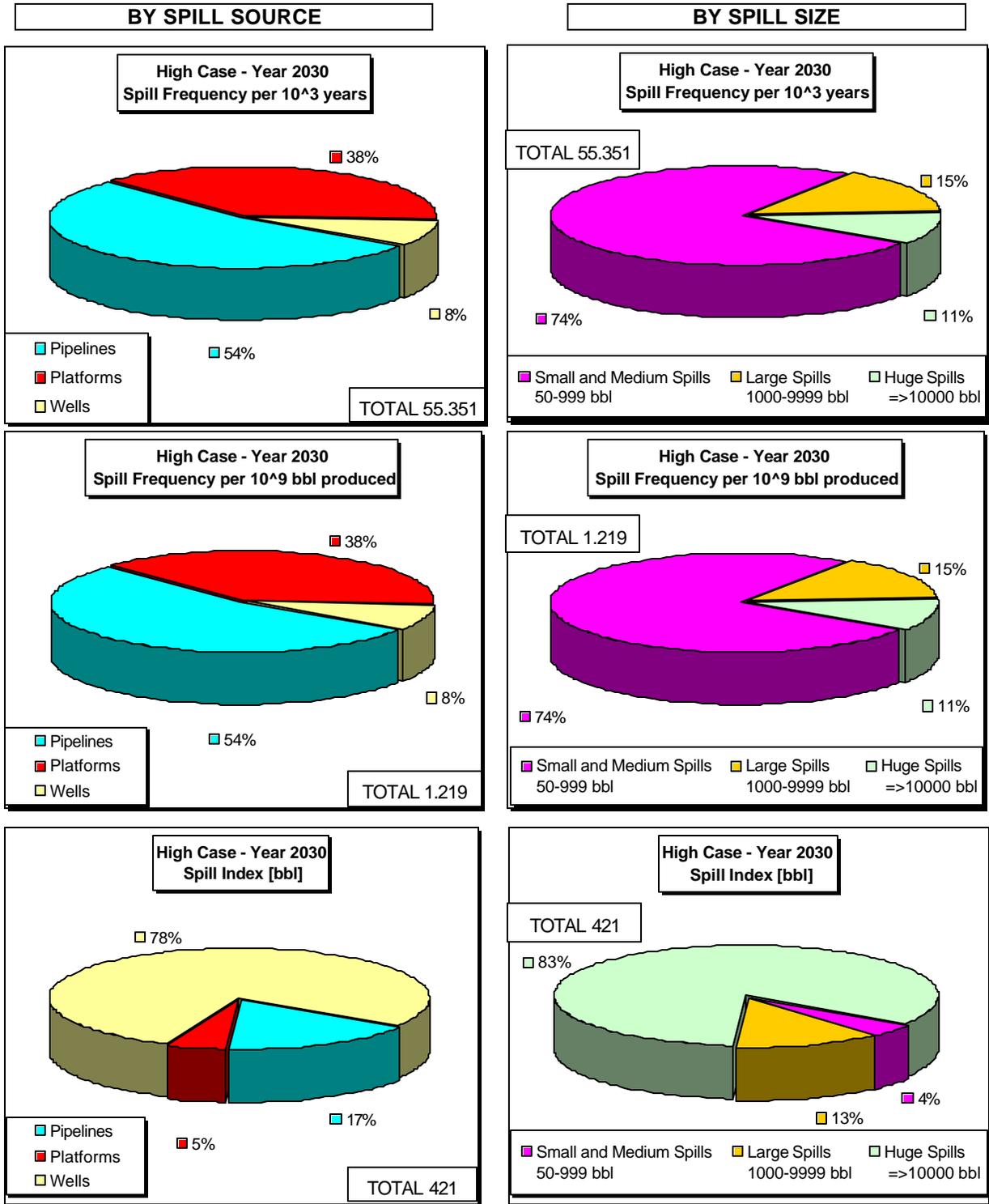


Figure 6.3
Chukchi Sea High Case – Year 2030 –
Spill Indicator Composition by Source and Spill Size
(Appendix Figure 4.2.17)

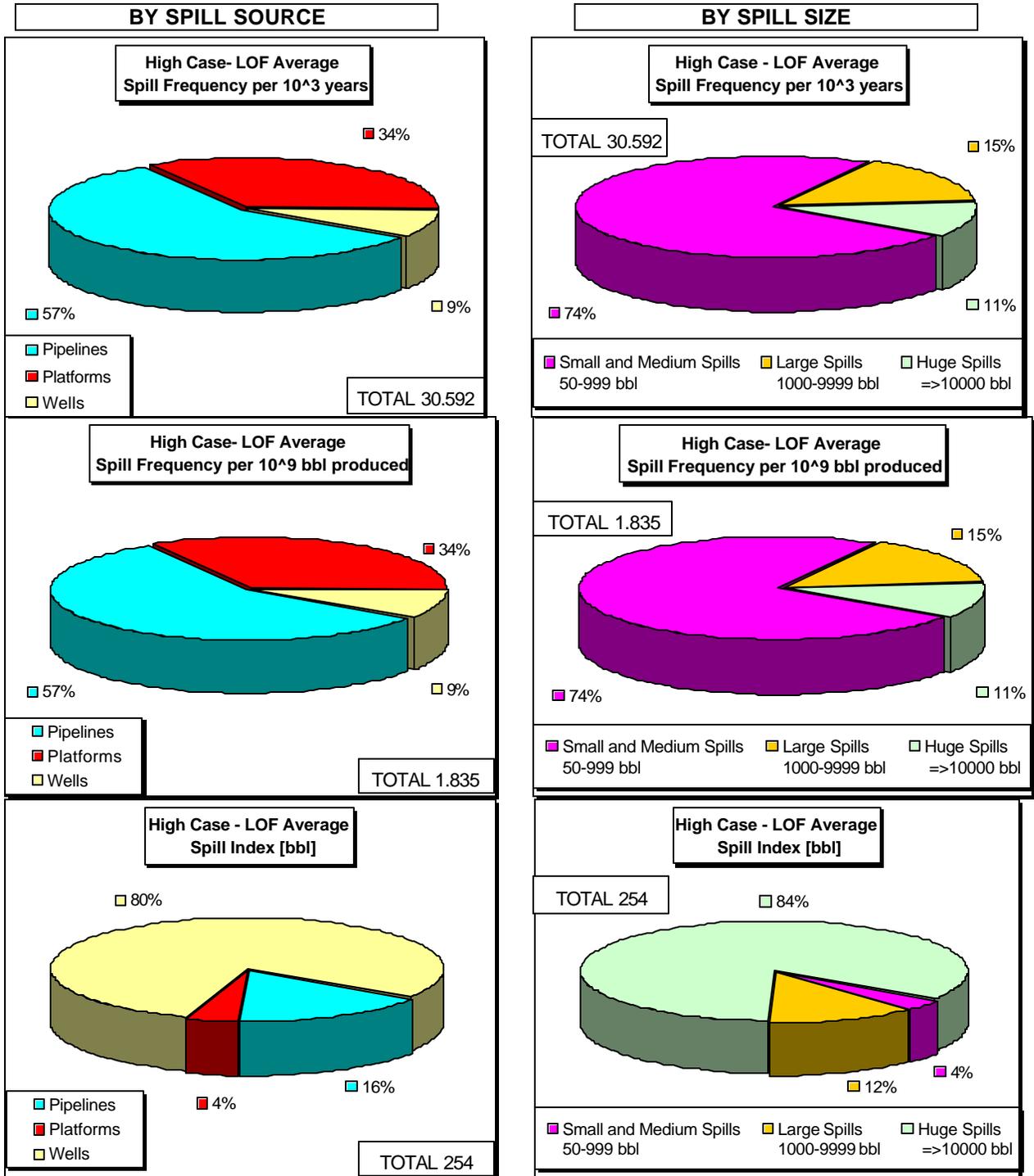


Figure 6.4
Chukchi Sea High Case – Life of Field Average Spill Indicator
Composition by Source and Spill Size
(Appendix Figure 4.2.18)

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

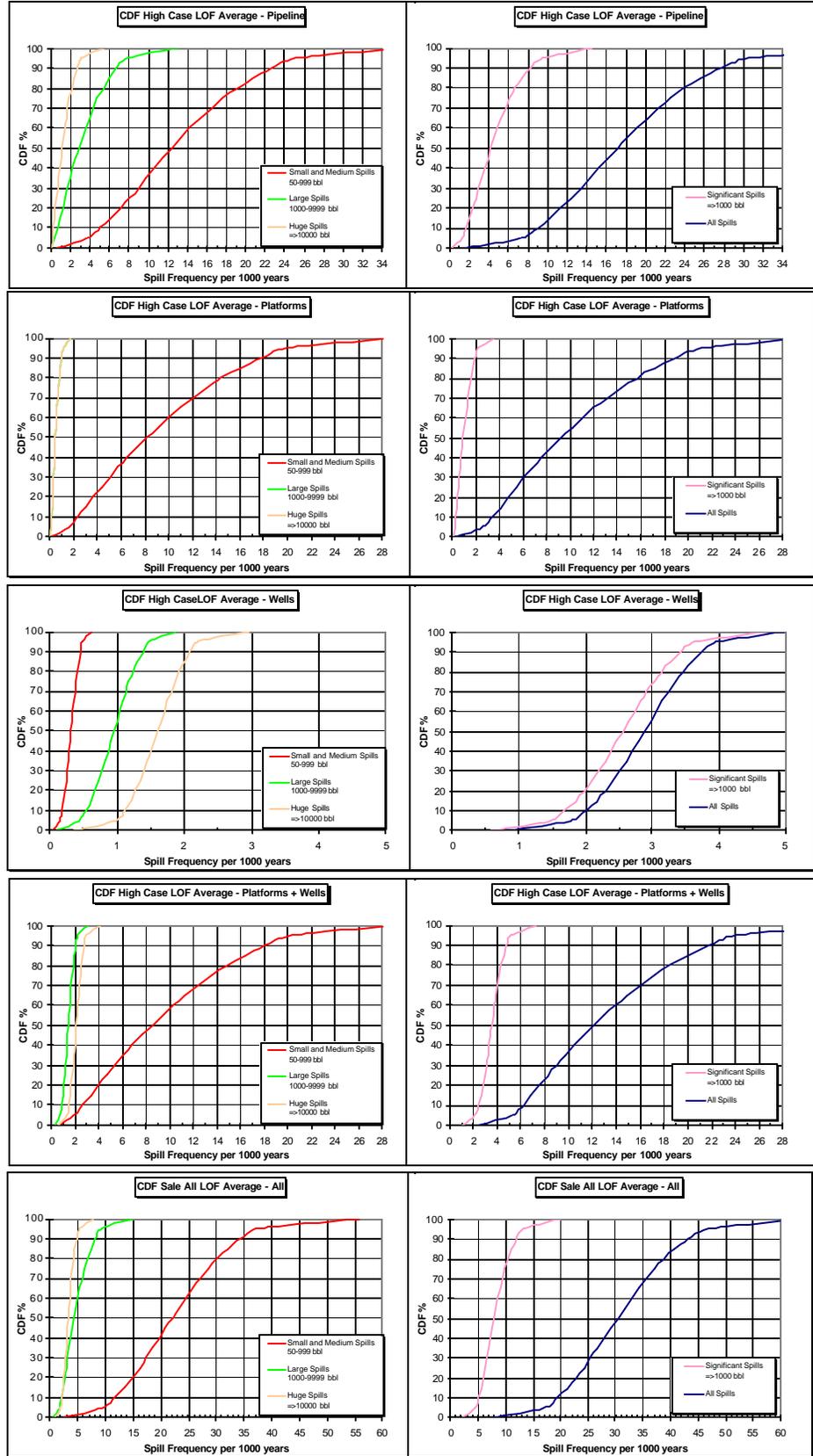


Figure 6.6
Chukchi Sea
High Case
Life of Field
Average Spills
per Barrel Produced
(Appendix
Figure 4.2.15)

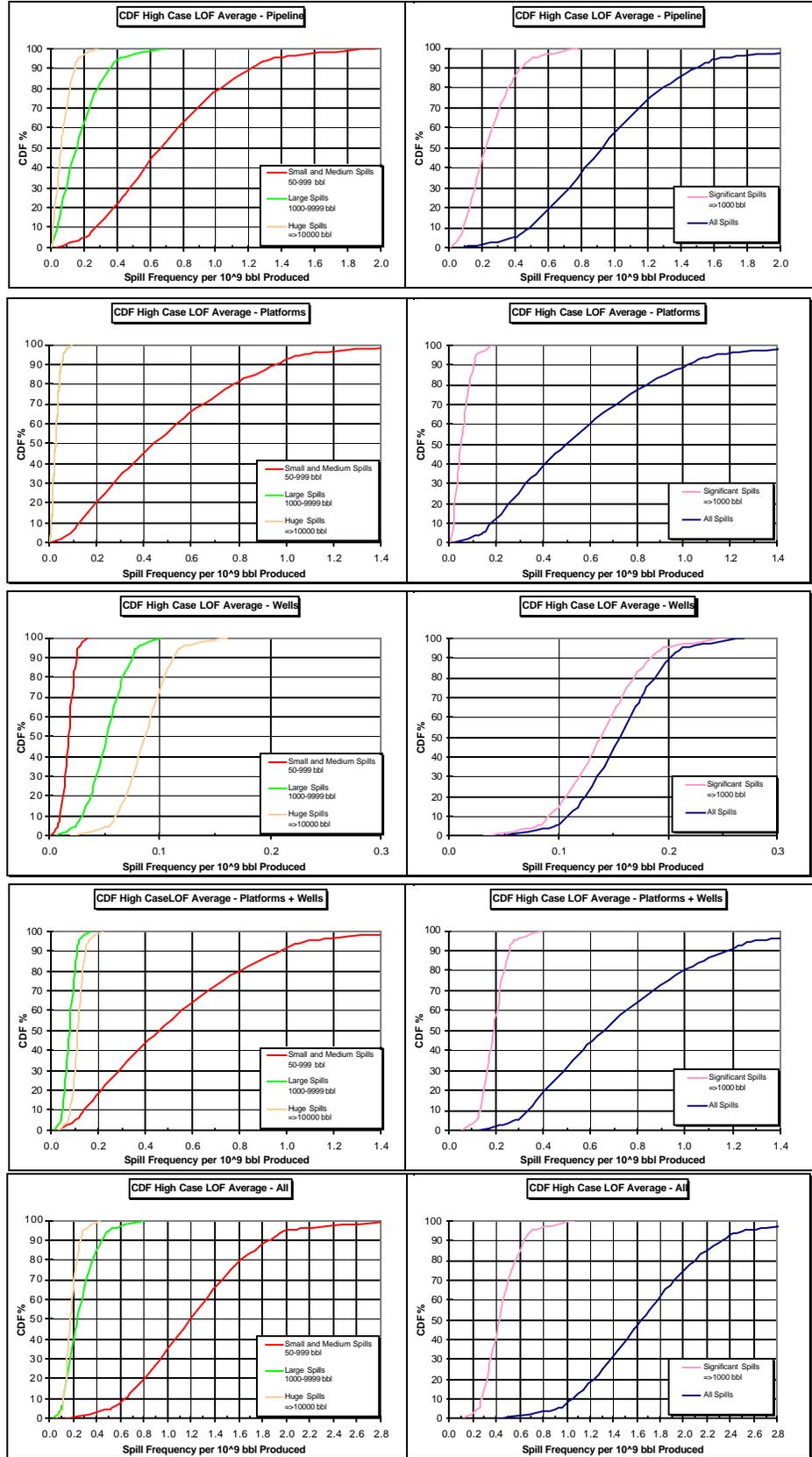
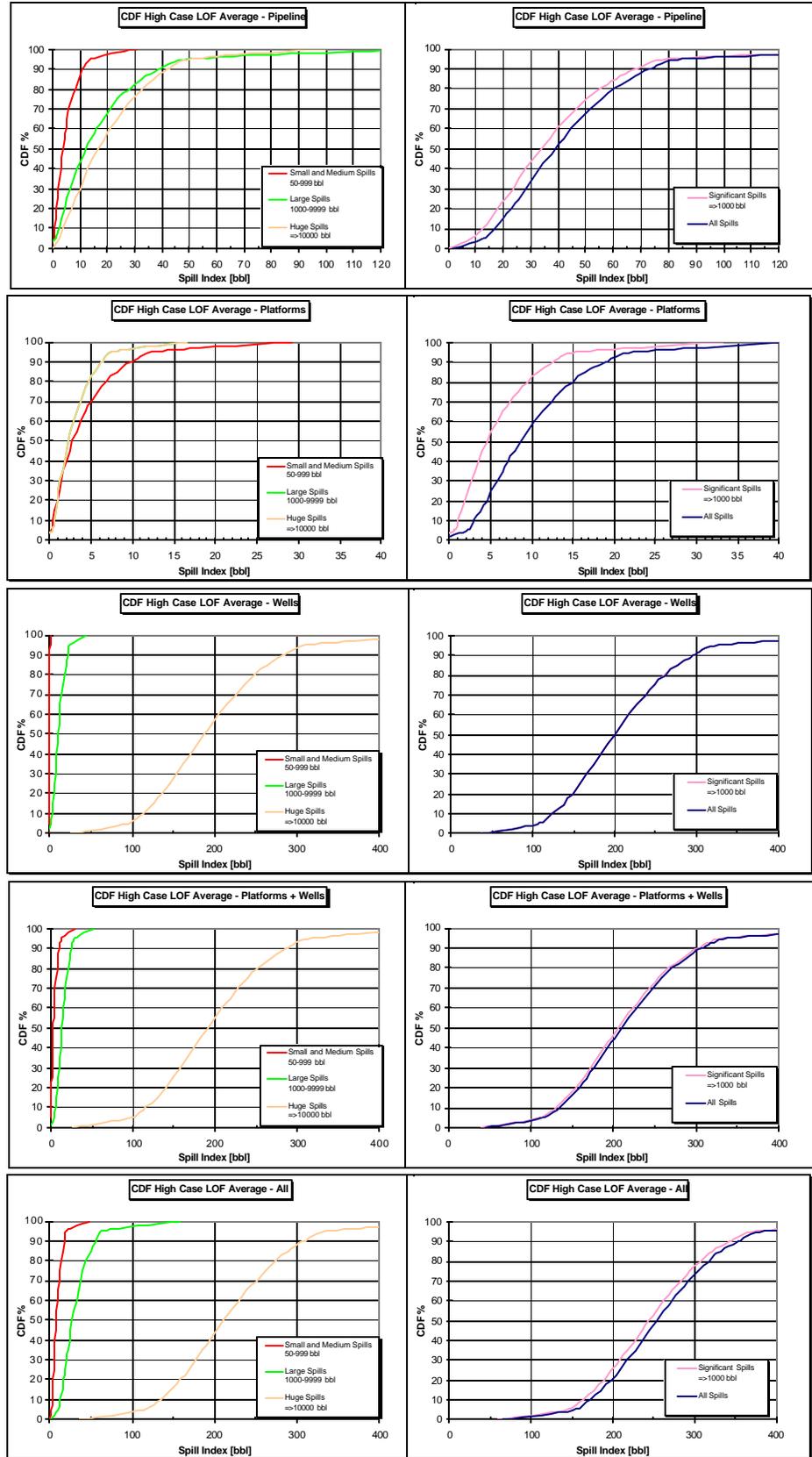


Figure 6.7
Chukchi Sea
High Case
Life of Field
Average
Spill Index (bbl)
– CDF
(Appendix
Figure 4.2.16)



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 Chukchi 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 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 relative cursory way restricted to engineering judgment.
- Upheaval buckling effect assessments were included on the basis of an educated guess used in previous studies; no engineering analysis was carried out for the assessment of frequencies to be expected for these effects.

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 the oil spill occurrence indicator model to generate additional model validation information, including direct application to specific non-Arctic scenarios, such as GOM projects, which have an oil spill statistical history.
- Utilize the oil spill occurrence indicator model in a sensitivity mode to identify the importance of different Arctic effect variables introduced to provide a prioritized list of those items having the highest potential impact on Arctic oil spills.
- 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.

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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.

