OCS Study BOEMRE 2011-030

SUMMARY FINAL REPORT

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

Contract Number M05PC00037

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By

BERCHA GROUP

Bercha International Inc.
Calgary, Alberta, Canada

BOEMRE USDOI Bureau of Ocean Energy Management, Regulation and Enforcement

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

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ABSTRACT

Probabilistic estimates of oil spill occurrences are used in the development of environment impact assessments for hypothetical developments in the US Chukchi and Beaufort seas. Due to the limited offshore oil development in this region, it was not possible to base these oil spill probability estimates on empirical data from that region. Rather, statistically significant non-Arctic empirical data from the US Gulf of Mexico (GOM) and world-wide sources, together with their variance, were used as a starting point. Next, both the historical non-Arctic frequency distributions and spill causal distributions were modified to reflect specific effects of the Arctic setting, and the resultant fault tree model was evaluated using Monte Carlo simulation to adequately characterize uncertainties treated as probability distribution inputs to the fault tree. A series of studies, associated with successive lease sale scenarios between 2000 and 2006, was carried out directed at developing and applying the fault tree methodology. In addition, a study directed solely at updating the GOM data was carried out. The series of studies consisted of five Beaufort and/or Chukchi application studies and the GOM data update studies. This report summarizes the methodology and gives results of its application to the estimation of oil spill probabilities and their characteristics for the Chukchi and Beaufort Seas region based on the most recent studies and statistics.

EXECUTIVE SUMMARY

A. General Introduction

The Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE) Alaska Offshore Continental Shelf (OCS) Region uses estimates of oil spill occurrences for the development of environmental impact statements for hypothetical offshore development scenarios resulting from the sale of leases for the US Beaufort Sea OCS. Since 2000, a series of studies (summarized in Section B, below) carried out by Bercha International Inc. (Bercha) directed at the development of a realistic method of projecting oil spill occurrences, including source, size distribution, location, and timing for hypothetical development scenarios associated with offshore OCS lease sales.

Although estimates of expected values of oil spill probabilities and sizes provide a simple basis for estimating environmental impacts, the magnitude and distribution of uncertainties can alter the significance of these expected values. Thus, to develop the probability distributions of oil spill occurrences, non-Arctic empirical data together with their variance as a starting point are used, and Arctic effect distributions and their impact on both the original data variance as well as additional unique Arctic effect distributions such as those for ice gouging and strudel scour were integrated. To provide the expected values and their variability, an oil spill occurrence model based on fault tree methodology was developed and evaluated using Monte Carlo methods with all significant inputs in distributed form. Four principal spill occurrence indicator probability distributions, as follows, were quantified:

- Annual spill frequency
- Annual spill frequency per barrel produced
- Spill index, the product of spill size and spill frequency
- Life of field averages of the above indicators.

These indicators were quantified for a range of four representative spill size distributions, from 50 bbl to huge spills exceeding 10,000 bbl as follows:

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

A wide range of details for each scenario was generated, including the following:

- (Statistical expected value) 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 projections between Arctic and non-Arctic scenarios.
- Life of field averages of spill occurrence estimators.

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

The study area was the Chukchi and Beaufort Sea Outer Continental Shelf locations generally shown in Figure 1.

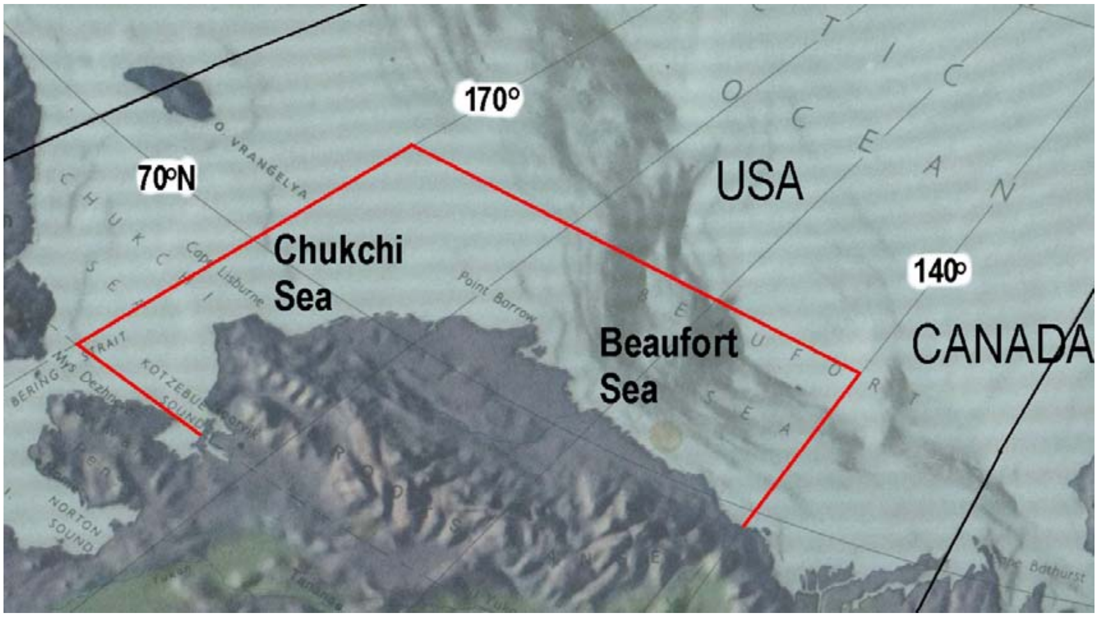

Figure 1. Study Area Map

B. Summary of Work Done

The following studies were carried out and reported between the inception in 2000, and this Summary Final Report in 2011:

a. Bercha International Inc., *Alternative Oil Spill Occurrence Estimators and their Variability for the Alaskan OCS – Fault Tree Method – Update of GOM OCS Statistics to 2006*, (OCS Study MMS 2008-025), Final Task 3.1 Report to U.S. Department of the Interior, Minerals Management Service, Alaska Outer Continental Shelf Region, March 2008c.

b. Bercha International Inc., *Alternative Oil Spill Occurrence Estimators and their Variability for the Beaufort Sea – Fault Tree Method*, (OCS Study MMS 2008-035), Final Task 4A.1 Report to U.S. Department of the Interior, Minerals Management Service, Alaska Outer Continental Shelf Region, Vols. 1 and 2, March 2008a.

c. Bercha International Inc., *Alternative Oil Spill Occurrence Estimators and their Variability for the Chukchi Sea – Fault Tree Method*, (OCS Study MMS 2008-036), Final Task 4A.2 Report to U.S. Department of the Interior, Minerals Management Service, Alaska Outer Continental Shelf Region, Vols. 1 and 2, March 2008b.

d. Bercha International Inc., *Alternative Oil Spill Occurrence Estimators and their Variability for the Beaufort Sea – Fault Tree Method*, (OCS Study MMS

2005-061), Final Report to U.S. Department of the Interior, Minerals Management Service, Alaska Outer Continental Shelf Region, January 2006b.

e. Bercha International Inc., *Alternative Oil Spill Occurrence Estimators and their Variability for the Chukchi Sea – Fault Tree Method*, (OCS Study MMS 2006-033), Final Task 1 Report to U.S. Department of the Interior, Minerals Management Service, Alaska Outer Continental Shelf Region, Vols. 1 and 2, October 2006a.

f. Bercha International Inc., *Alternative Oil Spill Occurrence Estimators for the Beaufort and Chukchi Seas – Fault Tree Method* (OCS Study MMS 2002-047), Final Report to US Department of Interior, Minerals Management Service, Alaska Outer Continental Shelf Region, August 2002.

Each of the above cited studies consists of two volumes; namely Volume 1, the final report, and Volume 2, a reproduction of all salient calculation results. Volume 1 of each report numbers in the range of 150 pages, while Volume 2 consists of up to 300 pages.

C. Conclusions on the Methodology and its Applicability

An analytical tool for the estimation of oil spill occurrence indicators for systems without history, such as hypothetical offshore oil exploration and production developments in the Beaufort and Chukchi seas, has been developed based on the utilization of fault tree methodology. Although the results generated are voluminous, they are essentially transparent, simple, and easy to understand. The analytical tool developed is also quite transparent, very efficient in terms of computer time and input-output capability. In addition, the predictive model is setup so that any input variables can be entered as distributions.

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

- Ability to generate expected and mean values as well as their variability in rigorous numerical statistical format.
- Use of verifiable input data based on BOEMRE 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. 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 BOEMRE needs, as it is currently the best model available for estimation of spill occurrence.
- Utilize this oil spill occurrence indicator model to generate additional model validation information, including direct application to specific non-Arctic scenarios, such as GOM projects, which have an oil spill statistical history.
- Utilize the oil spill occurrence indicator model in a sensitivity mode to identify the importance of different Arctic effect variables introduced to provide a prioritized list of those items having the highest potential impact on Arctic oil spills.
- Generalize the model so that it can be run both in an adjusted expected value and a distributed value (Monte Carlo) form with the intent that expected value form can be utilized without the Monte Carlo add-in for preliminary estimates and sensitivity analyses, while for more comprehensive rigorous studies, the Monte Carlo version can be used.

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GLOSSARY OF TERMS AND ACRONYMS

Bbbl	**B**illion Barrels
BOEMRE	United States Department of the Interior **B**ureau of **O**cean **E**nergy **M**anagement, **R**egulation and **E**nforcement
CDF	**C**umulative **D**istribution **F**unction
Consequence	The direct effect of an accidental event.
GOM	**G**ulf **o**f **M**exico
Hazard	A condition with a potential to create risks such as accidental leakage of natural gas from a pressurized vessel.
KBpd	Thousand Barrels per day
LOF	**L**ife of **F**ield
MMbbl	Million Barrels
MMS	**M**inerals **M**anagement **S**ervice, Department of the Interior
Monte Carlo	A numerical method for evaluating algebraic combinations of statistical distributions.
OCS	**O**uter **C**ontinental **S**helf
Risk	A compound measure of the probability and magnitude of adverse effect.
SINTEF	The Foundation of Scientific and Industrial Research at the Norwegian Institute of Technology
Spill Frequency	The number of spills of a given spill size range per year. Usually expressed as spills per 1,000 years (and so indicated).
Spill Frequency per Barrel Produced	The number of spills of a given spill size range per barrel produced. Usually expressed as spills per billion barrels produced (and so indicated).
Spill Index	The product of spill frequency for a given spill size range and the mean spill size for that spill size range.
Spill Occurrence	Characterization of an oil spill as an annual frequency and associated spill size or spill size range.
Spill Occurrence Indicator	Any of the oil spill occurrence characteristics; namely, spill frequency, spill frequency per barrel produced, or spill index (defined above).
Spill Sizes	Small (S): 50 - 99 bbl Medium (M): 100 - 999 bbl Large (L): 1,000 - 9,999 bbl Huge (H): >=10,000 bbl Significant (SG): >=1,000 bbl

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- Caryn Smith, Oil-Spill-Risk-Analysis Coordinator
- Cheryl Anderson, BOEMRE Spill Database Coordinator
- Debra Bridge, Contracting Officer
- 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 Bercha, Editorial and Word Processing Manager

SECTION 1
INTRODUCTION

1.1 General Introduction

The Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE) Alaska Offshore Continental Shelf (OCS) Region needs estimates of oil spill occurrences for the development of environmental impact statements for hypothetical offshore developments resulting from the sale of leases for the US Beaufort Sea Outer Continental Shelf. Since 2000, a series of studies [5, 6, 7, 8, 9, 10] carried out by Bercha International Inc. (Bercha) directed at the development of a realistic method of projecting oil spill occurrences, including source, size distribution, location, and timing for hypothetical development scenarios associated with offshore OCS lease sales. Additionally, result summaries were published in several publications [2, 3, 4].

Although estimates of expected values of oil spill probabilities and sizes provide a simple basis for estimating environmental impacts, the magnitude and distribution of uncertainties can alter the significance of these expected values. Thus, to develop the probability distributions of oil spill occurrences, non-Arctic empirical data together with their variance as a starting point are used, and Arctic effect distributions and their impact on both the original data variance as well as additional unique Arctic effect distributions such as those for ice gouging and strudel scour were integrated. To provide the expected values and their variability, an oil spill occurrence model based on fault tree methodology was developed and evaluated using Monte Carlo methods with all significant inputs in distributed form. Four principal spill occurrence indicator probability distributions, as follows, were quantified:

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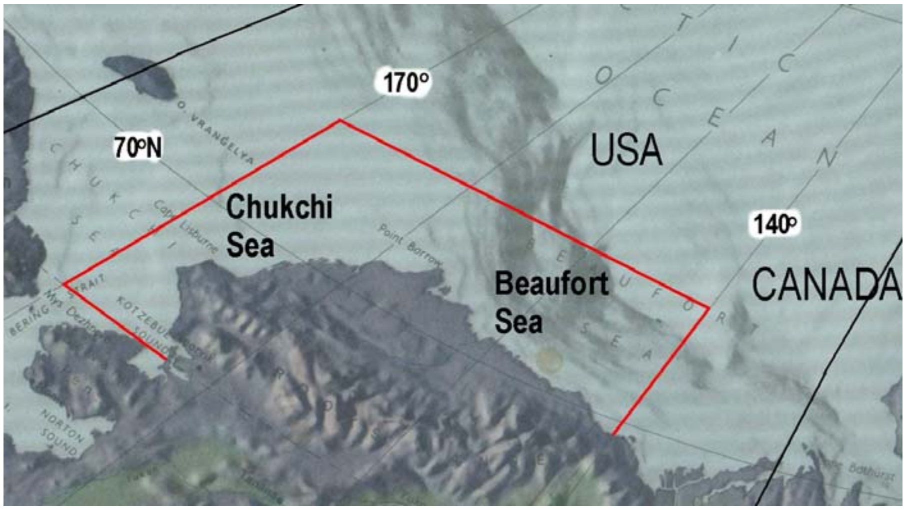

Figure 1.1. Study Area Map

1.2 Summary of Work Done

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1.3 Modeling Methodology

Probabilistic estimates of oil spill occurrences are used for the development of environment impact assessments for hypothetical developments in the US Chukchi and Beaufort Seas. Due to the short history of offshore oil development in this region, it was not possible to base these oil spill probability estimates on historical empirical data from that region. Rather, statistically significant non-Arctic empirical data from the US Gulf of Mexico (GOM) and world-wide sources, together with their variance, were used as a starting point. Next, both the historical non-Arctic frequency distributions and spill causal distributions were modified to reflect specific effects of the Arctic setting, and the resultant fault tree model was evaluated using Monte Carlo simulation to adequately characterize uncertainties treated as probability distribution inputs to the fault tree. A series of studies, associated with successive lease sale scenarios between 2000 and 2008, was carried out directed at developing and applying the fault tree methodology. In addition, a study directed solely at updating the GOM data was carried out. The series of studies consisted of five Beaufort and/or Chukchi application studies and the GOM data update studies.

For Arctic settings, the following two types of effects need to be introduced:

- Arctic modifications to non-Arctic causal probabilities, such as those of hurricanes.
- Arctic-unique effect probabilities, such as those of ice gouging.

These Arctic effects were introduced by systematically modifying and augmenting spill occurrence fault trees for each of the three main facility types; namely, pipelines, platforms, and wells.

A fault tree illustrating this process is shown in Figure 1.2. Here, the top numbers labeled “Historical Frequency” or “H” represent the historical (non-Arctic) causal probability contributions. The bottom numbers represent the modified probability values reflecting Arctic effects for the three water depths designated with “S” for shallow, “M” for medium, and “D” for deep. The “ARCTIC” sub-tree represents the Arctic-unique effects, some which vary with water depth, such as ice gouging.

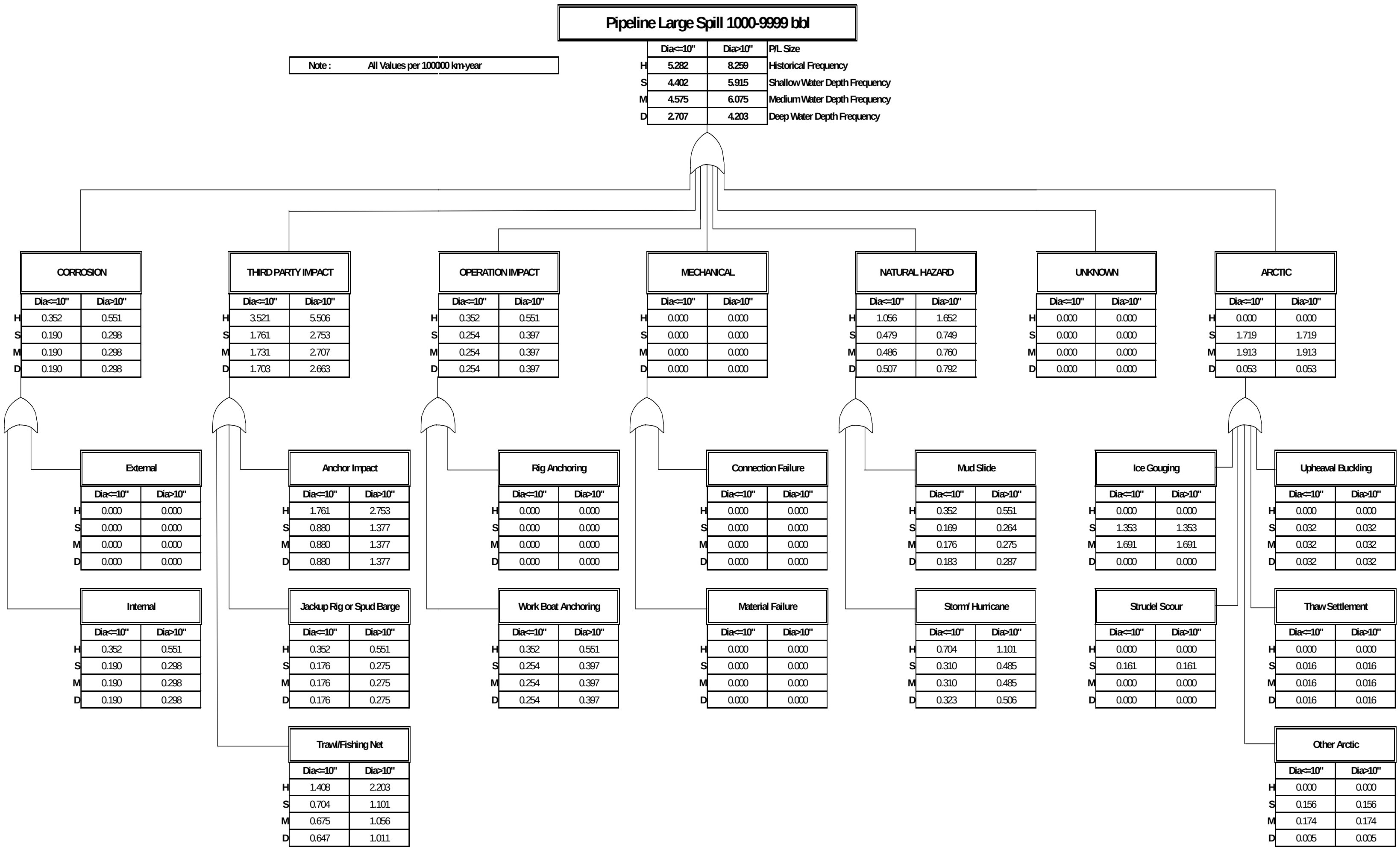


Figure 1.2. Large Spill Frequencies Fault Tree for Pipeline

In the analysis itself, fault trees were constructed for all representative categories of facilities, spill sizes, and water depth, and a calculation process (schematically illustrated in Figure 1.3) was carried out. With inputs as distributed values, the resultant spill rates were then evaluated using a Monte Carlo process (Bercha International Inc., 2006a and 2008a). These spill rates were then combined, again using Monte Carlo simulation methods, with specific development scenarios consisting of specified numbers of wells, platforms, and pipeline mileages, to give the annual and life of field average oil spill occurrence estimators. These results are presented subsequently.

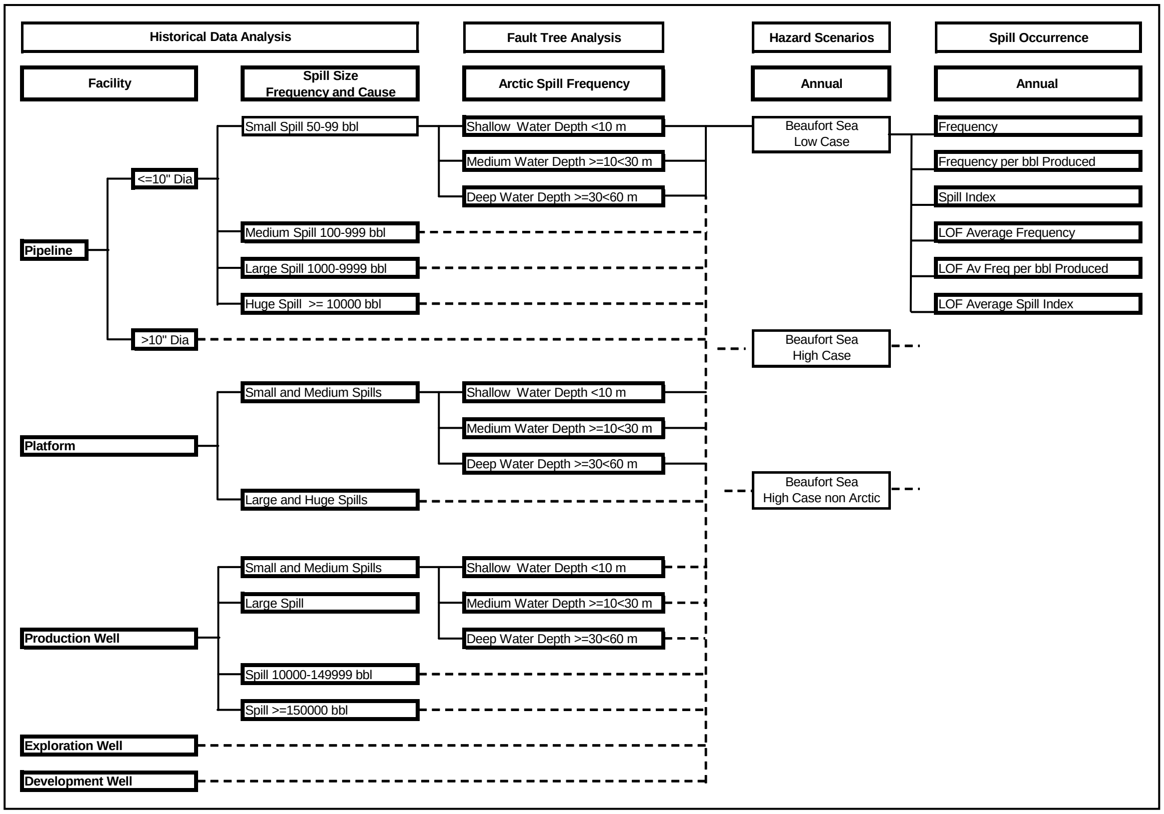


Figure 1.3. Calculation Flow Chart

1.4 Development Scenarios

For the purposes of the fault tree analysis utilized in the studies summarized, hypothetical offshore oil and gas development scenarios were characterized as follows for each year of the scenario:

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

Table 1.1 shows a general 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 1.1, 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 were not used in the studies. Note that water depth zones: Shallow (<10 m), medium (10-29 m), and deep (30-60 m) also reflect the differences in Arctic facilities needed for each zone.

Table 1.1. Classification of Exploration and Development Scenarios

Principal Activity	Water Depth (m)			
	Shallow (< 10)	Medium (10 to 29)	Deep (30 to 60)	Very Deep (> 60)
Exploration	▪ Artificial island ▪ Drill barge ▪ Ice island	▪ Artificial island ▪ Drill ship (summer) ▪ Caisson	▪ Drill ship (summer) ▪ Semisubmersible (summer)	▪ Drill ship (summer) ▪ Semisubmersible (summer)
Production	▪ Artificial island ▪ Caisson island	▪ Caisson island ▪ Gravity Base Structure (GBS)	▪ Caisson island ▪ Gravity Base Structure (GBS)	▪ New design structure ▪ Submarine habitat
Transport	▪ Subsea pipeline	▪ Subsea pipeline	▪ Subsea pipeline ▪ Storage & tankers	▪ Subsea pipeline ▪ Submarine storage ▪ Icebreaking tankers ▪ Submarine tankers

1.5 Objective of this Summary Final Report

The purpose of this report is to reference the work done and summarize the most recent salient results, conclusions, limitations, and recommendations. Accordingly this report is organized as follows:

- Section 2 – GOM Data and Statistical Update
- Section 3 – Beaufort Sea Oil Spill Indicators
- Section 4 – Chukchi Sea Oil Spill Indicators
- Section 5 – Conclusions, Limitations, and Recommendations

SECTION 2

GOM DATA AND STATISTICAL UPDATE

2.1 Introduction

Historical data and their statistical analyses are used as a starting point for fault tree application to oil spill indicator quantification for the Alaskan OCS. In the initial fault tree analysis [10], data from the GOM OCS were analyzed for the period from 1972 to 1999 [1]. Subsequently, a more refined publication of the data characteristics by BOEMRE[1] has made it possible to conduct a more thorough statistical analysis as well as an update of the data and its analysis to 2006. This section generally discusses and gives data summaries as well as typical statistical results for the re-analysis of the data, including an update of the GOM OCS data for platform and pipeline spills. In addition, a summary of worldwide blowout statistical data based on Holand [11] and others [13] is given.

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 BOEMRE database[1]. 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, in the small and medium size category, the calculated statistic is approximately 12.78 spills per 100,000 km-yrs. Of this rate, it is expected that approximately 1.1 per 100,000 km-yrs can be attributed to pipe corrosion.

Finally, Table 2.3 summarizes the pipeline hydrocarbon spill statistics by spill size and pipe diameter.

[1] BOEMRE Website, http://boemre.gov/incidents/IncidentStatisticsSummaries.htm; accessed as www.mms.gov/incidents/spills, 2008.

Table 2.1. GOM OCS Pipeline Hydrocarbon Spill Summary by Spill Size (1972-2006)

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	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
UNKNOWN	2	119	190																	2			2	
TOTALS	50																		12	23	12	3	35	15

Table 2.2. GOM OCS Pipeline Hydrocarbon Spill Statistics by Cause (1972-2006)

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		1.0955	6.67	1		0.3652
External	2.86	1		0.3652				
Internal	5.71	2		0.7303	6.67	1		0.3652
THIRD PARTY IMPACT	22.86	8		2.9213	66.67	10		3.6517
Anchor Impact	20.00	7		2.5562	33.33	5		1.8258
Jackup Rig or Spud Barge					6.67	1		0.3652
Trawl/Fishing Net	2.86	1		0.0365	26.67	4		1.4607
OPERATION IMPACT	8.57	3		1.0955	6.67	1		0.3652
Rig Anchoring	2.86	1		0.3652				
Work Boat Anchoring	5.71	2		0.7303	6.67	1		0.3652
MECHANICAL	5.71	2		0.7303				
Connection Failure	2.86	1	273847	0.3652			273847	
Material Failure	2.86	1		0.3652				
NATURAL HAZARD	48.57	17		6.2078	20.00	3		1.0955
Mud Slide	5.71	2		0.7303	6.67	1		0.3652
Storm/ Hurricane	42.86	15		5.4775	13.33	2		0.7303
ARCTIC								
Ice Gouging								
Strudel Scour								
Upheaval Buckling								
Thaw Settlement								
Other Arctic								
UNKNOWN	5.71	2		0.7303				
TOTALS	100.00	35		12.7809	100.00	15		5.4775

Table 2.3. GOM OCS Pipeline Hydrocarbon Spill Statistics by Spill Size and Pipe Diameter (1972-2006)

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

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 2.4 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 through 2006, however, is the tank failure which caused a spill of nearly 10,000 barrels.

Table 2.4. Summary of GOM OCS Platform Hydrocarbon Spills by Size and Cause (1972-2006)

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

The spill rate data, given per production well-year, is shown in Table 2.5, 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.

Table 2.5. GOM OCS Platform Hydrocarbon Spill Statistics (1972-2006)

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

2.4 Blowouts

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 [12], a study by ScanPower giving the cumulative distribution function for oil blowout releases [13], as well as the book by Per Holand entitled "Offshore Blowouts", which gives risk analysis data from the SINTEF worldwide offshore blowout database [11]. The most comprehensive historical information was found in the latter reference [11], 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 2.6 gives a summary of the historical data analysis by Per Holland [11] 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 [13], generated in support of the Northstar project, permits the blowout spill volume frequency distribution as summarized in Table 2.7. Finally, combining the population parameters of oil well blowouts from Table 2.6 with the size distribution factors – which can be derived from Table 2.7 – one arrives at the historical oil spill blowout distribution characteristics by spill size and well type, summarized in Table 2.8. The 2010 *Deepwater Horizon* blowout is too recent to be included in these tables, but an exploration well blowout $\geq$150,000 bbl is projected to occur at rate of 1.796 such spills per 10^4 wells.

Table 2.6. Summary of North Sea and Gulf of Mexico Blowout Rates (Holand, 1997 [11])

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 2.7. Well Blowout Historical Spill Size Distribution (ScanPower, 2001 [13])

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 2.8. Well Blowout Historical Spill Probability and Size Variability

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

SECTION 3
BEAUFORT SEA OIL SPILL INDICATORS

3.1 General Introduction

Oil spill occurrence indicators were quantified for hypothetical offshore development scenarios in the Beaufort Sea in the area of BOEMRE jurisdiction. The quantification included the consideration of the variability of historical and hypothetical scenario data, as well as that of Arctic effects in estimating 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. Finally, spill indicators assessed for the Arctic development were compared to what these spill indicators would be for a development of similar characteristics in a non-Arctic location, such as the GOM. This comparison was effected by utilizing the GOM data without the introduction of any variations for Arctic effects for a development consisting of identical quantities of wells, facilities, and pipeline miles. The results summarized in this section are based on the most recent Beaufort Sea study [5] with reference only to earlier results [8, 10].

3.2 Oil Spill Occurrence Indicators by Spill Size

How do spill indicators for the Beaufort scenario provided by BOEMRE and for its non-Arctic counterpart vary by spill size and location? Table 3.1 and Figures 3.1 and 3.2 summarize the Life of Field average spill indicator values by spill source and size for the Low (125 million bbl, 1 platform) and High Case (500 million bbl, 3 platforms) and Non-Arctic High Case (High Case as if in the GOM) scenarios. The following can be observed from Table 3.1:

- 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. The lower Arctic spill frequencies are due to the increases from Arctic-specific causes having less effect in the fault tree than the reductions from causes such as less offshore traffic, no hurricanes, and anticipated (better) modern maintenance technology.

3.3 Oil Spill Occurrence Indicators by Spill Source

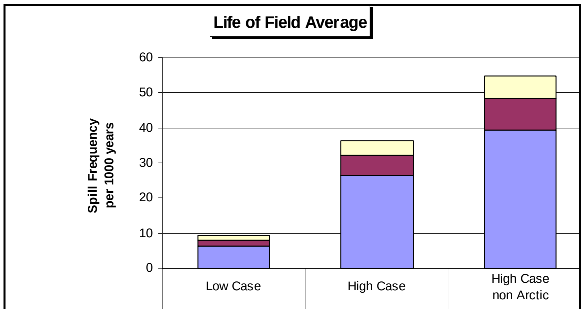
How do the spill indicators vary by facility type for the BOEMRE representative scenarios? The contributions of spill indicators by facility have been summarized in Table 3.1 and also in Figure 3.2. Table 3.1 and Figure 3.2 give the component contributions, in absolute value and percent, for each of the main facility types; namely, pipelines (P/L), platforms, and wells. The following may be noted from these for the High Case:

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

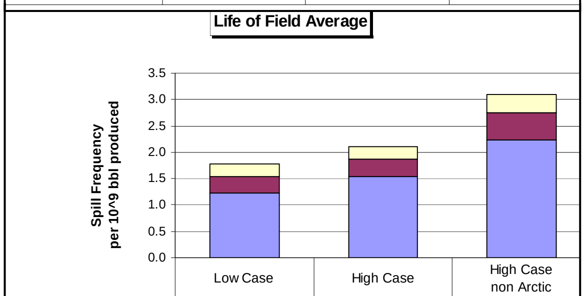
Figures 3.3 and 3.4 show relative contributions by facility and spill size to the maximum production year 2030 and Life of Field average spill indicators, respectively. Although Life of Field average absolute values are significantly smaller than the maximum production year values, the proportional contributions by spill facility source and spill size are almost identical. In Figures 3.3 and 3.4, "TOTAL" designates the sum of the spill indicators for all spill sizes and facility types. The spill frequency changes through the life of the field cycle, through exploration, development, production, and abandonment, as well and platform numbers and pipeline miles change.

Table 3.1. Beaufort Sea Summary of Life of Field Average Spill Indicators by Spill Source and Size

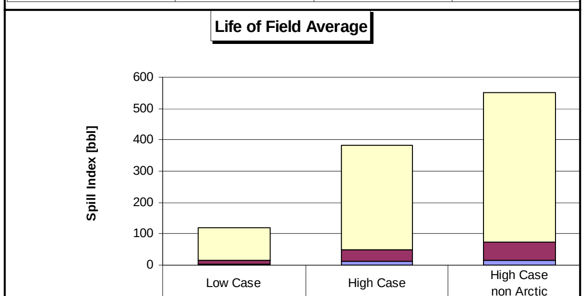
Spill Indicators LOF Average	Low Case			High Case			High Case Non-Arctic		
	Spill Frequency per 10^3 years	Spill Frequency per 10^9 bbl produced	Spill Index [bbl]	Spill Frequency per 10^3 years	Spill Frequency per 10^9 bbl produced	Spill Index [bbl]	Spill Frequency per 10^3 years	Spill Frequency per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



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

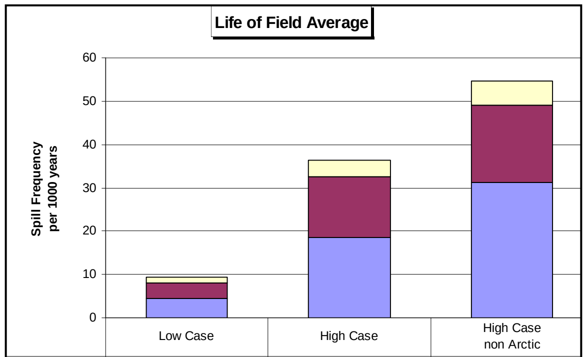


	Low Case	High Case	High Case non Arctic
Huge Spills =>10000 bbl	0.241	0.245	0.361
Large Spills 1000-9999 bbl	0.311	0.335	0.511
Small and Medium Spills 50-999 bbl	1.232	1.534	2.233

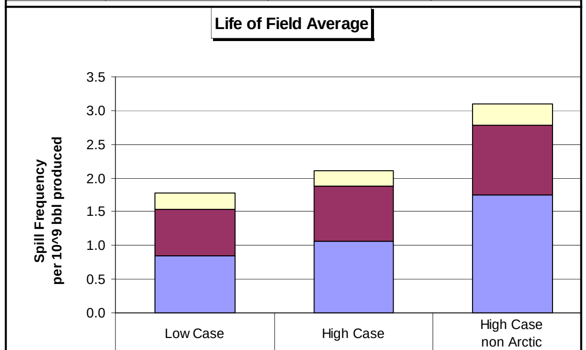


	Low Case	High Case	High Case non Arctic
Huge Spills =>10000 bbl	104	332	477
Large Spills 1000-9999 bbl	12	40	60
Small and Medium Spills 50-999 bbl	3	11	14

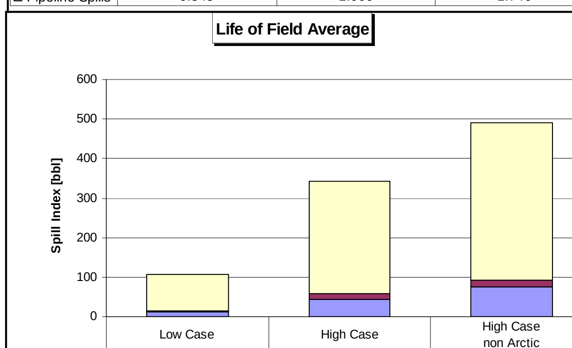
Figure 3.1. Beaufort Sea Life of Field Spill Indicators – By Spill Size



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



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



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

Figure 3.2. Beaufort Sea Life of Field Spill Indicators – By Source Composition

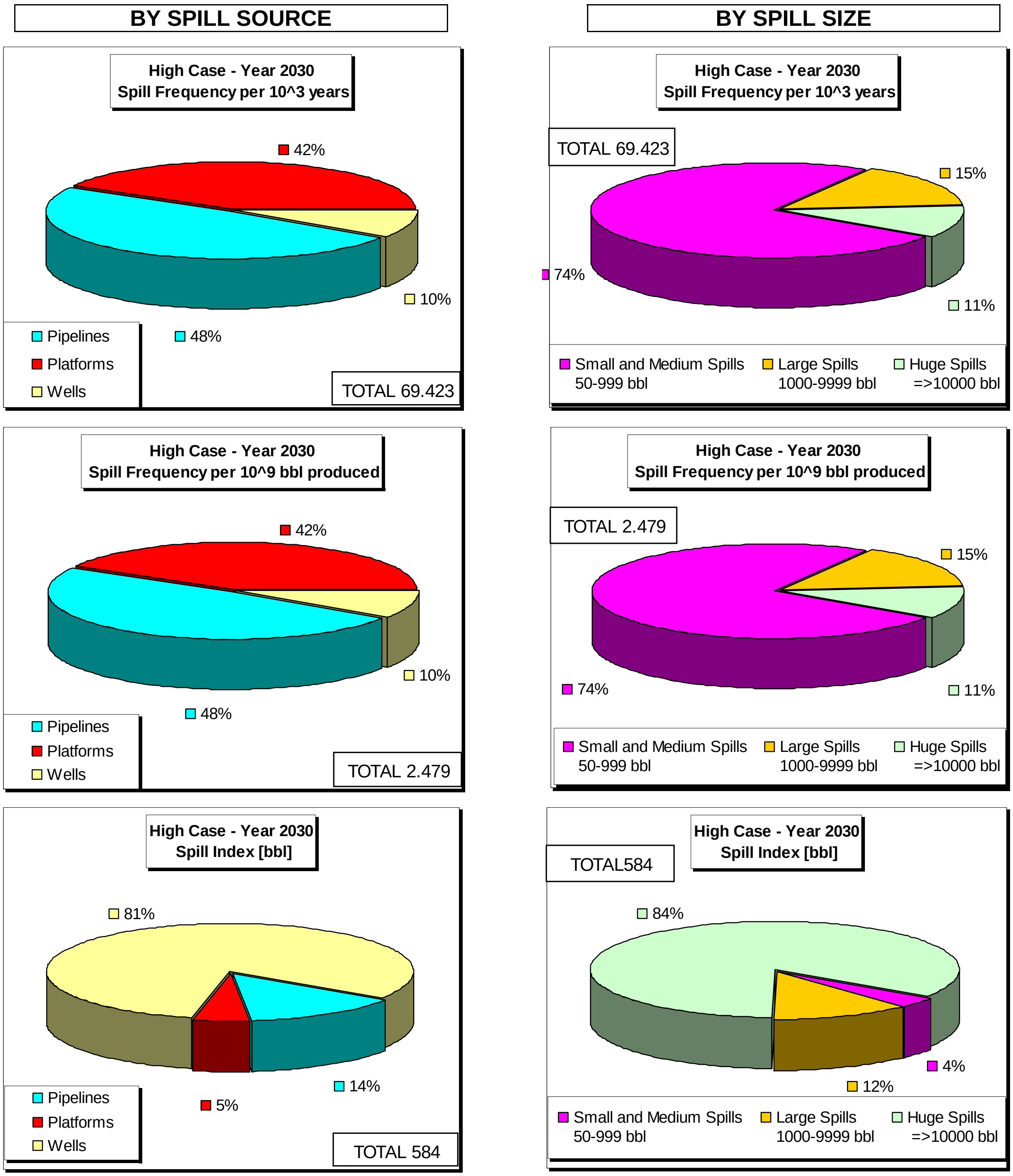


Figure 3.3. Beaufort Sea High Case – Year 2030 – Spill Indicator Composition by Source and Spill Size

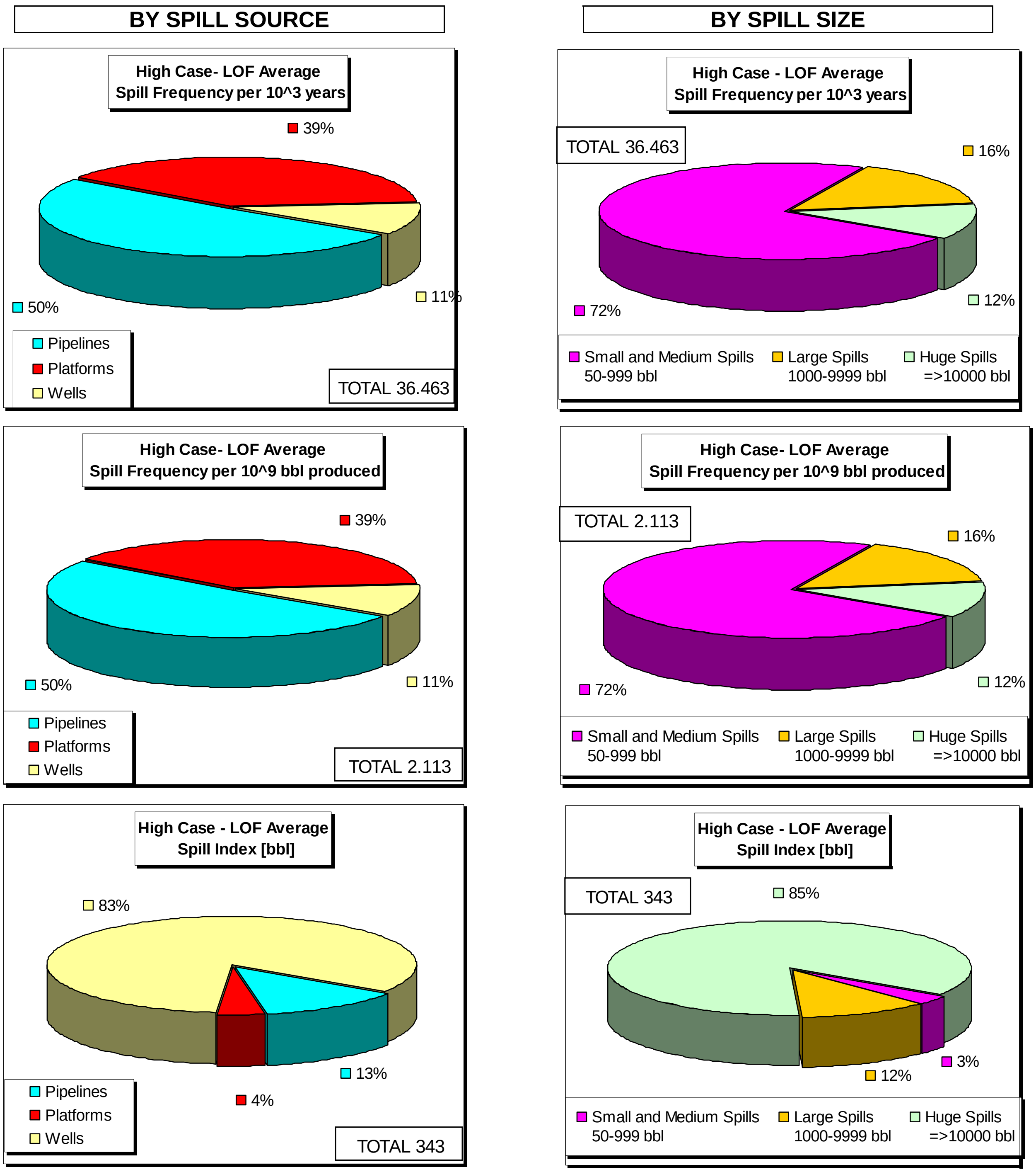


Figure 3.4. Beaufort Sea High Case – Life of Field Average Spill Indicator Composition by Source and Spill Size

3.4 Variability of Oil Spill Occurrence Indicators

Figures 3.5, 3.6, and 3.7 show the Cumulative Distribution Functions (CDF) for the Beaufort Sea Life of Field average spill indicators. The Cumulative Distribution Frequencies are derived from roughly 30 million arithmetic operations generated in the Monte Carlo process. The variability of these indicators is fairly representative of the trends in variability for spill indicators for the Low Case as well. Generally, the following can be observed from the figures:

- The variance of the frequency spill indicators (Figures 3.5 and 3.6) decreases as spill size increases for pipelines and platforms. In other words, small and medium spills illustrate the largest variability; huge spills show the least variability for pipelines and platforms.
- For wells, the frequency variability for different spill sizes does not change as much as that for platforms and pipelines.
- The variability of the spill index (Figure 3.7) shows an increasing variability with increasing spill size.

The Cumulative Distribution Functions contain extensive information on the statistical properties of the spill indicators. For example, from Figure 5 (bottom right-hand graph), it can be seen, for all significant spills, that the Life of Field average mean (50%) value of 10 (spills per 1,000 years) ranges between about 5 and 15 at the lower and 5% to 95% confidence intervals. A similar percentage variation is shown for the Life of Field average spill frequency per barrel produced in Figure 3.6. The spill index variability shown in Figure 3.7 is proportionally higher. For example, in Figure 3.7 (bottom right-hand corner graph), the mean value of the significant spills index of 325 per billion barrels produced ranges from 200 to 500 over the 5% to 95% confidence interval.

3.5 Comparison of Arctic and Non-Arctic Oil Spill Indicators

An evaluation of the oil spill indicators for a development identical in well facility and pipeline well quantities located in a non-Arctic setting, such as the GOM, was carried out. Figure 3.8 shows an annual spill frequency bar chart comparing the Beaufort Sea and the non-Arctic values. As can be seen, the non-Arctic values are roughly 35% higher than those in the Beaufort Sea. Why is this? Clearly, on balance, the oil spill causes in the non-Arctic location are more severe than those for the Arctic location. The non-Arctic location has a significant causal contribution from hurricanes, boat anchoring, platform-ship collisions, which significantly contribute to the spill probabilities. Conversely, the Arctic location does not have hurricanes, and has a relatively low vessel transit population. The Arctic location, however, does have the Arctic unique effects, including gouging, scour, thaw settlement, and upheaval buckling, which do exacerbate the spill frequency, but largely for the pipelines. In addition, because of the high cost of operations in the Arctic, it can be speculated that these operations are carried out with greater care and consequently less accidents. Thus, on balance, it has been estimated that developments in non-Arctic locations are likely to result in a somewhat higher oil spill occurrence probability than comparable developments in the Beaufort Sea.

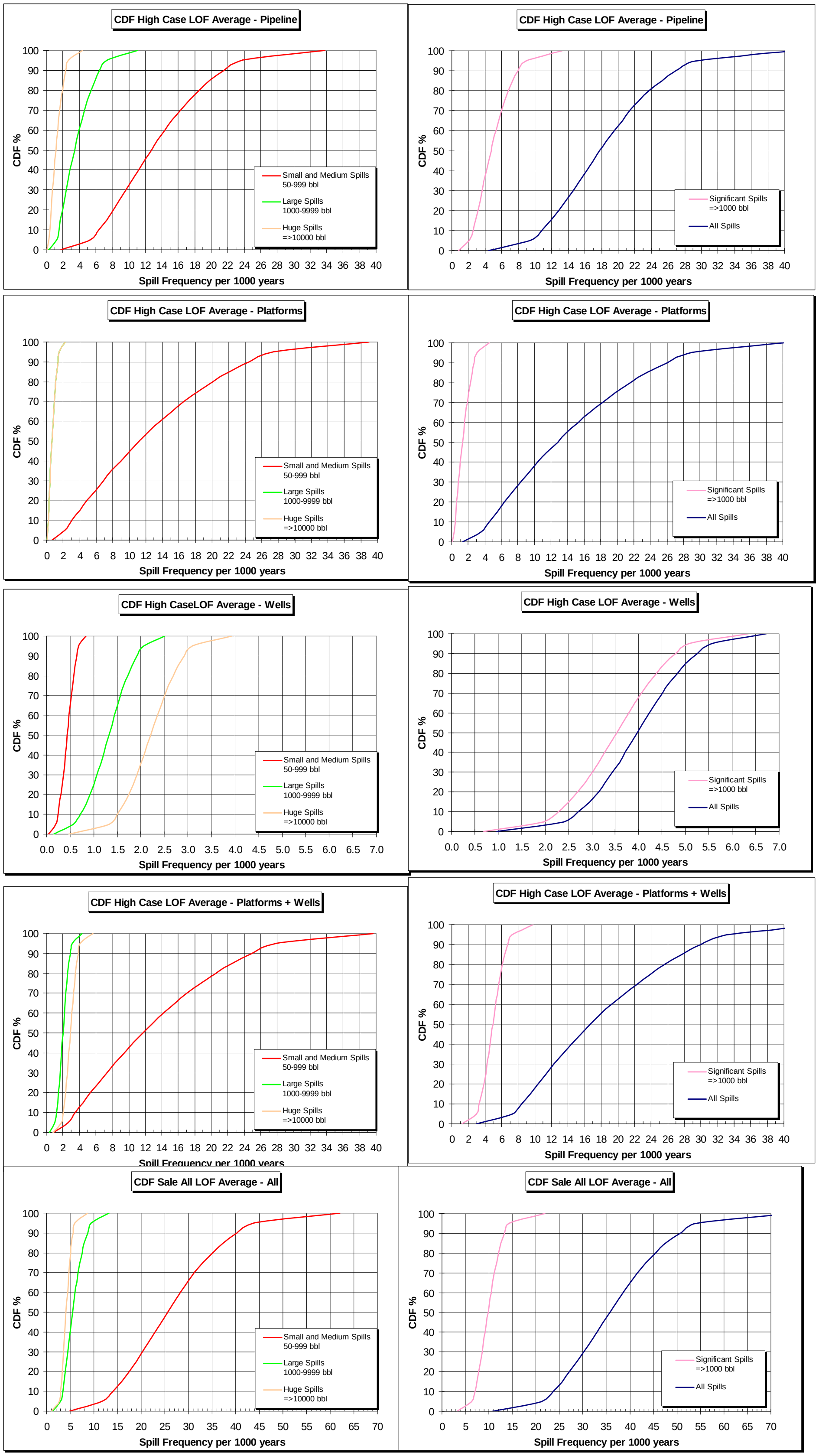


Figure 3.5. Beaufort Sea High Case Life of Field Average Spill Frequency

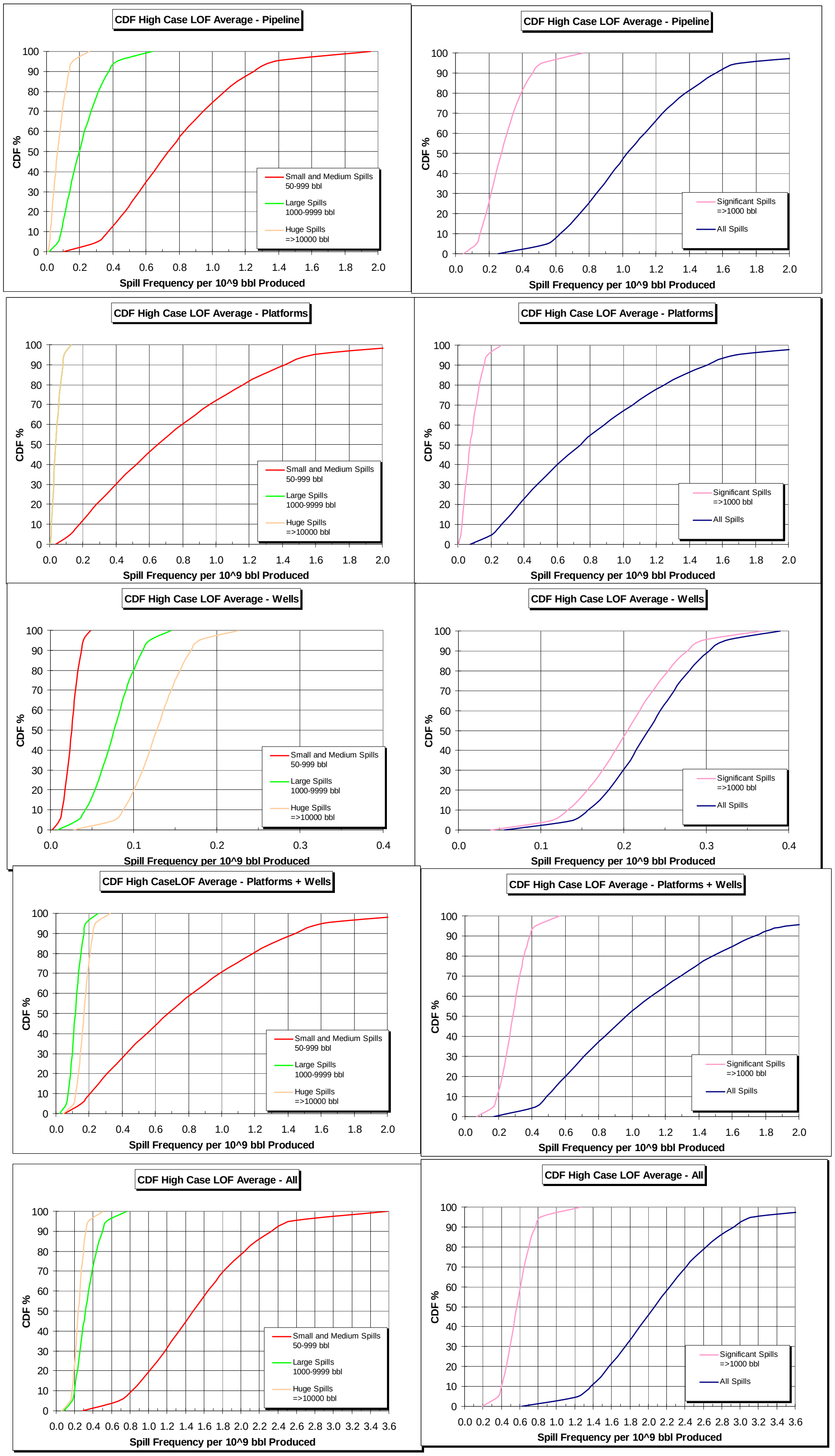


Figure 3.6. Beaufort Sea High Case Life of Field Average Spills per Barrel Produced

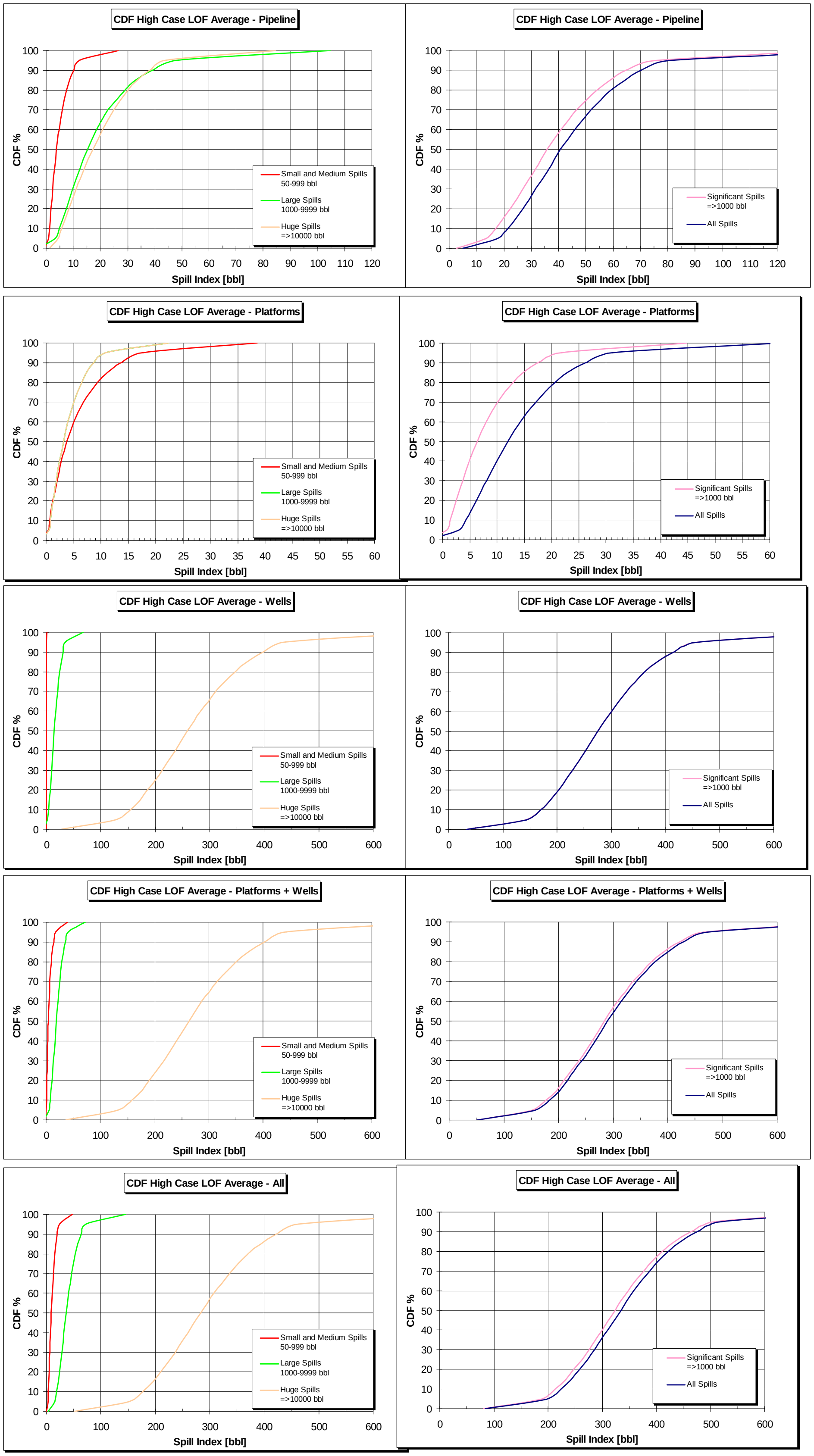


Figure 3.7. Beaufort Sea High Case Life of Field Average Spill Index (bbl) – CDF

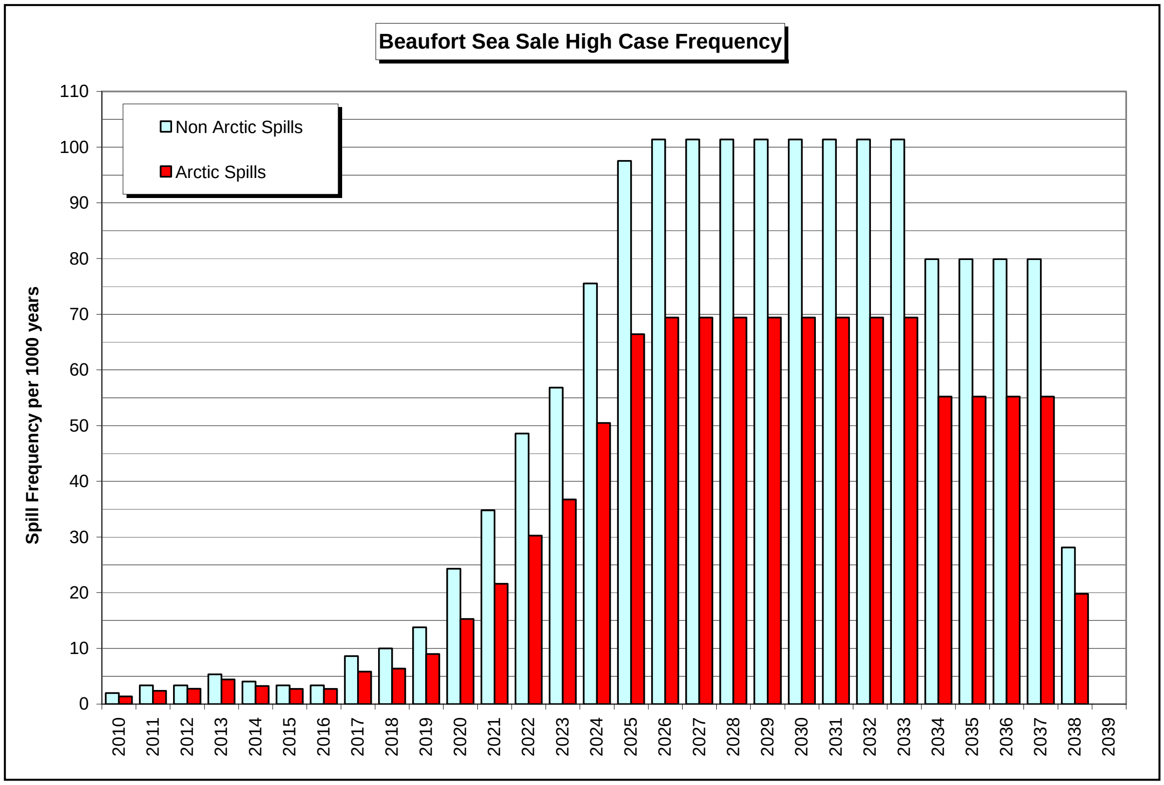


Figure 3.8. Beaufort Sea High Case Spill Frequency – Arctic and Non-Arctic

3.6 Results from Earlier Studies

Results from the 2006 [8] Beaufort Sea study were comparable to the more recent ones [5]. For example, the life of field averages by spill size and spill source composition, given in Figure 3.9 [8], are similar to the more recent ones shown earlier in this section in Figure 3.4.

Earlier [10] studies only provided these spill indicators by specific years, and hence are not directly comparable. However, the unit frequencies and indices from these earlier studies are similar to those for the most recent studies.

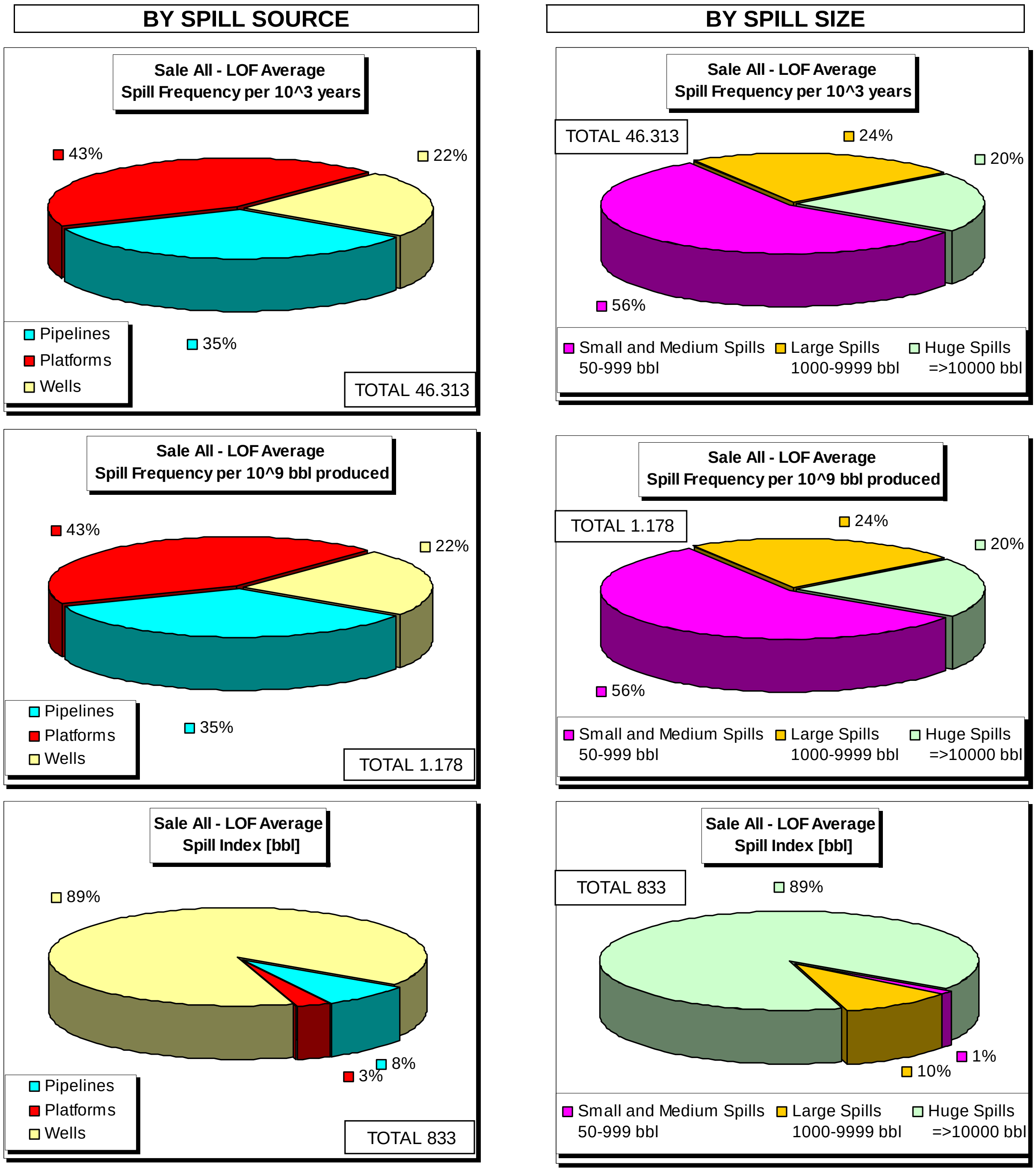


Figure 3.9. Results from Earlier Studies: Sale All – Life of Field Average Spill Indicator Composition by Source and Spill Size [8]

SECTION 4
CHUKCHI SEA OIL SPILL INDICATORS

4.1 General Introduction

Oil spill occurrence indicators were quantified for hypothetical deep water offshore development scenarios in the Chukchi Sea in the area of BOEMRE jurisdiction. The quantification included the consideration of the variability of historical and hypothetical scenario data, as well as that of Arctic effects in estimating 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. The results summarized in this section are based on the 2006 Chukchi study [6], with reference only to earlier results [9, 10].

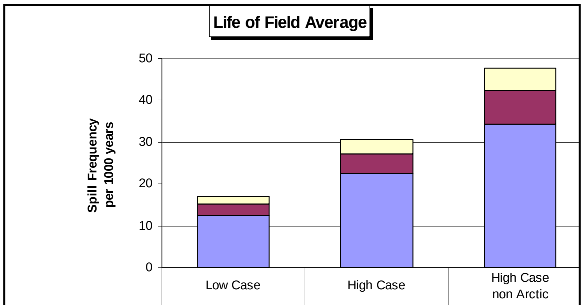
4.2 Oil Spill Occurrence Indicators by Spill Size

How do spill indicators for the Chukchi scenario and for its non-Arctic counterpart vary by spill size and location? Table 4.1 and Figures 4.1 and 4.2 summarize the Life of Field average spill indicator values by spill size and source [6]. The following can be observed from Table 4.1.

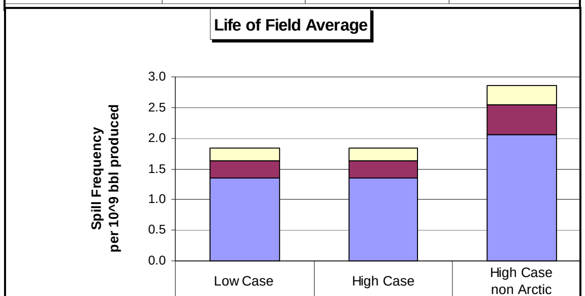
- Spill frequency per year and per barrel-year decreases significantly with increasing spill size for all scenarios.
- The spill index increases significantly with spill size for all scenarios.
- All non-Arctic scenario spill indicators are greater than their Arctic counterparts. High Case non-Arctic spill indicators are approximately 35% greater than Arctic High Case counterparts.

Table 4.1. Chukchi Sea Summary of Life of Field Average Spill Indicators by Spill Source and Size

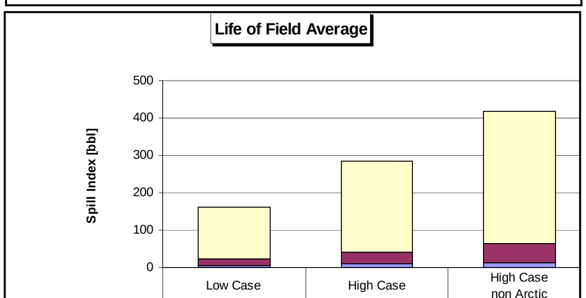
Spill Indicators LOF Average	Low Case			High Case			High Case Non-Arctic		
	Spill Frequency per 10^3 years	Spill Frequency per 10^9 bbl produced	Spill Index [bbl]	Spill Frequency per 10^3 years	Spill Frequency per 10^9 bbl produced	Spill Index [bbl]	Spill Frequency per 10^3 years	Spill Frequency per 10^9 bbl produced	Spill Index [bbl]
Small and Medium Spills	12.499	1.350	5	22.491	1.349	9	34.237	2.054	12
50-999 bbl	73%	73%	4%	74%	74%	4%	72%	72%	3%
Large Spills	2.631	0.284	18	4.715	0.283	31	8.155	0.489	52
1000-9999 bbl	15%	15%	12%	15%	15%	12%	17%	17%	14%
Huge Spills	1.899	0.205	121	3.385	0.203	213	5.239	0.314	302
=>10000 bbl	11%	11%	84%	11%	11%	84%	11%	11%	83%
Significant Spills	4.529	0.489	138	8.100	0.486	245	13.394	0.804	353
=>1000 bbl	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%



	Low Case	High Case	High Case non Arctic
Huge Spills =>10000 bbl	1.899	3.385	5.239
Large Spills 1000-9999 bbl	2.631	4.715	8.155
Small and Medium Spills 50-999 bbl	12.499	22.491	34.237

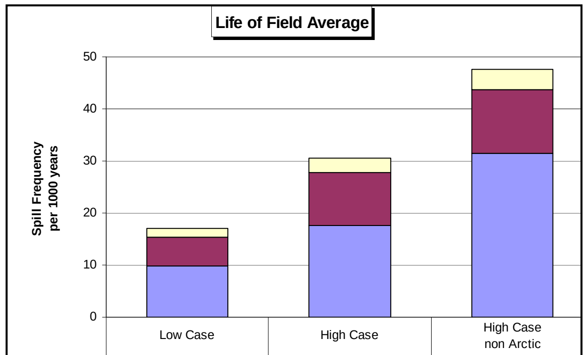


	Low Case	High Case	High Case non Arctic
Huge Spills =>10000 bbl	0.205	0.203	0.314
Large Spills 1000-9999 bbl	0.284	0.283	0.489
Small and Medium Spills 50-999 bbl	1.350	1.349	2.054

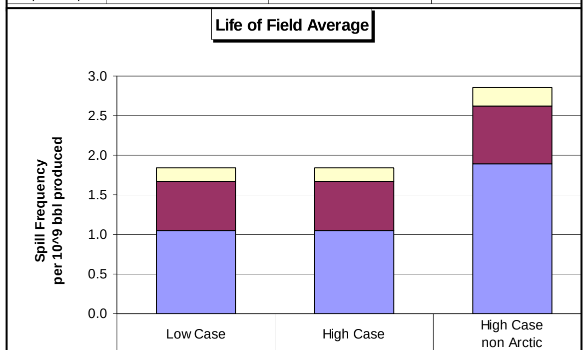


	Low Case	High Case	High Case non Arctic
Huge Spills =>10000 bbl	138	245	353
Large Spills 1000-9999 bbl	18	31	52
Small and Medium Spills 50-999 bbl	5	9	12

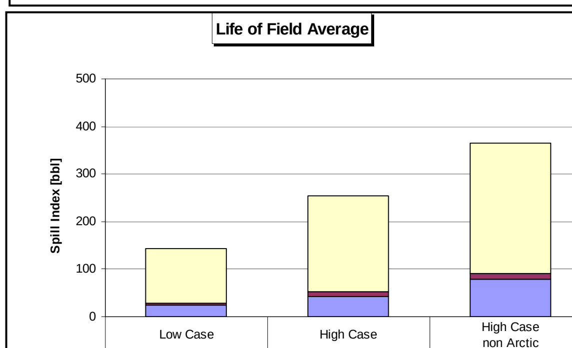
Figure 4.1. Chukchi Sea Life of Field Spill Indicators – By Spill Size



	Low Case	High Case	High Case non Arctic
Well Spills	1.601	2.823	3.848
Platform Spills	5.702	10.263	12.331
Pipeline Spills	9.725	17.506	31.452



	Low Case	High Case	High Case non Arctic
Well Spills	0.173	0.169	0.231
Platform Spills	0.616	0.616	0.740
Pipeline Spills	1.050	1.050	1.887



	Low Case	High Case	High Case non Arctic
Well Spills	114	202	275
Platform Spills	6	10	12
Pipeline Spills	23	42	78

Figure 4.2. Chukchi Sea Life of Field Spill Indicators – By Source Composition

4.3 Oil Spill Occurrence Indicators by Spill Source

How do the spill indicators vary by facility type for representative scenarios? The contributions of spill indicators by facility have been summarized by representative scenario years, again, in Table 4.1 and also in Figure 4.2. Table 4.1 and Figure 4.2 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 4.1:

- 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.

Figures 4.3 and 4.4 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 4.3 and 4.4, "TOTAL" designates the sum of the spill indicators for all spill sizes and facility types.

4.4 Variability of Oil Spill Occurrence Indicators

Figures 4.5, 4.6, and 4.7 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 4.5 and 4.6) decreases as spill size increases for pipelines and platforms. For example, in the top right-hand graph of Figure 4.5, 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 4.7) 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 4.5, 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 4.6. The spill index variability shown in Figure 4.7 is proportionally higher. For example, in Figure 4.7, the mean value of the significant spills index of 240 per billion barrels produced ranges from 150 to 400.

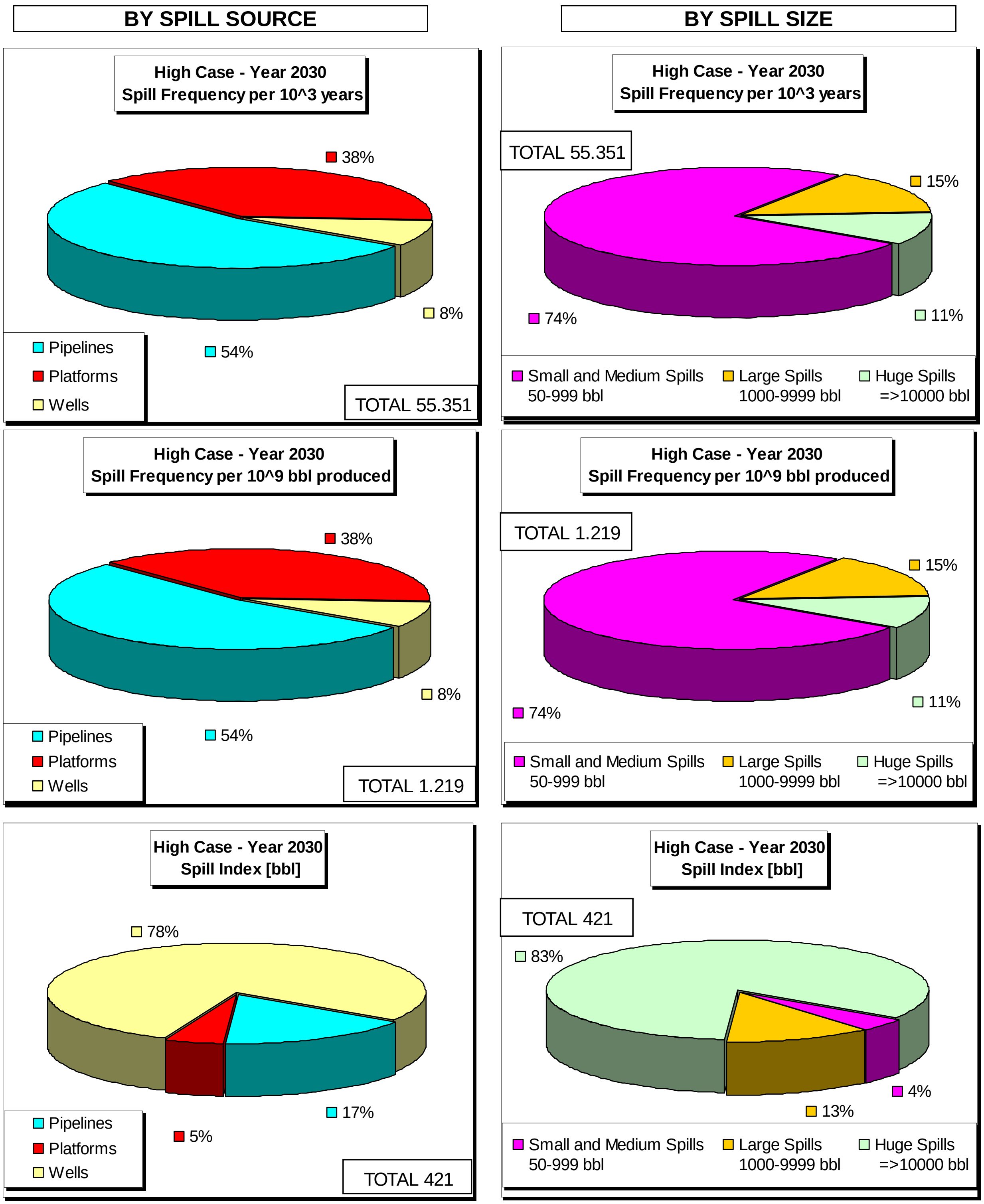


Figure 4.3. Chukchi Sea High Case – Year 2030 – Spill Indicator Composition by Source and Spill Size

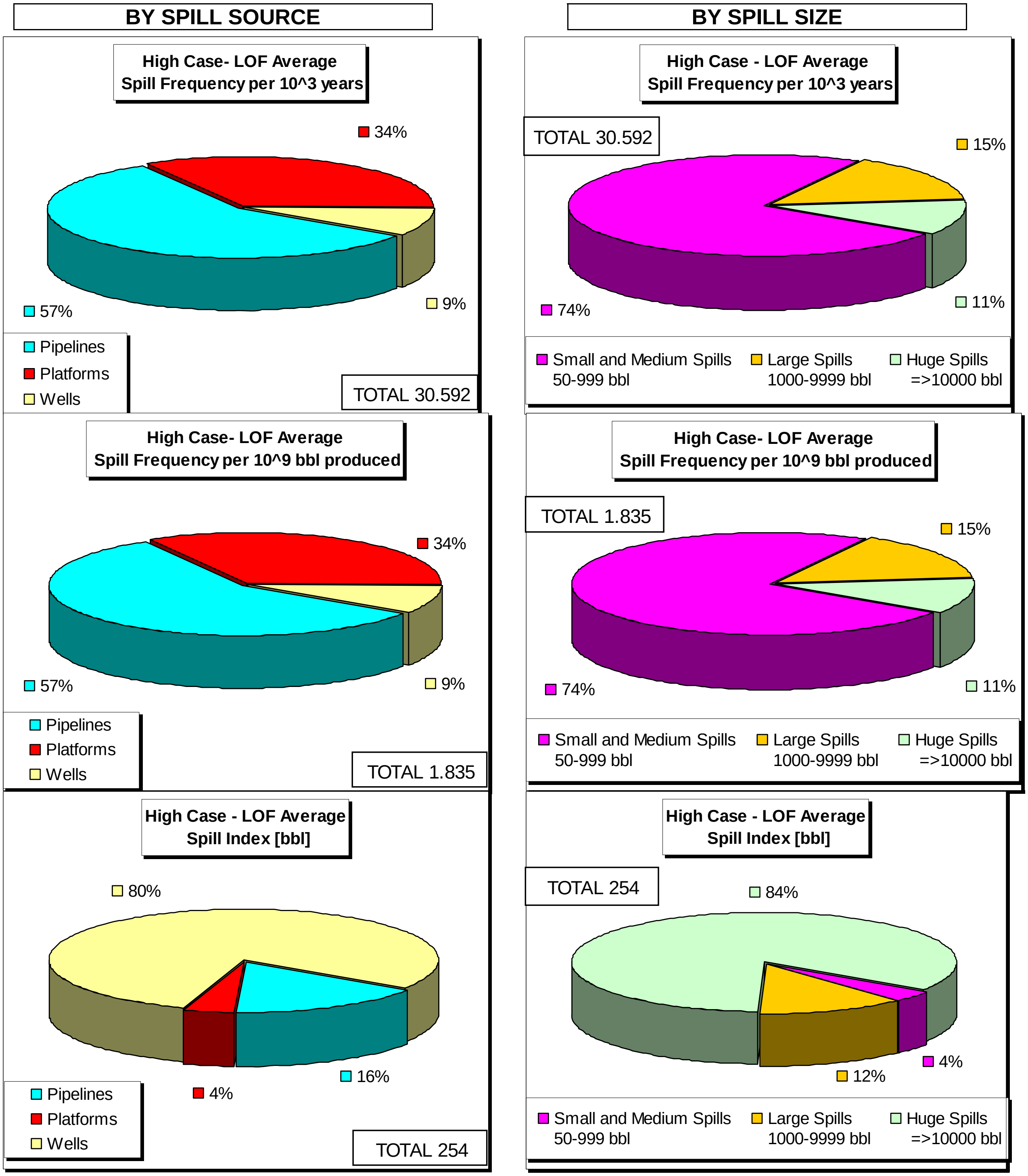


Figure 4.4. Chukchi Sea High Case – Life of Field Average Spill Indicator Composition by Source and Spill Size

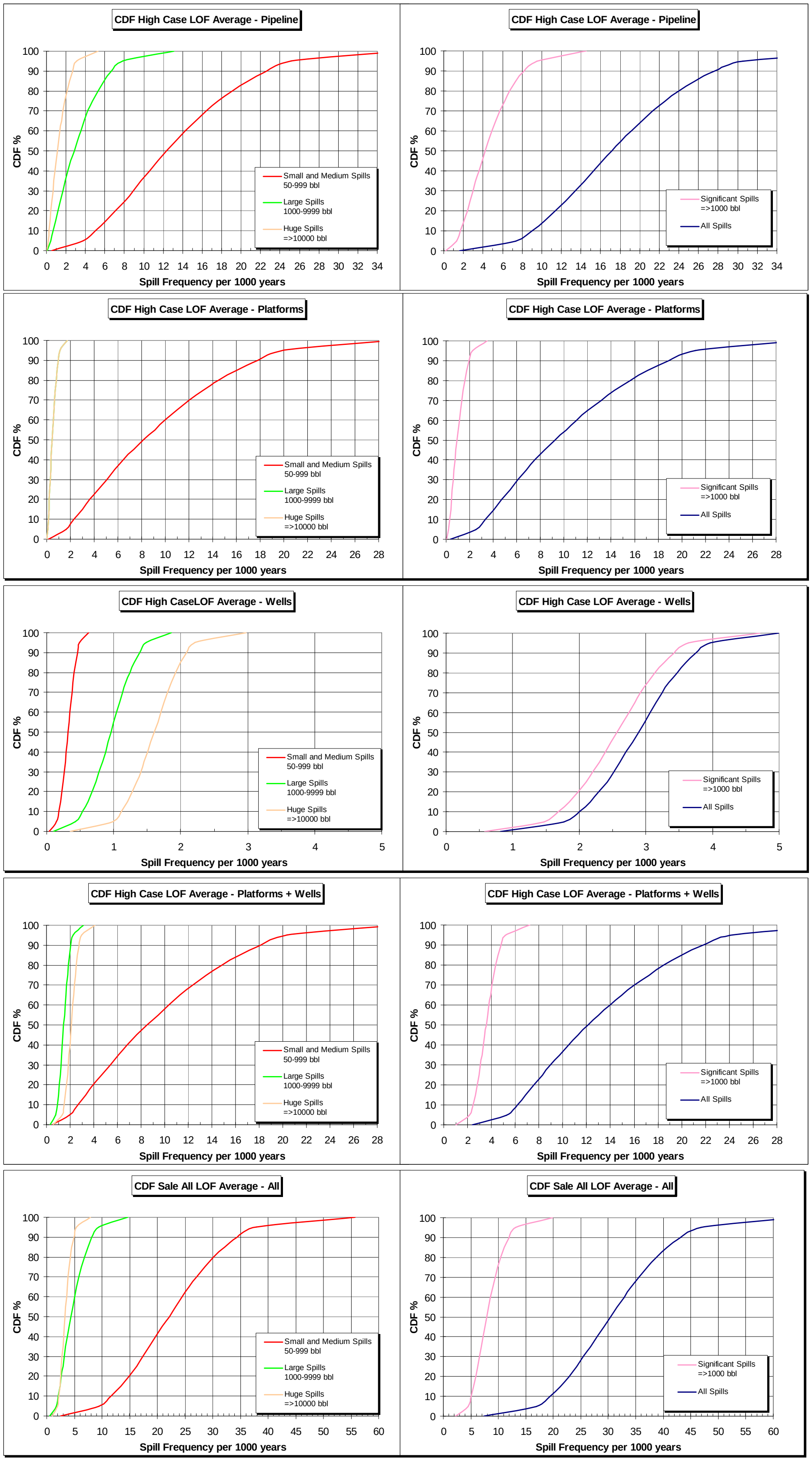


Figure 4.5. Chukchi Sea High Case Life of Field Average Spill Frequency

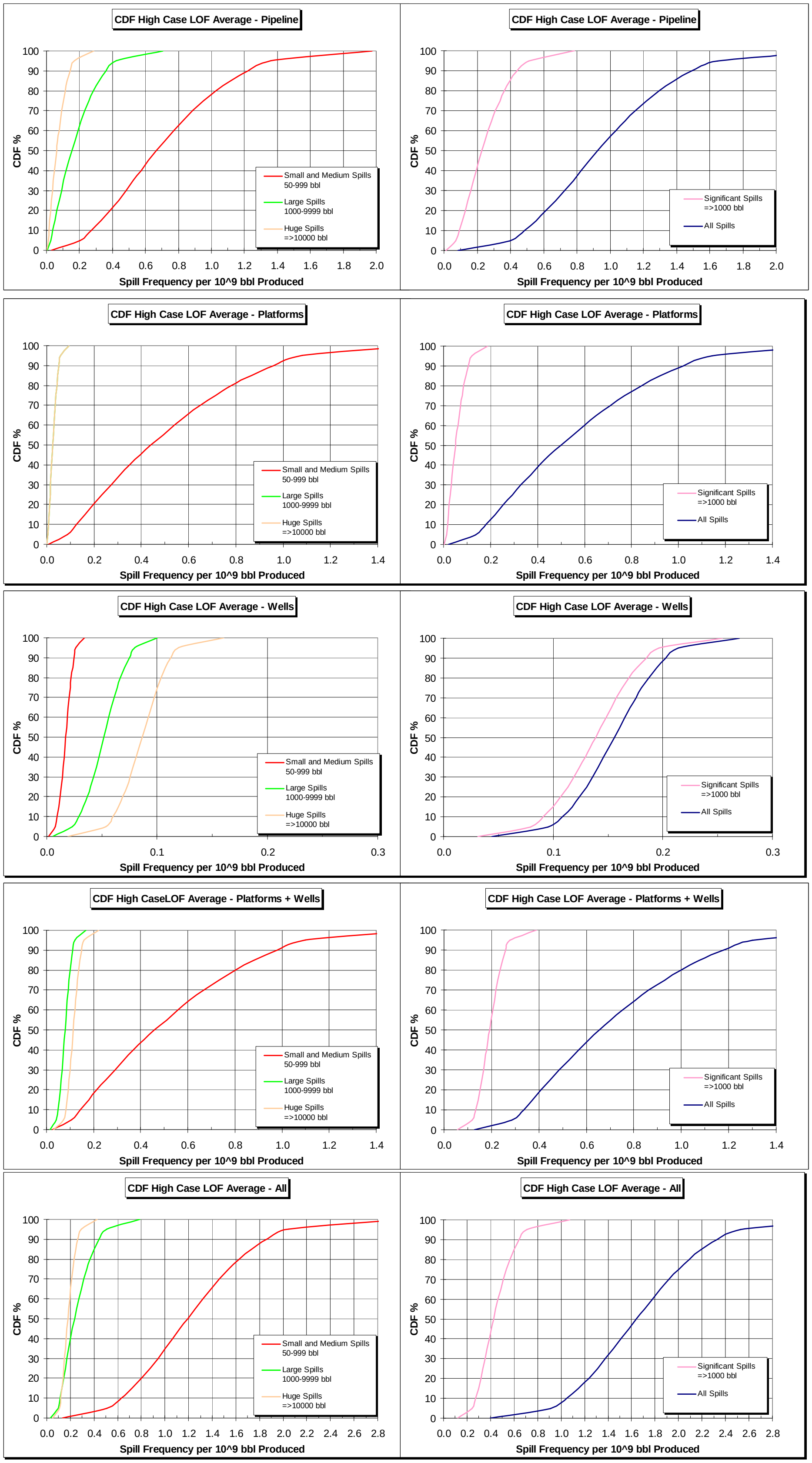


Figure 4.6. Chukchi Sea High Case Life of Field Average Spills per Barrel Produced

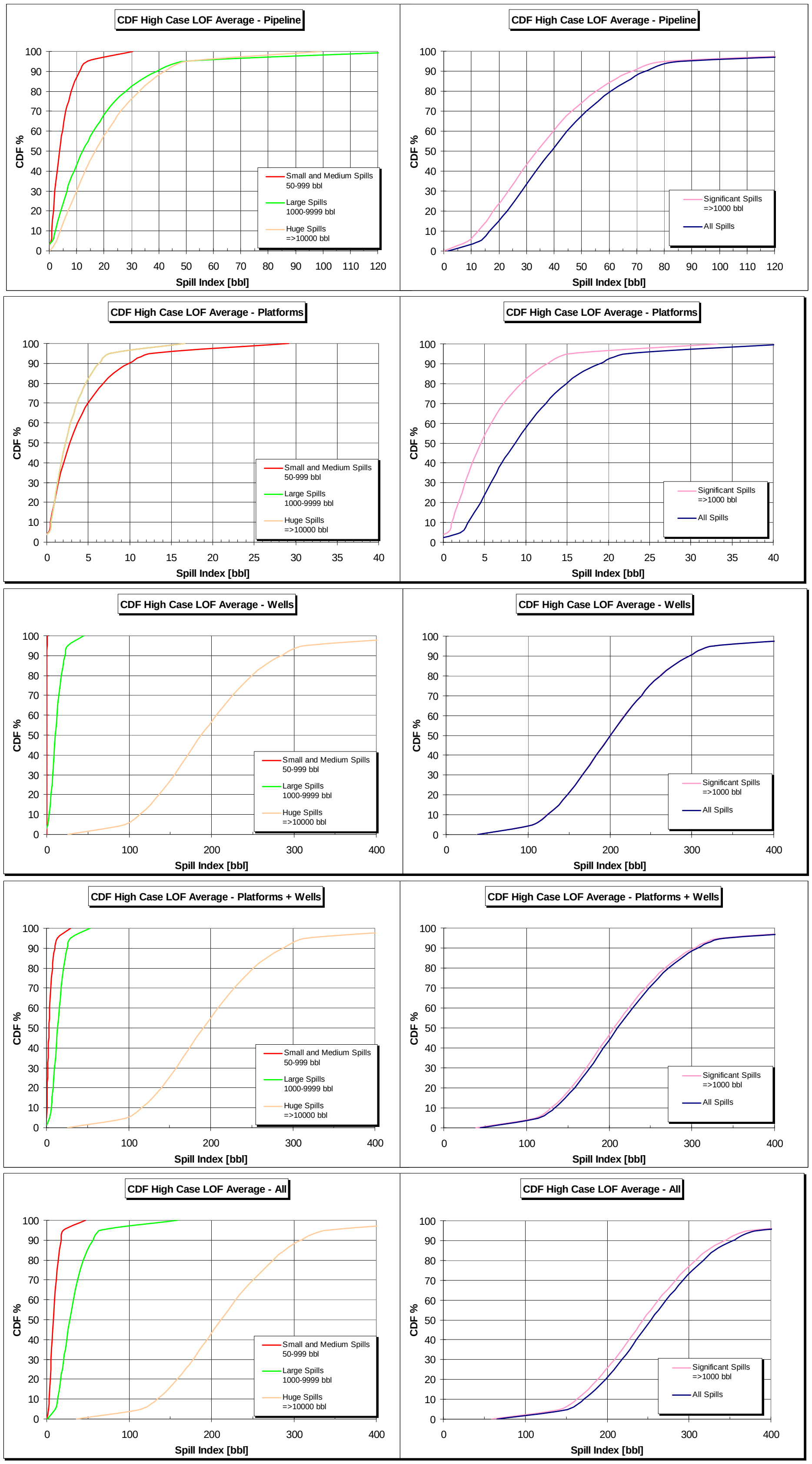


Figure 4.7. Chukchi Sea High Case Life of Field Average Spill Index (bbl) – CDF

4.5 Comparison of Arctic and Non-Arctic Oil Spill Indicators

An evaluation of the oil spill indicators for a development identical in facility, pipeline, and well quantities located in a non-Arctic setting, such as the GOM, was carried out. Figure 4.8 shows an annual spill frequency bar chart comparing the Chukchi Sea and the non-Arctic values. As can be seen, the non-Arctic values are roughly 30% higher than those in the Chukchi Sea. Why is this? Clearly, on balance, the oil spill causes in the non-Arctic location are more severe, or outweigh, those for the Arctic location. The non-Arctic location has a significant causal contribution from hurricanes, boat anchoring, platform-ship collisions, which significantly contribute to the spill probabilities. Conversely, the Arctic location does not have hurricanes, and has a relatively low vessel transit population. The Chukchi Sea Arctic location, however, does have the Arctic unique effects, including thaw settlement, upheaval buckling, and other Arctic effects, which do exacerbate the spill frequency. In addition, because of the high cost of operations in the Chukchi Sea, it can be speculated that these operations are carried out with greater care and consequently less accidents. Thus, on balance, it has been estimated that developments in non-Arctic locations are likely to result in a somewhat higher oil spill occurrence probability than comparable developments in Chukchi Sea locations.

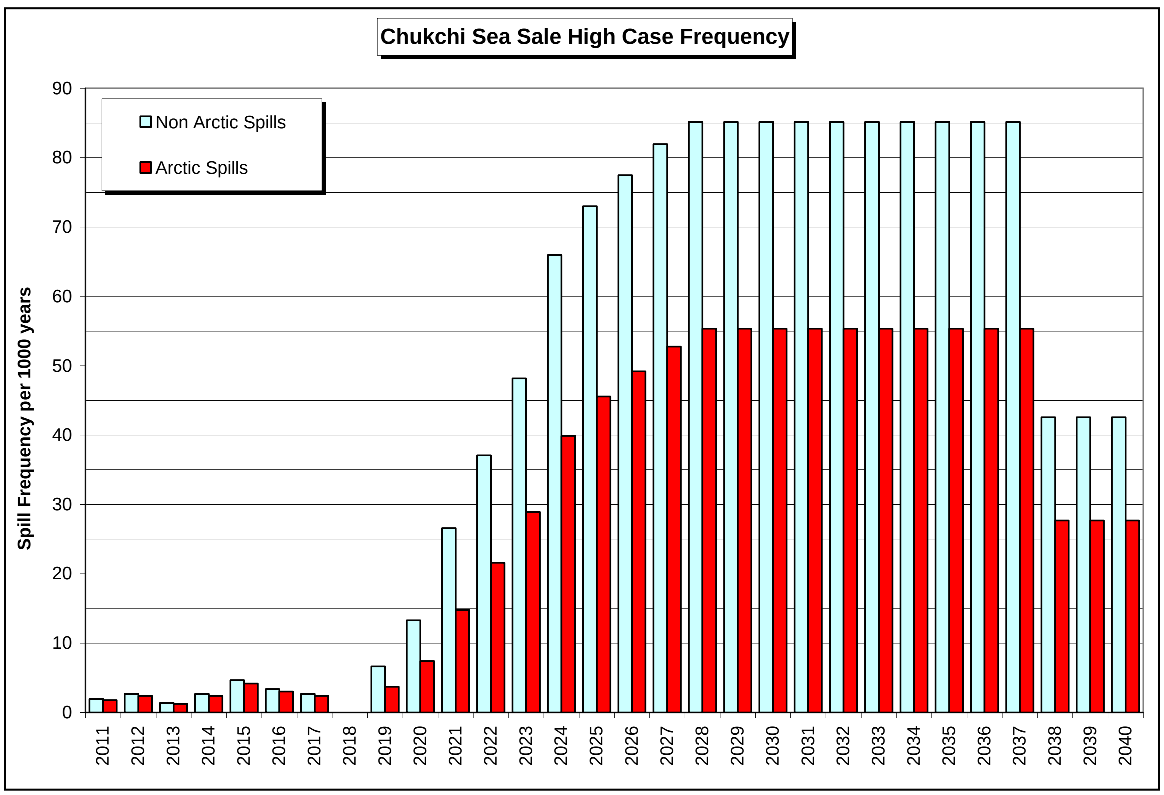


Figure 4.8. Chukchi Sea High Case Spill Frequency – Arctic and Non-Arctic

4.6 Results from Earlier Studies

Results from the 2006 [9] Chukchi Sea study were comparable to the more recent ones [6]. For example, the life of field averages by spill size and spill source composition, given in Figure 4.9 [9], are similar to the more recent ones shown earlier in this section in Figure 4.4.

Earlier [10] studies only provided these spill indicators by specific years, and hence are not directly comparable. However, the unit frequencies and indices from these earlier studies are similar to those for the most recent studies.

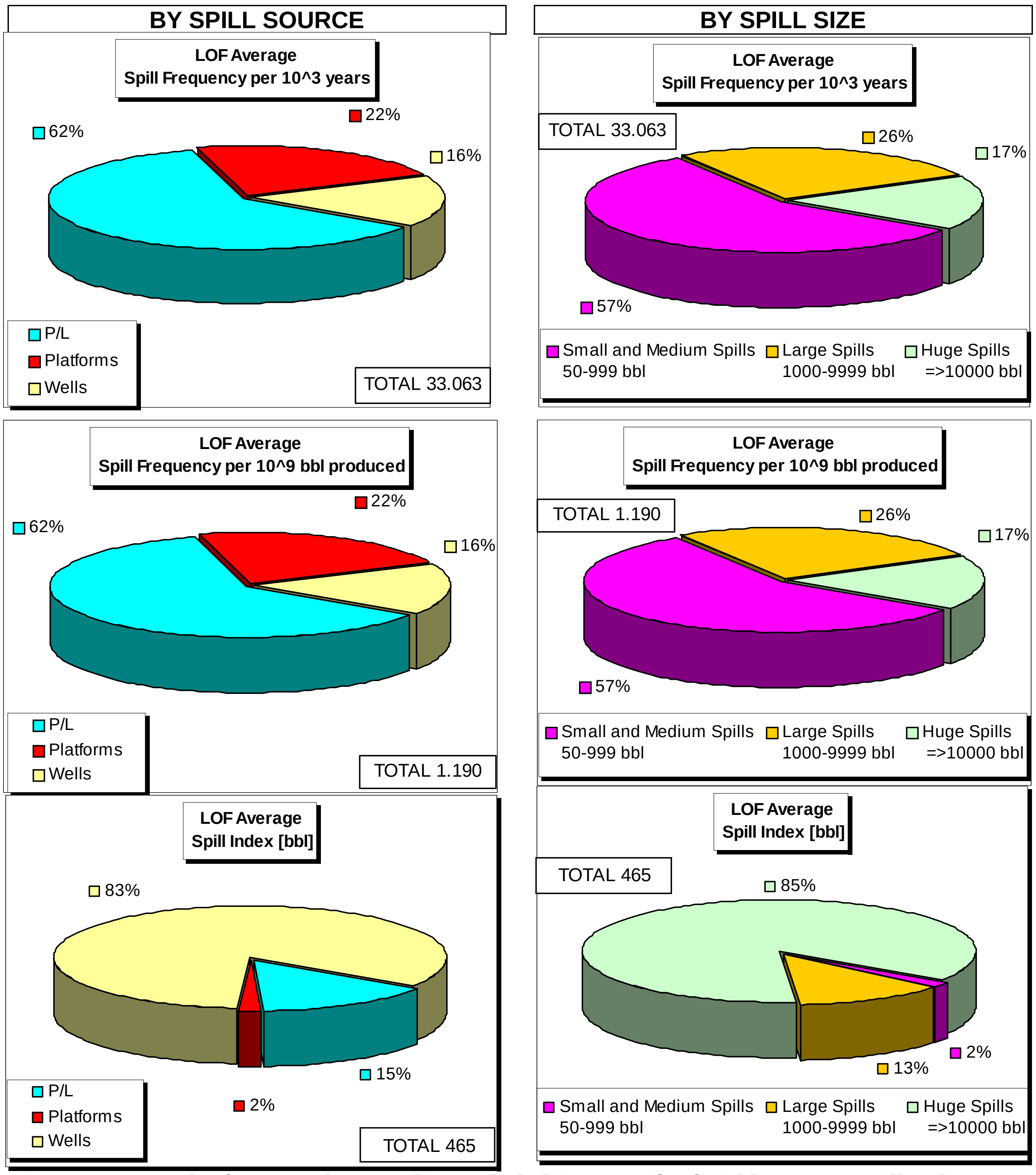


Figure 4.9. Results from Earlier Studies: Chukchi Sea – Life of Field Average Spill Indicator Composition by Source and Spill Size [9]

SECTION 5

CONCLUSIONS, LIMITATIONS, AND RECOMMENDATIONS

5.1 Conclusions on the Methodology and its Applicability

An analytical tool for the estimation of oil spill occurrence indicators for systems without history, such as hypothetical offshore oil production developments in the Beaufort and Chukchi Seas, 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 basic model is setup so that any input variables can be entered as distributions.

A wealth of information that can be utilized for lease sale analyses or, with site-specific information, 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 BOEMRE 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.

5.2 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 BOEMRE 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 to try to provide more robust statistics would be of interest. Unfortunately, data from a broader population base, such as the North Sea, do not contain the level of detail provided in the GOM data.
- The Arctic effects include modifications in causes associated with the historical data set as well as additions of spill causes unique to the Arctic environment. Quantification of existing causes for Arctic effects was done in a systematic manner dependent on engineering judgment.
- A reproducible but relatively elementary analysis of gouging and scour effects was carried out.
- Upheaval buckling effect assessments were included on the basis of an educated guess; no engineering analysis was carried out for the assessment of frequencies to be expected for these effects, as they are highly variable for different locations and pipeline characteristics. Such analyses could be part of a development fault tree.

The scenarios are those developed for use in the BOEMRE 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.

5.3 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 BOEMRE needs, as it is currently the best model available for estimating oil spill occurrence.
- Utilize this oil spill occurrence indicator model to generate additional model validation information, including direct application to specific non-Arctic scenarios, such as GOM projects, which have an oil spill statistical history.
- Utilize the oil spill occurrence indicator model in a sensitivity mode to identify the importance of different Arctic effect variables introduced to provide a prioritized list of those items having the highest potential impact on Arctic oil spills.
- Generalize the model so that it can be run both in an adjusted expected value and a distributed value (Monte Carlo) form with the intent that expected value form can be utilized without the Monte Carlo add-in for preliminary estimates and sensitivity analyses, while for more comprehensive rigorous studies, the Monte Carlo version can be used.

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