2016 Update of Occurrence Rates for Offshore Oil Spills

July 13, 2016

Submitted by
ABS CONSULTING INC.
1525 Wilson Blvd., Suite 625, Arlington, VA 22209
Contract # E15PX00045, Deliverable 7

2016 Update of Occurrence Rates for Offshore Oil Spills

2016 Update of Occurrence Rates for Offshore Oil Spills

Abstract

This report updates the 2012 oil spill occurrence rate estimates applicable to offshore oil exploration and development activity in the U.S. Outer Continental Shelf (OCS) (Anderson, Mayes, and LaBelle, 2012). Since the Oil Pollution Act of 1990 (U.S. Public Law 101-380), oil spill occurrence rates like those calculated in this report have increased in importance to regulatory and industry parties involved with offshore oil and gas (O&G) activities.

The updates to the U.S. OCS Platform and Pipeline spill rates and to Worldwide and U.S. tanker and barge oil spill rates use the most recent available data since the prior report to calculate rates consistent with current trends. The rates are calculated as the ratio of the count of occurrences of spills ≥1,000 barrels (159 m^3, 159 kiloliters, 136 metric tonnes, 42,000 U.S. gallons) to the volume of crude oil handled. Additional rates are calculated for spills ≥10,000 barrels (bbl) and ≥100,000 bbl. The report compares spills ≥1,000 bbl and ≥10,000 bbl to the results calculated by Anderson *et al*. (2012). This comparison is summarized below:

- No additional large spills impacted the spill rates for OCS platforms. The volume of oil handled has increased, leading to spill rates for OCS platforms continuing to decrease for spills ≥1,000 bbl. The rate, calculated at 0.22 spills per billion barrels (Bbbl), adjusts for trend early in the spill record by excluding spills prior to 1974. The rate for spills ≥10,000 remained steady at 0.06 spills per Bbbl when examined over the same period.
- When comparing the most recent 15-years data (2001 through 2015 data) to the 1996 through 2010 rates in Anderson *et al*. (2012), spill rates remained at 0.25 spills per Bbbl for spills ≥1,000 bbl and 0.13 spills per Bbbl for spills ≥10,000 bbl. These rates include a spill from Hurricane Rita (2005) and the Macondo well spill in 2010.
- Spill rates for OCS pipelines decreased slightly from 0.94 to 0.89 spills per Bbbl for spills ≥1,000 bbl. Although the trend analysis for pipeline spills was inconclusive, spills prior to 1974 were excluded from this rate, in keeping with the assumptions used for calculating platform rates, and from 0.19 to 0.17 spills per Bbbl for spills ≥10,000 bbl. When examining the record over the last 15 years (2001 through 2015), the rates dropped from 0.88 to 0.38 for spills ≥1,000 bbl and from 0.18 to 0.07 spills per Bbbl for spills ≥10,000 bbl.
- All tanker spill rates continued the substantial declines noted in the last review (Anderson *et al.*, 2012). Most likely, tanker spills have declined due to major regulatory changes in the early 1990s that substantially eliminated the use of single-hull tankers by requiring double hulls or their equivalent.
- Spill volumes for spills from OCS platforms were also updated to include the average and median spill sizes for the period from 1974 through 2015 and the period from 2001 through 2015. To illustrate the impact of the 2010 Deepwater Horizon spill and various hurricanes on these estimates, the statistics are calculated for various subsets of the spill record.

2016 Update of Occurrence Rates for Offshore Oil Spills

Table of Contents

List of Tables

List of Figures

Acronyms

ABSG	ABS Group
ANS	Alaska North Slope
bbl	Barrel or barrels; Barrel (42 U.S. gallons, 0.159 kiloliters, 0.159 m^3, or 0.136 metric tonnes)
Bbbl	Billion barrels, 10^9 bbl or 1,000,000,000 bbl
BOEMRE	Bureau of Ocean Energy Management, Regulation and Enforcement
BOEM	Bureau of Ocean Energy Management
BP	British Petroleum
BSEE	Bureau of Safety and Environmental Enforcement
DOI	Department of the Interior
DOT	Department of Transportation
DWH	Deepwater Horizon
MISLE	Marine Information for Safety and Law Enforcement
MMbbl	Millions of barrels
MMS	Minerals Management Service
MODU	Mobile Offshore Drilling Unit
NEPA	National Environmental Policy Act
NRC	National Response Center
O&G	Oil and Gas
OCS	Outer Continental Shelf
ONRR	Office of Natural Resource Revenue
OSRA	Oil Spill Risk Analysis
PHMSA	Pipeline and Hazardous Material Safety Administration
TAPS	Trans-Alaska Pipeline System
TIMS	Technical Information Management System
USACE	U.S. Army Corps of Engineers
USCG	U.S. Coast Guard

This page intentionally left blank

1. Introduction

This report updates the 2012 oil spill occurrence rate estimates applicable to offshore oil exploration and development activity in the U.S. Outer Continental Shelf (OCS) (Anderson, Mayes, and LaBelle, 2012). It builds on an extensive history of statistical analysis of oil spill occurrences, including Smith, Slack, Wyant, and Lanfear (1982); Lanfear and Amstutz (1983); and Anderson and LaBelle (1990, 1994, and 2000). It documents the development of the comprehensive spill dataset used for analysis, the performance of the analyses themselves, and the interpretation of findings.

1.1. Report Overview

This report has the following structure:

- Section 1. Introduction
- Section 2. Data
- Section 3. Methods and Assumptions
- Section 4. Platform Spill Analysis
- Section 5. Pipeline Spill Analysis
- Section 6. Tanker and Barge Spill Analysis
- Section 7. Results Summary
- Section 8. Conclusions
- Section 9. References

The analysis sections (Sections 4 through 6) of this report are structured based on the entity type from which the spill occurred: platforms, pipelines, or tankers/barges. In prior versions of this report, the analyses were structured based on the type of analysis being performed (e.g., rate calculation, trend analysis).

Following Section 9, the report includes two appendices that provide further details on the analysis techniques:

- Appendix A. Trend Analysis
- Appendix B. The Bootstrap Method

1.2. Background

The Bureau of Safety and Environmental Enforcement (BSEE) of the U.S. Department of Interior (DOI) contracted ABS Group (ABSG) in September 2015 to perform an analysis and update the report in partnership with the Bureau of Ocean Energy Management (BOEM) as part of their collective mission to protect the environment offshore. The agencies were created on October 1, 2011, during the reorganization of the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE), which succeeded the Minerals Management Service (MMS).

The current organization divides authority between BOEM and BSEE. With regards to oil and gas (O&G) production and development along the OCS, BSEE develops regulations, issues permits, performs inspections, conducts incident investigations, and ensures that industry is prepared for an oil spill response. BOEM handles leasing, evaluates resource levels, administers exploration and development plans, performs National Environmental Policy Act (NEPA) assessments, and conducts environmental studies. Additional information about BOEM's and BSEE's roles can be found on their websites[1].

This report will provide insights and trends in offshore oil spills over time, including a preliminary causal factor analysis. This information will help BSEE track environmental performance offshore, and form a basis of information that may help BSEE develop measures to enhance environmental performance in the future, particularly for spill prevention.

This report will also contribute to BOEM's mission. BOEM maintains the Oil Spill Risk Analysis (OSRA) model, which was originally developed by the DOI in 1975 (Smith *et al.*, 1982; LaBelle and Anderson, 1985; Ji, Z.-G., W. Johnson, and Z. Li., 2011). This model uses oil spill occurrence, meteorological, oceanographic, and, where appropriate, sea ice information to estimate oil spill trajectories to identify spill risk and probability of oil contact with the shorelines and resources. In turn, the OSRA model results support several environmental reports and functions, including:

- BOEM OSRA reports
- NEPA environmental impact statements
- NEPA environmental assessments
- Endangered species; essential fish habitat; and Section 106, National Historic Preservation Act consultations

This report generally supports this effort with insights and trends in offshore spills. This information may help BSEE track environmental performance offshore and analyze trends to enhance oil spill prevention. It will underpin the OSRA model by providing the objective, data-driven spill occurrence rates. Moving forward, BOEM and BSEE will continue to maintain and develop this process, ensuring a stable, relevant foundation for this work.

---

[1] www.boem.gov; www.bsee.gov

2. Data

The analyses presented in this report require data. This section describes the methods used to collect, aggregate, and validate these data. This discussion provides an indication of the quality of the data finally accepted for analysis. In addition, it documents the various data sources which were reviewed and compiled to construct the *U.S. DOI/BSEE OCS Spill Database.* All of the spill data and analysis presented in this report come from this database.

2.1. Incident Data Sources

BSEE requires oil spills to be reported to the National Response Center and, in the event of a spill of 1 barrel (bbl) or more, to notify the Regional Supervisor (30 CFR 254.46). However, OCS spills are also reported to other government agencies as specified by their own regulations. These specifically include the U.S. Coast Guard (USCG) and the Department of Transportation (DOT) Pipeline and Hazardous Material Safety Administration (PHMSA). Furthermore, tanker and barge spills worldwide and in U.S waters are not reported to BSEE. Table 1 identifies the datasets that were included in this analysis, their source, applicability to each entity type, and the timeframe covered by the dataset.

Table 1. Analysis Datasets

Source Agency	Description	Platforms	Pipelines	Tankers	Barges	Timeframe
BSEE	2012 Report Spills: The data collected to perform the previous version of this analysis (Anderson *et al.*, 2012)	✓	✓			1964 to 2010
	Pacific OCS Spills: Supplemental to 2012 Spill Report Data	✓	✓			1969 to 2010
	Offshore Incidents: Event Data housed in BSEE/BOEM Technical Information Management System (TIMS) database	✓	✓			2000 to 2015
	Worldwide Tanker Spill Database[2]: Database of large tanker and barge spills worldwide			✓	✓	1942 to 2010
	National Response Center (NRC) Data Stream	✓	✓	✓	✓	1999 to 2015
USCG	Pollution Incidents from the Marine Information for Safety and Law Enforcement (MISLE) System	✓	✓	✓	✓	2002 to 2015
	NRC spill incidents (Supplemental to NRC Data Stream)	✓	✓	✓	✓	2010 to 2016
PHMSA	Offshore Pipeline Spills		✓			1986 to 2015
ABSG[3]	Worldwide Tanker Spills (Supplemental to Worldwide Tanker Spill Database)			✓		2010 to 2015

---

[2] BSEE collects these data—the data are not reported to BSEE.

[3] These data were assembled by ABSG through detailed open-source research of tanker spills.

2.2. Data Conditioning

Prior to analysis, each of the datasets was assimilated into a single, comprehensive spill data table. This was accomplished in four sequential steps:

1. Prescreening
2. Formatting
3. Matching
4. Consolidating

2.2.1. Prescreening

First, the data were screened in order to minimize irrelevant processing in later stages. This primarily involved aligning the collected data with the scope of the report. Incidents that did not involve spills, spills that were less than 1 bbl, spills of a nonpetroleum fluid, spills that occurred over land or state waters, or spills occurring from entity types outside the scope of the analysis were removed from the data.

Low data quality for some records made it difficult to determine if the spills, such as those occurring in state waters, were in or out of scope. Throughout each of the remaining data conditioning steps, additional spills were flagged as out of scope as the conditioned data made it clear whether or not a spill should be included.

2.2.2. Formatting

After screening out records outside the scope of the analysis, each dataset was individually mapped into a common table format. The fields in this table capture all of the essential data for the analysis, describing the causes, context, and outcome of the incidents, including:

- Unique spill ID
- Date
- Latitude
- Longitude
- Entity type involved
- Spill volume
- Fluid
- Mode
- Operation
- Hurricane flag
- Incident description
- Causal factors
- Loss of well control flag

In general, this information was provided by each dataset, although in some instances it was necessary to infer these data from values included in the source data. For example, BSEE data often encode spill location information as the protraction area and block in which a spill occurred. These area/block combinations were mapped to latitude and longitude coordinates representing the average values for the block vertices. Source file data formats were standardized and spill volumes were converted to consistent units.

2.2.3. Spill Event Matching

The next step was to match records that referred to the same incident. This occurred in the data for a variety of reasons. Some of the source datasets contained multiple records for the same event. In the NRC data, this commonly occurs when updates to a spill event are reported. This issue also arises when separate datasets report on the same event. Data analysts manually performed this process because many duplicate records contain slightly different information, and it was important to maintain all key information. Matches were identified by rating the equality of the spill dates, volumes, locations, and fluids.

Potential matches were identified when these values were approximately equal. Spill event descriptions and other information were often used to confirm potential matches. As part of the data conditioning process, data analysts maintained a list of matches with data flags to identify which of the records should be used in the analysis (i.e., the most accurate record of the event), which were redundant, and which needed to be combined.

2.2.4. Consolidating Spills and Spill Categories

The final conditioning step was to combine all of the source tables into a single table, using the matching information to remove duplicates and combine the appropriate records. During this process, instances of potentially conflicting information were resolved.

For example, if one of a duplicate set of records indicated that it was a production platform spill and the other indicated that drilling fluid was spilled, it would be assumed that the incident actually involved drilling, rather than production. In general, this process reduced the number of combinations of spill features.

2.3. Spill Categories

Each spill was categorized considering a variety of variables. Each variable and its potential values are described in the following sections.

2.3.1. Entity Types

Spills from the following entity types are included in this analysis: platforms, pipelines, tankers, and barges. Platforms include all OCS facilities offshore for petroleum exploration, development, and production. This definition is very broad, encompassing all production platforms and types of drilling rigs[4]. Floating platforms, fixed platforms, caisson platforms, well protectors, drill ships, jack-up rigs, and semisubmersibles are all included. When pipelines are damaged due to toppling platforms, these incidents are also categorized as platform incidents. Although these types of facilities exist throughout the world, only facilities on the OCS are included in this analysis to ensure that the analysis results are particularly relevant to the activity under BOEM and BSEE jurisdiction.

Pipeline spills are spills associated with the transportation of oil via pipeline. This includes damage to risers connecting a platform to a subsea pipeline, but does not include damage to marine risers used in drilling. Once again, only pipelines in the OCS are included in this analysis.

---

[4] BSEE data differentiate between rigs and platforms by using a different ID number schema to identify them. Generally, rigs move from place-to-place performing one-time operations, while platforms are associated with a lease and are long-term installations.

Tankers and barges are treated differently than platforms and pipelines. This is due in part to the absence of a readily accessible exposure metric for the OCS region specifically. Platform and pipelines are stationary, making it easy to identify whether they are in the OCS. Tankers and barges constantly transit in and out of the OCS. Alternatively, exposure for tanker spills in regions besides the OCS can be easier to work with. This analysis considers tanker spills worldwide and tanker spills involving crude transmitted by the Trans-Alaska Pipeline System (TAPS). Tankers in U.S. coastal and offshore waters are considered, despite difficulty in assigning an appropriate exposure variable. Finally, barges in coastal, offshore, and inland waters are considered.

2.3.2. Spill Sizes

Several analyses presented in this report involve classifying spills by spill volume. Table 2 identifies the categories of spill sizes by introducing their upper and lower bounds (in bbl).

Table 2. Spill Size Categories

Lower Bound (inclusive) (in bbl)	Upper Bound (exclusive) (in bbl)
1	5
5	10
10	20
20	50
50	100
100	500
500	1,000
1,000	10,000
10,000	—

Throughout this report, these size categories will be grouped into “large” and “small” spills. BOEM refers to spills of 1,000 bbl or more as “large” spills. This terminology will be maintained throughout this report. To avoid confusion, the words “smaller” and “larger” will only be used as nontechnical terms describing the relative size of spills.

Historically, only the rates of large spills have been included in BOEM’s OSRA model estimation of spill rates since smaller spills generally dissipate quickly. Some analyses will focus on large spills for this reason. For BSEE, smaller spills of over 1 bbl are required to be reported, and spills over 50 bbl are reported with additional information on the sea state, meteorological conditions, and the size and appearance of the slick.

2.3.3. Spill Fluids

In general, this report is concerned with spills of oil. However, for different entity types, this is interpreted differently based on the available data.

The first interpretation includes a broad array of petroleum products, including crude and condensate. Throughout the report, these spills are referred to as petroleum and include almost any product derived from naturally occurring crude or condensate oil. Fluids described as hydraulic fluid, other oil, drilling fluid, diesel, gasoline, fuel oil, jet fuel, kerosene, naphtha, motor oil, mineral oil, and lubricating oil could all be considered petroleum. However, some of these products are occasionally marked as “synthetic,” "environmentally safe," "eco-friendly," or "food grade" and are excluded from the analysis. Furthermore, whenever possible, the quantities of drilling fluid were represented as the volume of base oil rather than the amount of drilling fluid itself.

The second interpretation includes only unrefined crude and condensate. The report refers to these as spills of crude oil.

For platforms, pipelines, and barges, the analysis uses petroleum spills. For tankers, only crude oil spills are used.

2.3.4. Modes and Operations

Offshore O&G activities are varied. For platforms in particular, this report provides details related to the mode in which the platform was operating at the time of the incident.

In BSEE's incident data, platforms are typically classified in one of two modes: exploration or development/production. Exploration activity typically involves drilling exploration and delineation wells to prove new reserves. The operator may not choose to develop a well further if exploration activities do not identify a viable reserve. Development/production activities involve moving to full-scale production. These modes encompass multiple platform operations. This report groups these operations into the following categories:

- Completion/workover
- Construction
- Decommissioning/abandonment
- Drilling
- Production
- Pipeline
- Vessel

The pipeline and vessel categories are not operations, but indicate platform spills related to other entity types. For example, in the event that a platform topples, a pipeline can disconnect and spill its contents. Because this spill was initiated by a platform failure, it is associated with platforms, not pipelines. Similarly, BSEE's incident data includes several instances of platform service vessels spilling fluids while servicing platforms. These source data include these platform spills associated with vessel operations as platform spills. This convention was maintained for this analysis.

For pipelines, no operational categories were identified. While there are activities, such as pigging, associated with pipeline operations, analysis of these activities was not supported by the data.

Tanker spills are classified in two modes: at sea and in port. No other operation modes were identified in these data.

2.3.5. Causal Factors

Each spill record often provided sufficient data for identifying multiple causal factors. In the consolidation stage of data conditioning, each spill was tagged for each causal factor category identified as a contributor to the spill. As a result, some causal factor summaries are normalized in order to avoid distorting the number of spills by counting each spill once for each of its causal factor tags. This method accurately reflects the impact that prevalence of the causal factors has on the aggregate spill count.

For platforms, many sources provided information distinguishing between the following causal factors:

- Human error
- Equipment failure
- Weather/natural causes
- External/other factors
- Unknown

The data for pipeline operations used some of the same causal factor categories. In addition, the analysis identified specific words in the incident description such as “corrosion,” “anchor,” and “trawl” and tagged the spill incidents accordingly for these specific causes:

- Equipment failure
- Weather/natural causes
- External/other factors
- Anchor/trawl/vessel
- Corrosion
- Unknown

“Unknown” signifies when a spill record does not include causal factor information.

This report does not include analysis of tanker or barge spill causal factors.

2.3.6. Hurricanes

This report emphasizes the impact that hurricanes have had on platform and pipeline spill history. To better identify these spills, data analysts performed word searches in the spill records to identify spills that occurred during hurricanes. The search identified incidents featuring the words “hurricane” and “typhoon” and also specific hurricane names (e.g., Ivan, Katrina, Rita).

2.4. Exposure Data

The exposure data sources used in this report reflect the methodology of prior reports, but also include a number of sources for alternative exposure variables.

Table 3 summarizes the data sources for the exposure variables by entity type.

Table 3. Exposure Variables and Associated Data Sources by Entity Type

Exposure Type	Exposure Variable	Data Source	Platforms	Pipelines	Tankers	Barges
Oil Handled	OCS Production Volume	BSEE	✓	✓		
	Worldwide Crude Trade	BP			✓	
	Petroleum Commerce on U.S. Waterways	U.S. Army Corps of Engineers (USACE) – Waterborne Commerce			✓	✓
	TAPS Throughput	Alyeska Pipeline			✓	
Entity Count	Structure Years	BSEE Data Center	✓			
	Pipeline Segment Years	BSEE Data Center		✓		
	Tanker Years	IHS Maritime's World Register of Ships			✓	

OCS crude and condensate production data were provided by BSEE and supplemented with data available on BSEE's website[5]. It is assumed that these production volumes are for production within the OCS only. Production of gas is excluded from this exposure variable since gas releases to the atmosphere, rather than spilling.

Worldwide crude trade by tanker is inferred from the BP Statistical Review of World Energy (BP, 2015). It is assumed that the total crude export volume represents a multiple of the volume of crude transported by tanker. The 2014 exposure variable values were taken from the 2015 report table entitled "Imports and Exports 2014."

The USACE Waterborne Commerce data are taken from Tables 2-1 and 2-3 of "Part 5 – National Summaries of Domestic and Foreign Waterborne Commerce." This report provides details about crude and other petroleum shipping flows within the U.S.

Historically, loadings of Alaska North Slope (ANS) crude into tankers at the terminal of the TAPS pipeline have been used as the exposure metric for spills of ANS crude. This data source is no longer publicly available. As a result, the total throughput of the TAPS pipeline has been used instead. The tanker loadings volume and TAPS throughput have been nearly equivalent (Figure 34, on page 56, plots these

---

[5] Links for BSEE production data:
http://data.bsee.gov/homepg/pubinfo/repcat/product/pdf/Annual%20Production%202005%20-%20Present.pdf
http://data.bsee.gov/homepg/data_center/production/PacificFreeProd.asp

two exposure variables side-by-side) since the beginning of the pipeline's operations. Throughput data are available on Alyeska Pipeline's website.[6]

The structure years and pipeline segment years data are available from BSEE's website. The tanker years data are based on a summary of tanker commissioning and decommissioning dates from IHS Maritime's World Register of Ships.

Some of the exposure variables used in this report required computation of values based on the original data. These computations are explained in Section 3.1.

3. Methods and Assumptions

3.1. Exposure Variable Selection and Computation

Oil handled has long been used as an exposure variable for estimating spill rates. It is easily and intuitively defined, can be easily computed from historical production and commerce data, and can be estimated for future periods. Each of these factors makes it particularly applicable.

Alternative exposure variables were identified and evaluated for this analysis by considering three criteria:

- **Feasibility** – describes the ability to compute historical exposure levels and estimate future exposure levels
- **Relevance** – describes the exposure variable's statistical correlation or theoretical association with the threat of spills
- **Comparability** – describes the presence of similar exposure variables across entity types

After considering a broad range of alternative exposure variables, the analysis team selected entity count as the best alternative exposure variable to be considered with the oil handled variable.

The source data most often included entity counts by storing the commissioning and decommissioning information for each entity in the database. To convert this to an annual count, the data were queried to identify, for each year, the number of unique entity IDs included in the data table where it was true that the commissioning data were prior to the given year and the decommissioning data were either blank or after the given year. This type of query calculation was used for platforms, pipelines, and tankers alike.

3.2. Spill Rates and Distribution

BOEM's oil spill analysis uses estimates of spill occurrence rates for different size classes of spills. This is the primary type of spill rate calculated in this report. It is defined as the expected number of spill occurrences per exposure unit. Historically, the exposure unit has been the volume of oil handled. However, spill rates using alternative exposure variables are calculated using the same methodology. In order to make it somewhat likely for a spill to occur in any given exposure unit, it is necessary for the exposure units to be very large. For example, platform spill rates using the oil handled exposure variable use 1 billion[7] barrels (Bbbl) of produced oil as the exposure unit, resulting in 21 exposure intervals since

---

[6] Link for throughput data: http://alyeska-pipe.com/TAPS/PipelineOperations/Throughput

[7] Billion is understood to be mean 10^9, as is expected in the United States.

1964. Because of the large number of tanker and barge spills, spill rates for these entity types can be computed annually.

Prior reports have included two essential rate estimates for each spill source (Anderson and LaBelle, 2000; Anderson *et al.*, 2012). They presented a rate based on the full record of data, sometimes removing select portions of the data that were statistically shown to be unrepresentative of current spill frequencies. They also presented a 15-year rate based on a shorter and more recent data range. Improvement in the spill occurrence rate over time has caused these two rates to vary significantly. This effort follows the same rate estimation methodology, balancing relevance and statistical precision.

3.3. Trend Analysis

This study performed trend analysis to statistically verify that changes in spill occurrence rates are real and not the product of randomness. In addition, trend analysis is useful in identifying the most recent period of stability in the data in order to identify the period of data that should be used for calculation of a rate that reflects current expectations rather than average historical experience over the long term.

For large spills, trend analyses were performed using Kendall's test, a Runs-Up/Runs-Down test, and the Pearson's Rank Order Correlation test to identify whether unidirectional changes in spill rates are actually occurring or simply appear to be occurring because of random fluctuations. These tests were applied to the entire spill record, as well as to subsets of the record in order to determine what time periods of the historical record are relevant to current operations. Subsets were selected iterating both forward (e.g., starting at the beginning of the record set and moving forward) and backward (e.g., starting at the most recent time in the record set and moving backward) in time. When possible, the report identifies spill rates using periods of stable experience. Appendix A provides further details on the trend analysis methodology.

For smaller spills, trend analysis is performed simply by calculating a best-fit curve based on the historical data. Although this curve is not appropriate for spill rate forecasting, its slope does provide a rough approximation of the trend at that point on the curve.

3.4. Spill Rate Distribution

A spill occurrence rate is the expected number of spills to occur within an exposure interval. The actual number of occurrences is assumed to follow a statistical distribution. Past spill reports (Anderson and LaBelle, 1990, 1994, 2000; Anderson *et al*., 2012) have assumed that spill occurrences follow a Poisson distribution. Spill incidents can be thought of as a counting process where the number of spills that have occurred $N(t)$ is a function of the amount of time that has elapsed, t. In the case of a spill rate, the amount of exposure accumulated over time can substitute for the amount of time elapsed. λ is the true spill rate. A counting process is a Poisson process if it meets the following criteria (Ross, 1985):

1. The probability that $N(0) = 0$ is 100%
2. The process must have independent increments (i.e., the number of spills observed in an interval must not be dependent on the number of spills observed in a prior interval).
3. The number of events in any interval of length t must be Poisson distributed with a mean of λt (i.e., only the length of the interval determines the probable number of spills).

The Poisson rate criteria are assumed to have been met under certain conditions. If spills arising from a single hurricane are treated as a single spill, then the probability of simultaneous spills (occurring without any oil being produced between them) is effectively reduced to zero. The statistical tests mentioned as tools for trend analysis are actually testing for dependence so that a time period for calculating spill occurrence rates can be appropriately identified to ensure that the number of spills in an interval is independent of the number of spills in preceding intervals. If data are selected from a period with minimal trend, then it can be assumed that the number of spills occurring in an interval is approximately a function only of the length of the interval. For a more detailed discussion and sample calculations demonstrating independent increments, see Appendix A.

The most significant assumption is that spills associated with the same hurricane are combined into a single event when calculating rates. If simultaneous hurricane spills are not combined into a single event, the second criterion is violated since the data would indicate dependence among some spills due to a common cause – hurricanes.

3.5. Output Distributions and Confidence Intervals

Poisson spill rates can be used to directly estimate spill rate confidence intervals using a normal approximation of the Poisson distribution if the number of observations used to generate the rates are relatively high (>20 exposure periods). When the number of observations is lower, as in the case of large platform and pipeline spills, this report applies the bootstrap method (see Appendix B). This method uses the values (such as the number of spills) observed over a set of observations (such as exposure intervals) to simulate other potential outcomes based on the original distribution of results for each observation. Fluctuation in estimates based on these simulated values are then used to establish confidence intervals under the assumption that any of the simulated outcomes is theoretically just as likely to occur as the actual observed outcome.

3.6. Limitations

The results in this report are based on aggregations of data collected from specific geographic regions related to specific activities. As such, they should be applied carefully. While the OCS includes waters surrounding Alaska and the west coast, the majority of offshore activity occurs in the Gulf of Mexico (GOM). Before these results are applied, it should be considered whether or not underlying, implicit assumptions of the data remain true within the specific application.

4. Platform Spill Analysis

Between 1964 and 2015, OCS operations have produced just under 20.7 Bbbl of oil. This activity has taken place on over 4,000 platforms[8] operating for a combined total of 151,000 operating years. Approximately 5.2 million barrels (MMbbl) of oil have been spilled during these operations. The Deepwater Horizon (DWH) tragedy alone accounts for the vast majority of this estimate. The Deepwater Horizon Oil Budget Calculator listed the spill volume as 4.9 MMbbl (2010). Other large spills (≥1,000 bbl) make up the majority of the remaining recorded spill volume.

---

[8] Platform structures as defined in BSEE/BOEM facility data.

4.1. Platform Spill Occurrences and Oil Handled

This section reviews the historical spills that have most threatened the environment offshore. It focuses on the frequency of large spills in the OCS. Although there are many smaller spills, 17 recorded spills (Table 4) exceeded the large spill threshold and account for the vast majority of oil spilled during petroleum extraction activities. In general, these are crude oil spills. Exceptions include instances of fuel spilled due to failure of a storage tank (November 23, 1979) and losses of platforms due to severe weather (September 24, 2005). Condensate, a product of natural gas extraction, has also been spilled on multiple occasions (July 19, 1965; September 24, 2005).

Crude and condensate production volume is assumed to be indirectly related to the probability of fuel or condensate spill; therefore, no additional exposure variables are necessary. While reservoirs vary in the mix of crude and natural gas they contain, increased offshore extraction activity leads to increases in both O&G production volumes. Increased offshore activity also requires greater stores of fuel to power the process.

Table 4. Large (≥1,000 bbl) U.S. OCS Platform Spills, 1964 to 2015

Spill Date	Planning Area[1] Block Number	Water Depth (feet)	Miles to Shore	Volume Spilled (bbl)	Operator	Spill Description: Cause and Consequences
4/8/1964	EI 208	94	48	2,559	Continental Oil	Freighter struck Platform A, fire, platform and freighter damaged
10/3/1964	*Hurricane*			*11,869*	*Event Total*	*Five platforms destroyed during Hurricane Hilda*
	EI 208	94	48	5,180	Continental Oil	Platforms A, C, and D destroyed, blowouts (several days)
	SS 149	55	33	5,100	Signal O&G	Platform B destroyed, blowout (17 days)
	SS 199	102	44	1,589	Tenneco Oil	Platform A destroyed, lost storage tank
7/19/1965	SS 29	15	7	1,688[2]	Pan American	Well #7 drilling, blowout (8 days), minimal damage
1/28/1969	6B 5165 Santa Barbara Channel, CA	190	6	80,000	Union Oil	Well A-21drilling, blowout (10 days), 50,000 bbl during blowout phase, subsequent seepage 30,000 bbl (over decades), 4,000 birds killed, considerable oil on beaches
3/16/1969	SS 72	30	6	2,500	Mobil Oil	Submersible rig Rimtide drilling in heavy seas bumped by supply vessel, rig shifted and sheared wellhead, blowout (3 to 4 days)
2/10/1970	MP 41	39	14	65,000	Chevron Oil	Platform C, fire of unknown origin, blowout 12 wells (49 days), lost platform, minor amounts of oil on beaches
12/1/1970	ST 26	60	8	53,000	Shell Oil	Platform B, wireline work, gas explosion, fire, blowout (138 days). Four fatalities, 36 injuries, loss of platform, loss of 2 drilling rigs, minor amounts of oil on beaches

Spill Date	Planning Area[1] Block Number	Water Depth (feet)	Miles to Shore	Volume Spilled (bbl)	Operator	Spill Description: Cause and Consequences
1/9/1973	WD 79	110	17	9,935	Signal O&G	Platform A oil storage tank structural failure
1/26/1973	PL 23	61	15	7,000	Chevron Oil	Platform CA storage barge sank in heavy seas
11/23/1979	MP 151	280	10	1,500[3]	Texoma Production	Mobile Offshore Drilling Unit (MODU) Pacesetter III's diesel tank holed, workboat contact in heavy seas
11/14/ 1980	HI 206	60	27	1456	Texaco Oil	Platform A storage tank overflow during Hurricane Jeanne evacuation
9/24/2005	*Hurricane*			*5,066*	*Event Total*	*One platform and two rigs destroyed by Hurricane Rita*
	EI 314	230	78	2,000[2]	Forest Oil	Platform J destroyed, lost oil on board and in riser
	SM 146	238	78	1,494	Hunt Petroleum	Jack-up Rig Rowan Fort Worth swept away, never found
	SS 250	182	69	1,572[4]	Remington O&G	Jack-up Rig Rowan Odessa legs collapsed
4/20/2010	MC 252	4,992	53	4,900,000	BP E&P	DWH rig, gas explosion, blowout (87 days to cap well), fire. Eleven fatalities, multiple injuries, loss of drilling rig sank, considerable oil on beaches, wildlife affected, and temporary closure of area fisheries

[1] Planning Area in GOM unless otherwise noted. GOM Planning Areas: EI - Eugene Island, HI - High Island, MC - Mississippi Canyon, MP - Main Pass, PL - South Pelto, SS - Ship Shoal, SM - South Marsh Island, ST - South Timbalier, WC - West Cameron, WD - West Delta GOM Planning Area Maps http://www.boem.gov/GOM-Official-Protraction-Diagrams/

[2] Condensate

[3] Diesel

[4] Fuel and other petroleum products

Source: U.S. DOI/BSEE OCS Spill Database, December 2015

No additional large spills have been identified since the report by Anderson *et al*. in 2012. One additional historical spill was considered for inclusion but was ruled out after significant deliberation. It began on September 15, 2004, in the wake of Hurricane Ivan. A platform owned by Taylor Energy toppled, damaging the wellhead. Since that time, the wellhead has been plugged and abandoned, but has continued to leak small volumes of oil. The source data include 469 records associated with light sheens near this wellhead. The total volume of these records exceeds 1,000 bbl, but the presence of duplicate records provided by multiple government agencies makes it difficult to calculate a true total spill volume. For this analysis, this spill is counted as a series of smaller spills (one per quarter year) to better reflect the environmental impact and spill response requirements for this spill. It is not considered a large spill.

Figure 1 illustrates the count of large spills versus the annual oil production volume. The years with the most spills are 1964 and 2005. Hurricanes toppled multiple platforms in both of those years. This figure depicts each hurricane-induced spill individually. Later analyses in this report treat these instances of multiple simultaneous hurricane spills as single spills in order to maintain the necessary statistical assumptions for trend analysis and rate calculation as described in Sections 4.3 and 4.3.1.

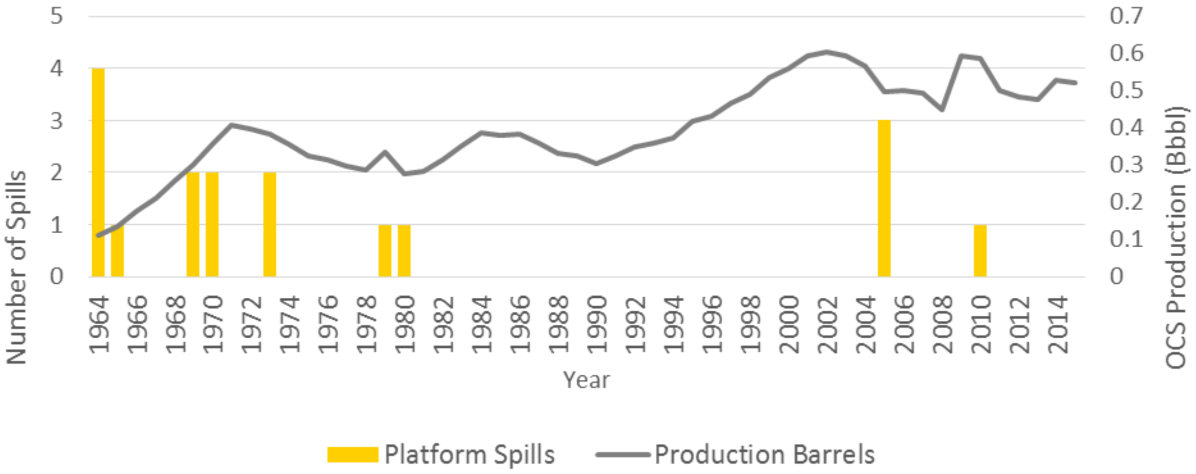

Figure 1. OCS Oil Production vs. Large Platform Spills (≥1,000 bbl), 1964-2015

Table 5 provides additional details on the magnitude of large spills and small spills. Prior to the DWH incident, the volume of oil spilled per Bbbl of production was relatively stable at between 1,000 and 4,000 bbl of oil spilled per Bbbl produced. Anderson *et al*. (2012) noted the observable improvement in the average spill size for large spills since 1975. DWH disrupted this trend of improvement.

Table 5. Platform Spill Rate and Spill Volume Trends Based on Oil Produced, 1964 to 2015

Years	bbl Spilled per Bbbl Produced	bbl Produced per bbl Spilled	Production (Bbbl)	bbl Spilled by Spill Size			# of Spills by Spill Size[1]		
				1 - 999 bbl	≥1,000 bbl	Total	1 - 999 bbl	≥1,000 bbl	Total
1964-1970[2]	142,035	7,041	1.54	2,760	216,616	219,376	11	9	20
1971-1975	11,962	83,601	1.87	5,407	16,935	22,342	721	2	723
1976-1985	3,750	266,682	3.22	9,121	2,956	12,077	671	2	673
1986-1995	1,162	860,805	3.53	4,097	0	4,097	286	0	286
1996-2005	3,478	287,486	5.34	13,508	5,066	18,574	401	3	404
2006-2015	955,179	1,047	5.14	10,951	4,900,000	4,910,951	334	1	335
2006-2015 w/o DWH	2,130	469,478	5.14	10,951	0	10,951	334	0	334
Total	**251,321**	**3,979**	**20.6**	**45,844**	**5,141,573**	**5,187,416**	**2,424**	**17**	**2,441**
Total w/o DWH	**13,925**	**71,814**	**20.6**	**45,844**	**241,573**	**287,416**	**2,424**	**16**	**2,440**

[1] In 2004, MMS changed spill reporting standards to included inventories on OCS structures that were destroyed, heavily damaged, or missing. These passive spills have impacted the number and volume of spills, though these spills were neither observed nor required response.

[2] Spills <50 bbl were not recorded during this period.

Sources: U.S. DOI/BSEE OCS Spill Database, December 2015 (Spills); U.S. DOI/ONRR OCS Production Data, December 2015 (Production)

4.2. Platform Spill Risk Exposure and Causal Factors

In the 2012 report, oil handled by offshore facilities is represented by the total crude and condensate production volume offshore. This exposure metric is readily available since operators report and pay royalties on the crude and condensate that they extract. Practically, this metric has an intuitive, cost-benefit interpretation. Combined with spill data, it answers the question "How many spill occurrences (cost) arise from a certain amount of production (benefit)?" This report continues the use of the oil handled exposure variable, but also considers alternatives. Table 6 summarizes the key alternative metrics related to platforms that were considered for analysis.

Table 6. Platform Exposure Metrics

Exposure Metric	Feasibility	Relevance	Comments
Oil Volume Produced	**High**	**Medium**	Existing metric. Production volume data readily available. Spill rate per production relevant for understanding spills in terms of cost/benefit.
Structure Count	**High**	**Medium**	Readily available data within BSEE databases. Relevant to stationary platform spills, but not necessarily spills associated with moveable facilities.
Complex Count	**High**	**Medium**	Like structures, readily available data within BSEE databases. Relevant to stationary platform spill risk, but not necessarily spills associated with moveable facilities.
Sum of Facility Age	**Medium**	**Low**	Although this information can be determined from the data, preliminary analysis did not reveal a statistical relationship with spill experience.
Count of Wells	**Low**	**Medium**	The analysis team did not locate sufficient data to estimate this metric.

The most straightforward alternative to production for assessing offshore facilities' spill risk exposure is a count of structures. Using BSEE's facility data, the analysis team derived counts of structures and counts of structure complexes. In general, there are a large number of single-structure complexes, so these metrics are not significantly different. Table 7 presents the same results as Table 5 except with structure years as the exposure variable.

Normalizing spill rates by the number of facilities ensures that any remaining variation in spill rates over time are because of other factors such as changes in technology, operating environment, or mitigation measures.

Table 7. Platform Spill Rate and Spill Volume Trends Based on Structure Years, 1964 to 2015

			bbl Spilled by Spill Size			# of Spills by Spill Size[1]		
Years	bbl Spilled per Structure Year	Structure Years	1 - 999 bbl	≥1,000 bbl	Total	1 - 999 bbl	≥1,000 bbl	Total
1964-1970[2]	26.83	8,176	2,760	216,616	219,376	11	9	20
1971-1975	2.41	9,288	5,407	16,935	22,342	721	2	723
1976-1985	0.46	26,462	9,121	2,956	12,077	671	2	673
1986-1995	0.11	37,059	4,097	0	4,097	286	0	286
1996-2005	0.48	38,525	13,508	5,066	18,574	401	3	404
2006-2015	156.57	31,365	10,951	4,900,000	4,910,951	334	1	335
2006-2015 w/o DWH	0.35	31,365	10,951	0	10,951	334	0	334
Total	**34.38**	**150,875**	**45,844**	**5,141,573**	**5,187,416**	**2,424**	**17**	**2,441**
Total w/o DWH	**1.90**	**150,875**	**45,844**	**241,573**	**287,416**	**2,424**	**16**	**2,440**

[1] In 2004, MMS changed spill reporting standards to included inventories on OCS structures that were destroyed, heavily damaged, or missing. These passive spills have impacted the number and volume of spills, though these spills were neither observed nor required response.

[2] Spills <50 bbl were not recorded during this period.

Source: U.S. DOI/BSEE OCS Spill Database, December 2015 (Spills); U.S. DOI/BSEE Data Center, December 2015 (https://www.data.bsee.gov/homepg/data_center/platform/platform.asp) (Structure Years)

The primary advantage of a simple count-based exposure metric is that it is easy to interpret and implement, and intuitively, increasing the number of facilities should increase the likelihood of spill.

A potential downside of this exposure variable is that rigs are not included in the structure count. This is a weakness that is shared with the oil handled exposure variable since rigs seldom are involved in production. The fact that production levels and structure counts are correlated with rig activity offsets this potential weakness for the oil handled variable.

4.2.1. Causal Factors

Inspection of the causal factors for platform spills throughout the spill record reveals insight into the decreasing spill rate. Figure 2 shows instances of equipment failure, human error, weather/natural causes, and other/external factors. As mentioned before, multiple causal factors can be assigned to a single spill event simply by counting each causal factor rather than each spill. To maintain the one-to-one relationship between causal factor values in Figure 2 and the number of spills recorded for each year, the figure normalizes the causal factor counts so that the aggregate count is equal to the spill count.

Two trends in the data feature most prominently. First, the hurricanes of the 2000s have a dramatic impact on the observed causal factors. Weather, natural causes, external factors, and other factors were not previously frequently recorded in the data. Second, the dominant driver of improved spill rates appears to be a reduction in equipment failures. While the number of human errors recorded is almost as high in the 2000s as in the 1970s and 1980s, the number of equipment failures has steadily decreased since 1975. This may suggest that technology improvements have played a significant role in the improving spill rate.

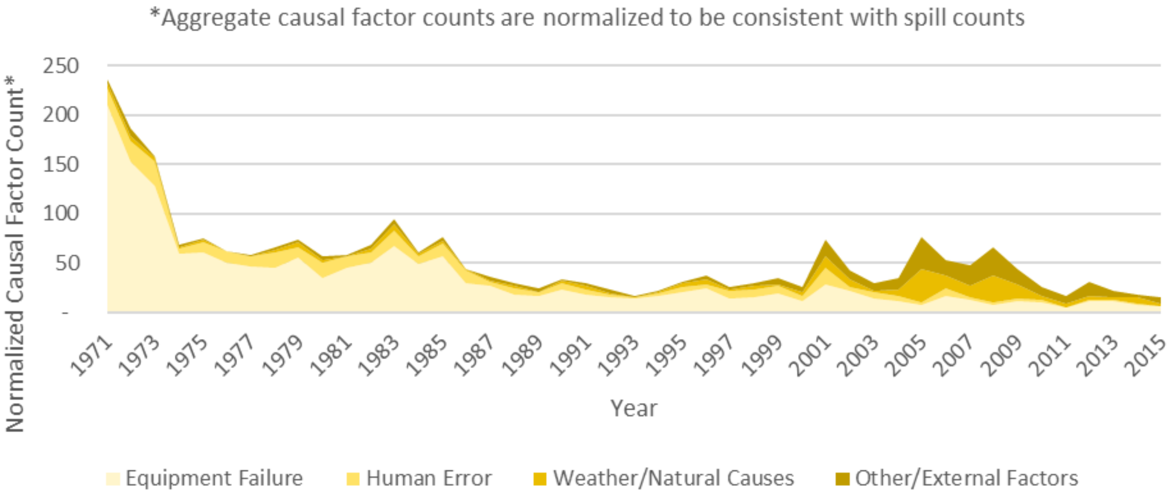

Figure 2. Platform Spill Causal Factor Summary

Figure 3 presents the causal factor data by spill size category. Just as human error instances are stable over time, they appear to contribute similarly to the frequency of spills of different sizes. On the other hand, instances of equipment failure dominate the smaller spill size categories, becoming less prevalent among the larger spill size categories, which are frequently caused by weather/natural and other/external causes. Equipment failures have also played a significant role in spills of ≥10,000 bbl.

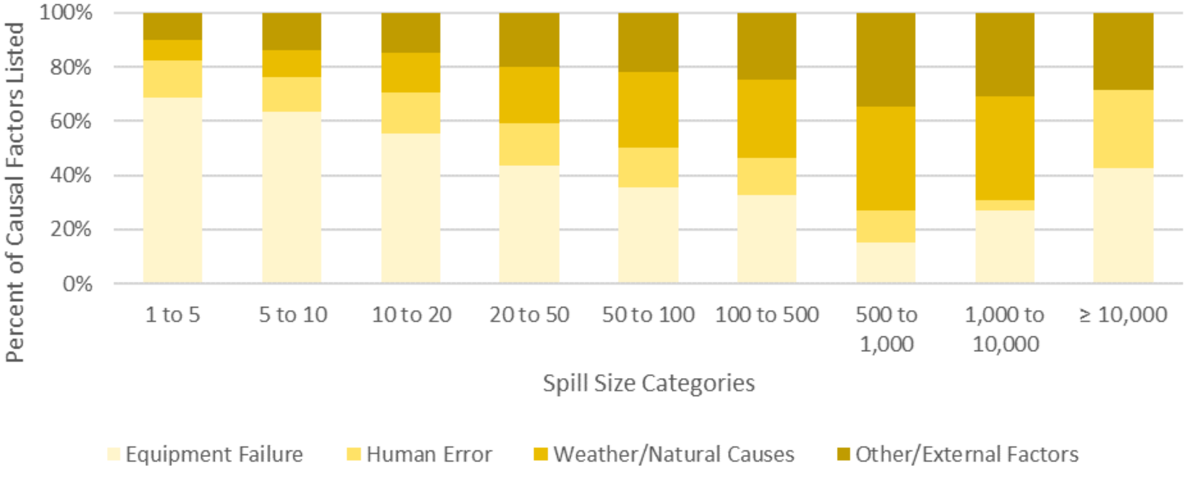

Figure 3. Platform Spill Causal Factor Summary by Spill Size Category

4.2.2. Loss of Well Control Spills

Loss of well control (LOWC) resulting in a spill occurs relatively infrequently compared to spills of other types. Figure 4 depicts spills from LOWC as a rare, but consistent causal factor throughout the spill record.

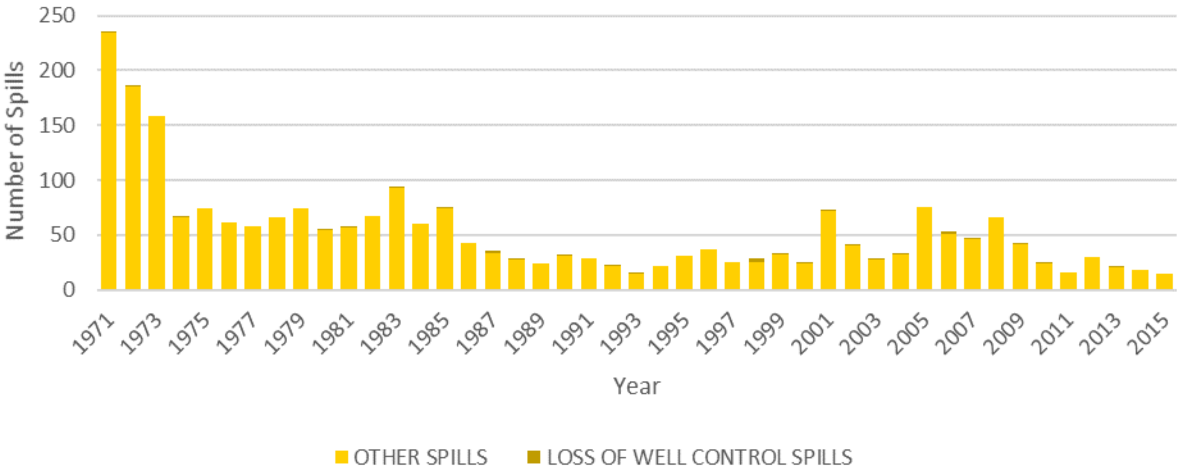

Figure 4. Platform Spill Loss of Well Control Summary

Figure 5 highlights the significance of LOWC events resulting in a spill. The likelihood of a spill being caused by an LOWC leading to a blowout increases with the size of the spill. All four platform spills ≥10,000 bbl were flagged as LOWC and, with the exception of DWH, occurred prior to 1971.

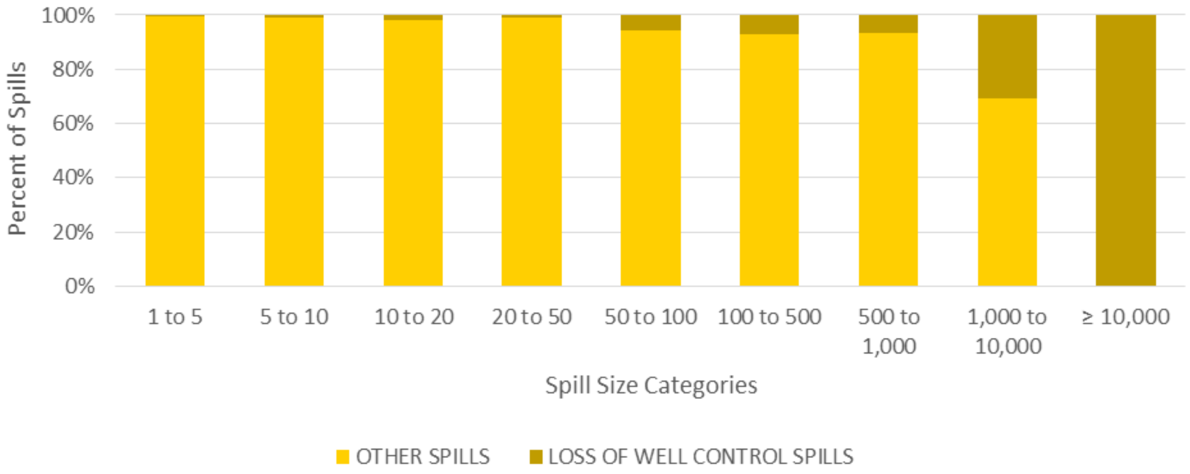

Figure 5. Platform Spill Loss of Well Control Summary by Spill Size Category

4.2.3. Platform Spills by Operating Mode

This spill record also provides insights into the changes in the operating modes that drive spill events. Just as the decrease in equipment failures has contributed to the overall frequency of spills, Figure 6 illustrates a dramatic decline in production spills since the 1970s and 1980s. In the 2000s, the operating mode during hurricane spills was often not indicated in the data, resulting in a swell in unknown operations during that time.

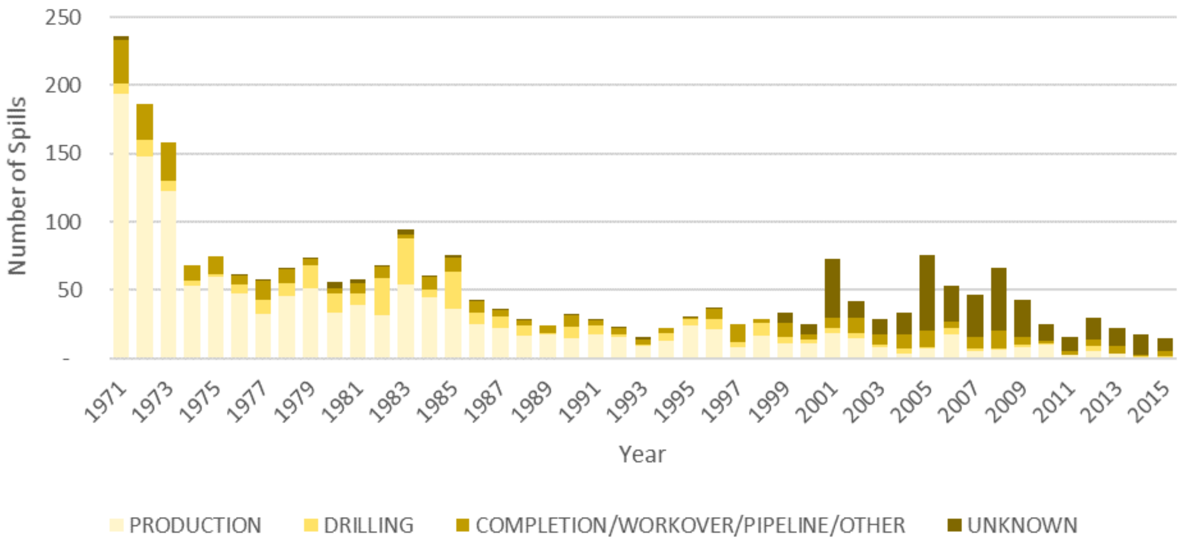

Figure 6. Platform Spill Operating Mode Summary

Production incidents dominate the smaller spill size categories, while “unknowns” contribute significantly to the occurrences of larger spills. Drilling, completion, workover, pipeline, and other modes have higher prevalence among the larger spill size categories. Figure 7 illustrates these trends.

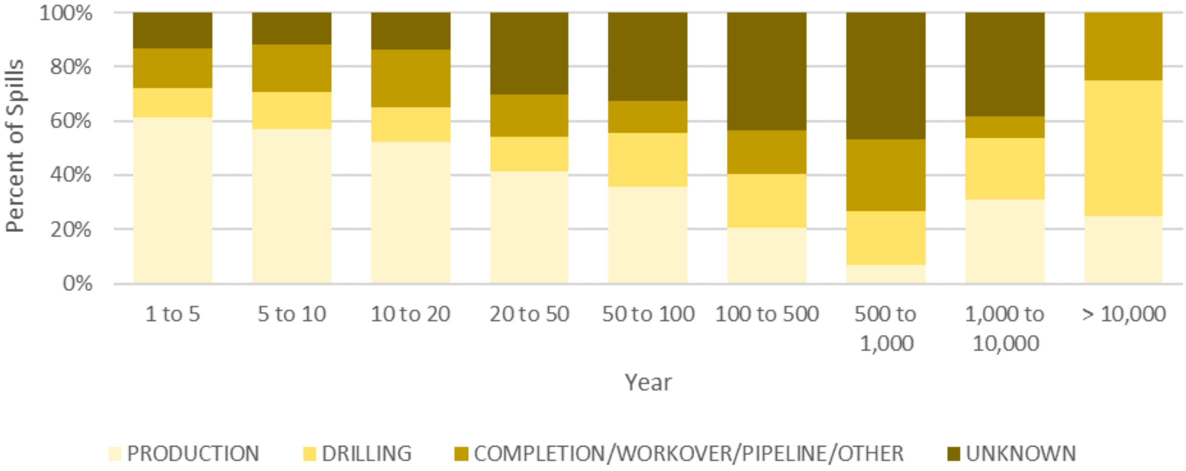

Figure 7. Platform Spill Operating Mode Summary by Spill Size Category

4.2.4. Hurricanes

Each of the preceding causal factor analyses shows a noticeable increase in spill frequency in the 2000s. The weather/natural causal factor suggested that these were potentially hurricane-initiated spills. Figure 8 confirms this by indicating the spill events where a hurricane was a contributing factor. From this graph, it can be clearly seen that operational spills (excluding hurricanes) have continued along a stable trend, while hurricane-initiated spills were frequent during the 2000s. Hurricanes Cindy, Ike, Ivan, Katrina, Lili, and Rita all occurred during that decade.

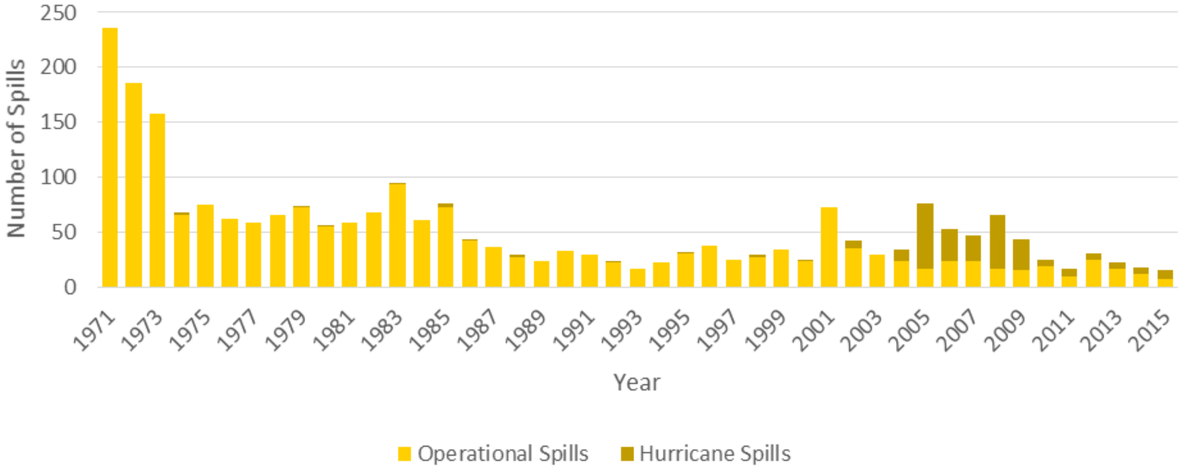

Figure 8. Platform Spill Hurricane Summary

Even one hurricane can have dramatic effects on the number of spills recorded on the OCS as shown in Figure 9. Ivan occurred in 2004, Rita and Katrina occurred in 2005, and Ike occurred in 2008. In the years following these disasters, operators continued to attribute minor losses to the damage done by these storms. In the case of Hurricane Ivan, the damaged Taylor energy platform has continued to leak small amounts of oil since 2004.

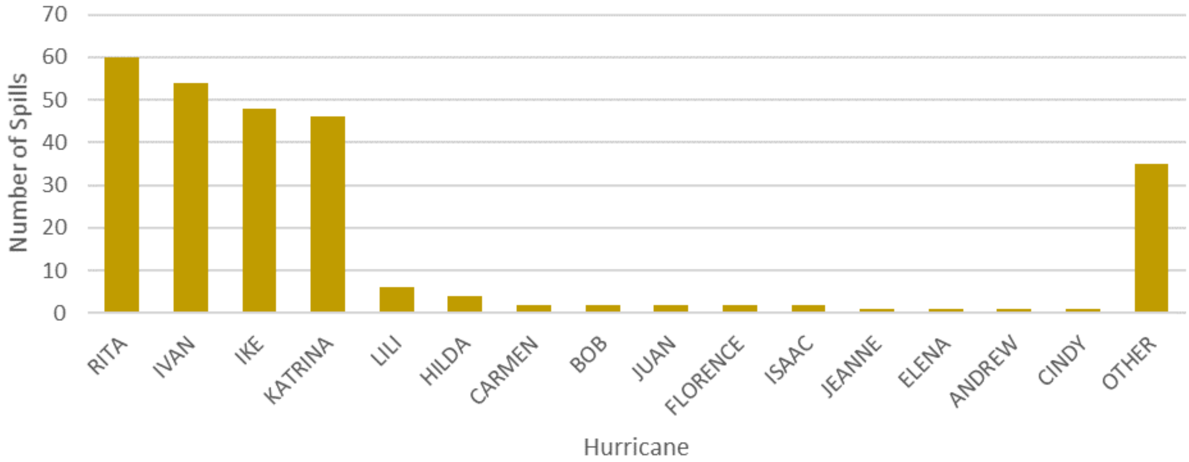

Figure 9. Platform Spills by Hurricane

Figure 10 indicates the prevalence of hurricanes in the larger spill size categories but not those greater than or equal to 10,000 bbl.

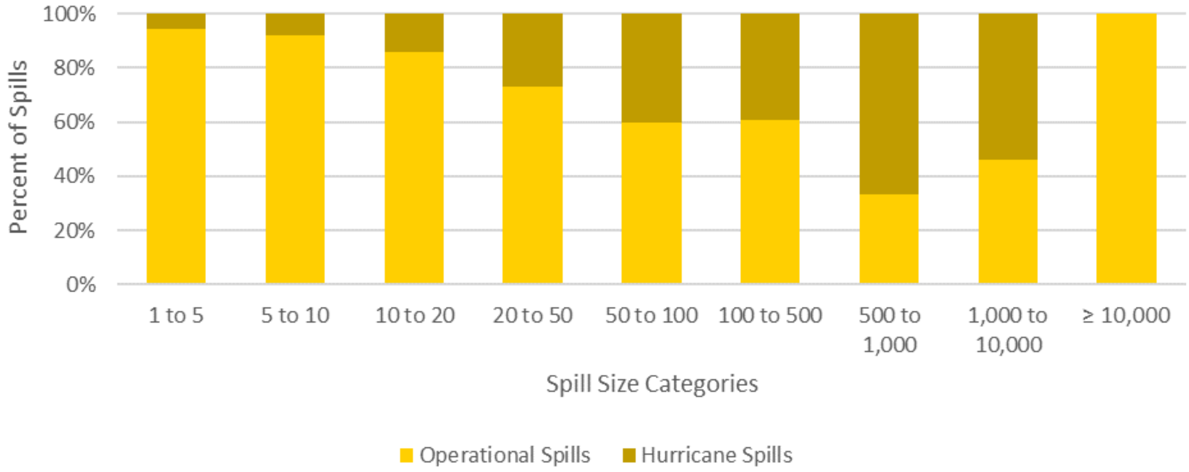

Figure 10. Platform Spill Hurricane Summary by Spill Size Category

Figure 11 illustrates the causal factor results from Figure 2 with the hurricane events excluded. This indicates an overall improving trend for OCS spills.

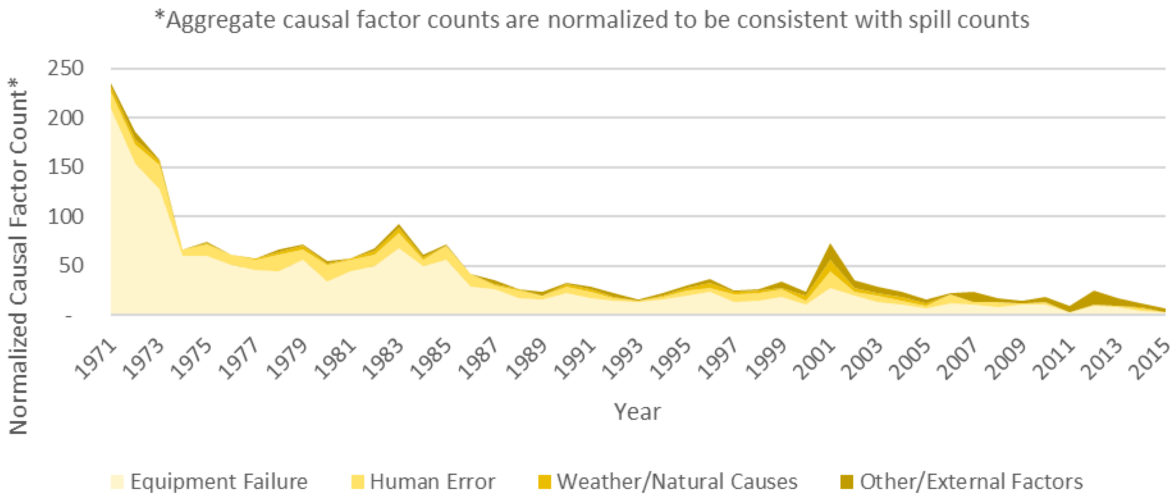

Figure 11. Platform Spill Causal Factor Summary – Excluding Hurricanes

4.2.5. Causal Factors by Operating Mode

The underlying causal factors of spill events can vary depending on the mode in which the platform is operating. Figure 12 compares the contribution of the causal factor categories to spills by operating mode. Equipment failures drive the spill events for all modes with the exception of the Unknown category, which has significant contribution from external forces and weather/natural causes.

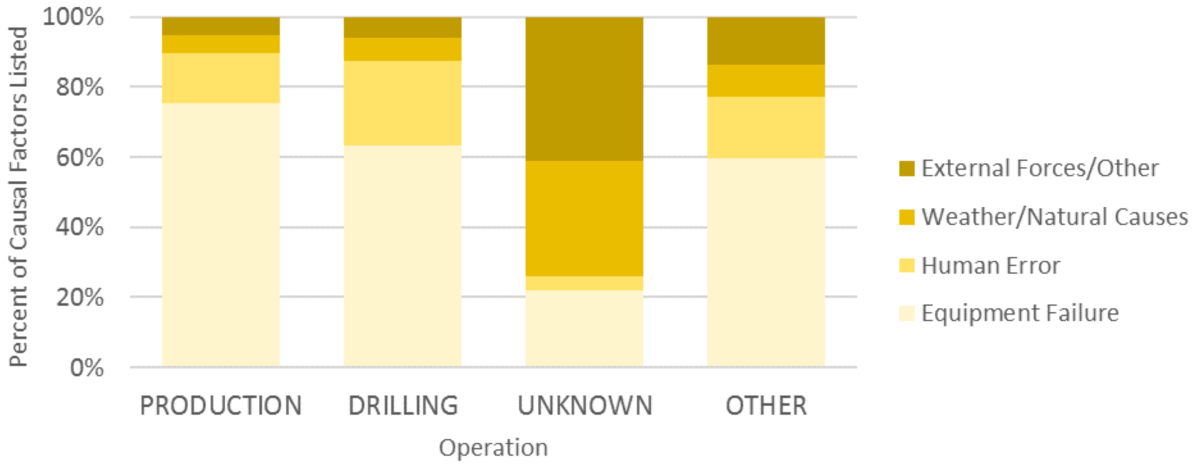

Figure 12. Platform Spill Causal Factor by Operating Mode

Figure 13 illustrates causal factor category contribution for LOWC events. Equipment failure and human error are dominant contributors across the modes.

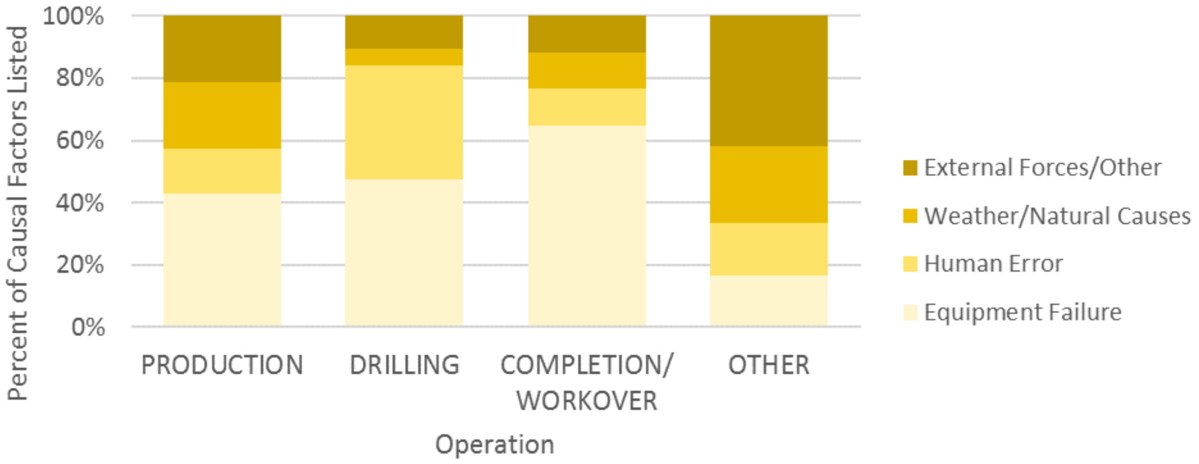

Figure 13. Platform Spill Loss of Well Control Causal Factor by Operating Mode

4.3. Platform Trend Analysis

This analysis considers trends in overall spill frequency and trends in the frequency of large spills. Although the two may be related, it can be seen from the causal factor analysis that the underlying causes for large spills are often different from those of smaller spills. Therefore, their trends are considered separately.

4.3.1. Trends in Large Spills

The analysis of trends in large spill occurrences reflects the methodology used in prior versions of this report. Kendall's test is used to identify date ranges in the data where correlation between the order in which the spills occurred and the volume of production occurring between each spill and the prior spill indicates changing levels of exposure between spills. For the purpose of this discussion, a trend is an increase or decrease in the ratio of spills to exposure over time. Appendix A includes sample calculations of the test statistics and explains their use. For the Kendall's test, the analysis maintains the method of combining simultaneous hurricane spills.

Figure 14 normalizes the spill experience by considering spills per Bbbl production interval rather than per year. Although the Kendall's test identified a long-term downward trend over the whole record of spills (1964 to 2015), it appears that this is primarily due to a short-term downward trend early in the record (1964 to 1974). This is confirmed by the fact that no trend is statistically discernable over the period from 1970 to 2015.

The significance levels provided in Figure 14 identify the likelihood that the observed trends are actually the result of randomness.[9] A smaller significance level indicates a high confidence that a trend exists. A significance level greater than 10% suggests that no strong trend exists.

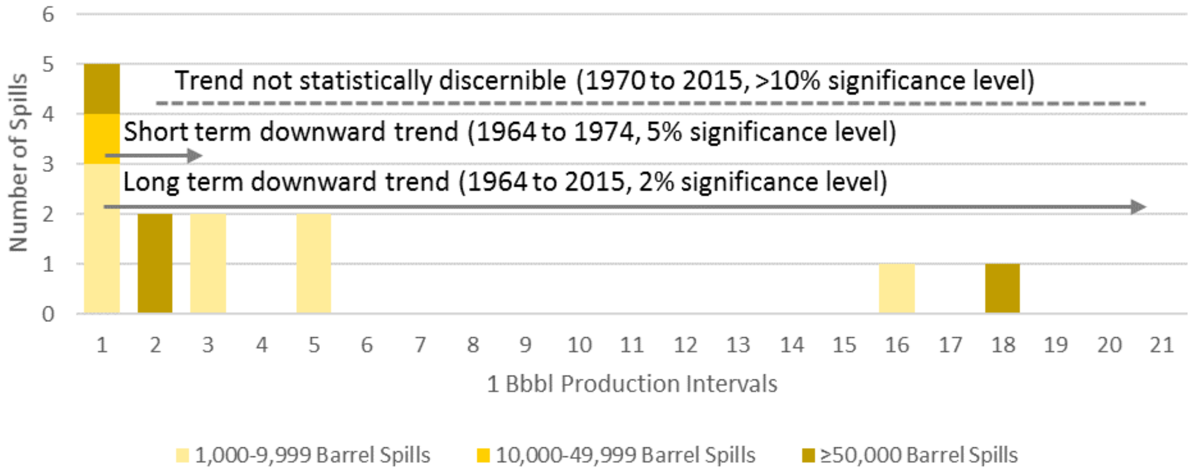

Figure 14. Platform Large Spill Trends by Production Intervals – Including Hurricane Spills

These trend findings were further confirmed by the runs-up, runs-down test and the Spearman rank correlation test. The runs-up, runs-down test had a test statistic of 8 runs, indicating that the independence of the spills could not be disproved. The Spearman rank correlation test produced a correlation of 0.626 for the entire time period. This value identified that the spills were not independent (at the 2% significance level). However, when using only the spills from 1970 to 2015, the assumption of independence could not be rejected.

Figure 15 considers the same trend, but excludes hurricanes from the analysis. This analysis is restricted by the absence of sufficient data following period 2 since the Kendall's test requires at least four observations and there are only four observations following period 2. However, the same downward trend as identified in Figure 14 is clearly visible.

---

[9] Two-sided tests were used such that the null hypothesis was that no statistical trend exists while the alternative hypothesis was that either an increasing or decreasing trend exists.

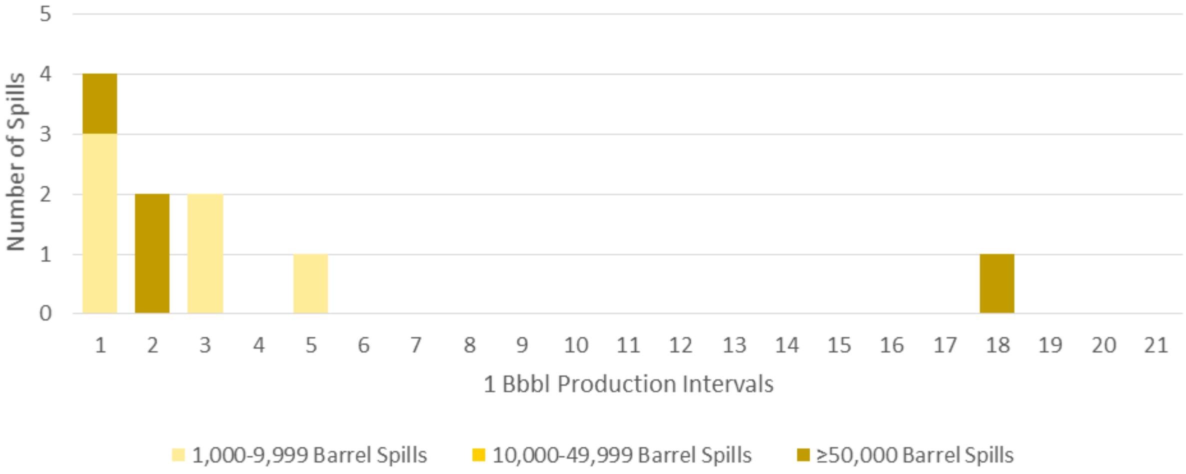

Figure 15. Platform Major Spill Trends by Production Intervals – Excluding Hurricane Spills

4.3.2. Trends in All Spills

Although small spills are less damaging to the environment than large spills, they offer insights into the overall changes in the frequency of platform spills. Figure 16 shows the count of spills ≥1 bbl normalized by production volume for each year since 1970. Prior to 1971, spills <50 bbl were not well reported, resulting in unusable data for that time range. It is important to note that these are not proper spill rates since they do not appropriately adjust for hurricane incidents.

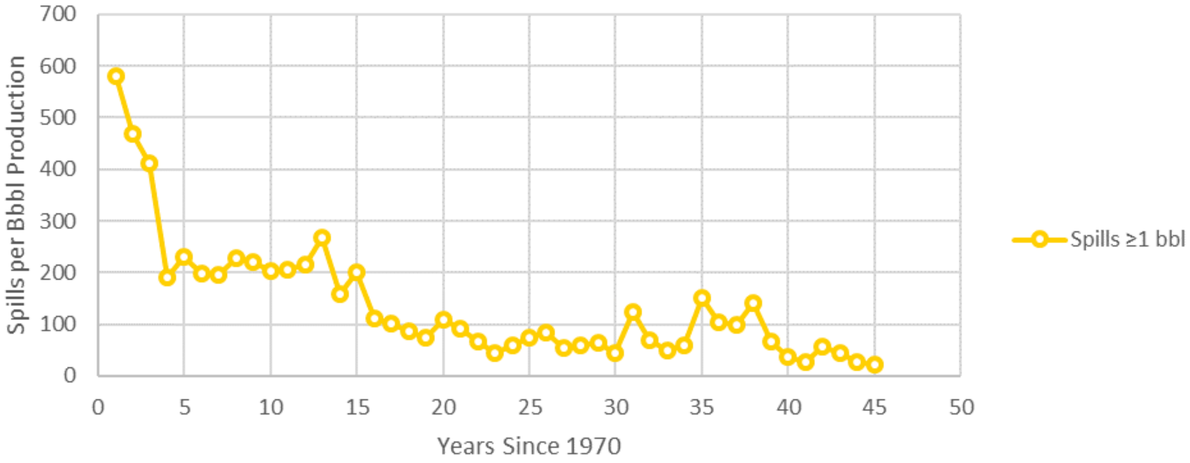

Figure 16. Platform Spill Trends by Year – 1971-2015

The downward slope of the spill occurrence data is easily discernable. Most notably, the first three years of data indicate much higher spill occurrence levels than the rest of the data, similar to the findings for large spills.

Excluding the first three data as outliers, Figure 17 includes an exponential best-fit trend line providing a rough quantitative estimate that confirms the downward trend observed over the last 40 years. This trend line formula is not intended for projecting future spill incidence rates. It is beyond the scope of this report to perform the in-depth analysis required to construct a model that adequately addresses key time series forecasting requirements such as data independence, lack of autocorrelation, and the normality and homoscedasticity of residuals from the predicted values.

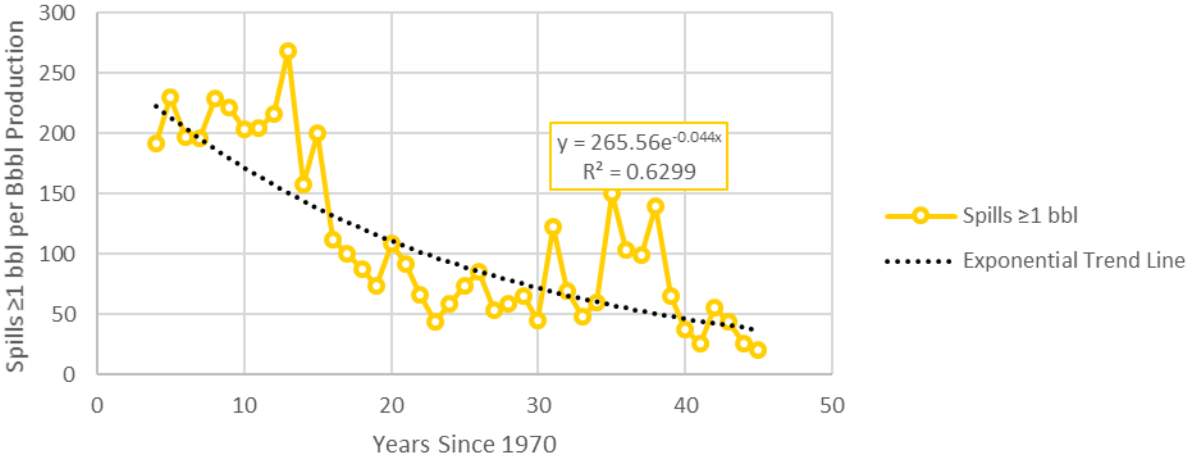

Figure 17. Platform Spill Trend Line – 1974-2015

Figure 18 provides additional details about the fit of trend line. Although the residuals of this regression model appear to be somewhat normal, it is not clear whether they are homoscedastic. Furthermore, the data portrays clear temporal autocorrelation, violating a key requirement for accurate time series forecasting. In addition to the expected variation in a typical residual plot, the temporal autocorrelation of the residuals may arise from any number of sources, ranging from multiyear cycles in spill reporting standards to industry factors affecting the prevalent operating modes taking place in a given year.

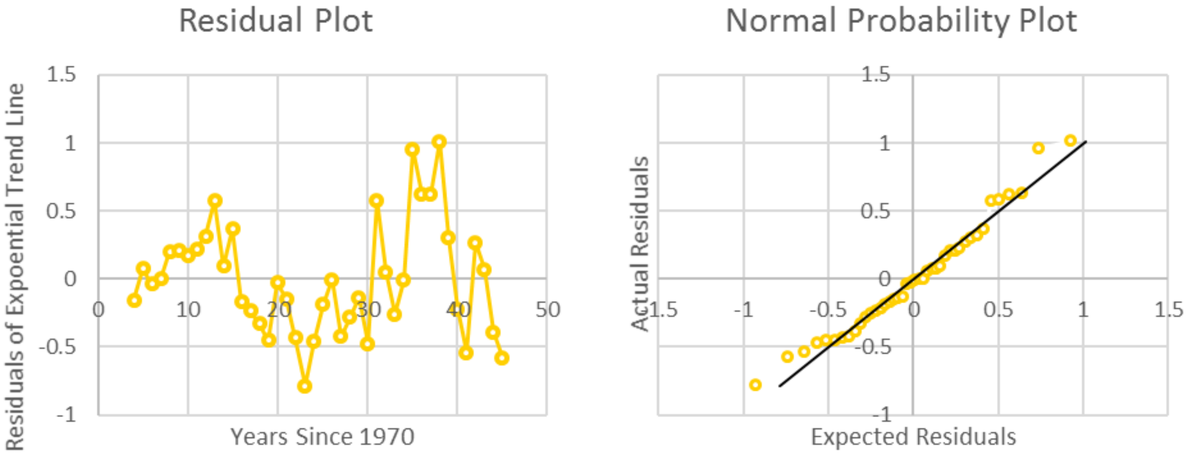

Figure 18. Platform Spill Trend Line Residual Plots

Based on the trend analysis of all spills and the analysis of large spills alone, there is a clear break in the pattern of spill occurrences between 1970 and 1974. In particular, the analysis of all spills reveals a compelling transition in 1974 to a relatively stable, long-term trend of slightly decreasing spill occurrence levels. Anderson *et al.* (2012) identified a similar trend period, including one additional spill that occurred in 1973 in the rate-setting period.

4.4. Platform Spill Rates

This report presents multiple rate estimates based on different assumptions and criteria. There are estimates developed based on the full spill record as well as 15-year estimates based only on recent history. As described in section 4.3, both statistical and qualitative methods suggest a period for calculating rates starting in 1974 regardless of the distinction hurricane-induced spill and operational spills and between small and large spills. Therefore, the full record rate for large spills includes spills and exposure occurring between January 1, 1971, and December 31, 2015, inclusive. The 15-year rate includes spills and exposure occurring between January 1, 2001, and December 31, 2015, inclusive.

This section also presents spill rates for various subsets of the data based on whether a spill was hurricane-related or not. For this purpose, the report calculates two base spill rates: one including hurricane spills and the other excluding hurricane spills.

4.4.1. Platform Base Spill Rates

Table 8 compares the full record and 15-year spill rates to the full record estimates from the previous report (Anderson *et al*., 2012) for both the ≥1,000 and ≥10,000 spill size categories.

Table 8. Platform Oil Handled Spill Rate Comparison (Previous to Updated Rates)

Spill Size and Source	Previous Rate, 1973 - 2010[1,2]			Updated Rate, 1974 - 2015			2001 - 2015		
	Oil Handled (Bbbl)	# of Spills	Spill Rate	Oil Handled (Bbbl)	# of Spills	Spill Rate	Oil Handled (Bbbl)	# of Spills	Spill Rate
Including Hurricane Spills									
≥1,000 bbl	15.8	5	0.32	17.9	4	0.22	8.0	2	0.25
≥10,000 bbl	15.8	1	0.06	17.9	1	0.06	8.0	1	0.13
Excluding Hurricane Spills									
≥1,000 bbl				17.9	2	0.11	8.0	1	0.13
≥10,000 bbl				17.9	1	0.06	8.0	1	0.13

[1] Anderson *et al*., 2012.

[2] The previous report uses production intervals 4 through 18 (Figure 14) as the rate period. This is approximately 1973 to 2010.

Source: U.S. DOI/BSEE OCS Spill Database, December 2015 (spills); U.S. DOI/ONRR OCS Production Data, December 2015 (Production)

Table 9 provides confidence intervals for the updated spill rates. These intervals use the bootstrap method to overcome the statistical challenge of a small number of data points. While a normal approximation to a confidence interval may erroneously provide a negative lower bound for small spill rates, the bootstrap method will not.

Table 9. Platform Oil Handled Spill Rate Confidence Intervals (Full Record and 15-year Rate)

Spill Size and Source	Full Record Rate: 1974 - 2015			15-year Rate: 2001 - 2015		
	Lower Bound (95% Confidence)	Spill Rate	Upper Bound (95% Confidence)	Lower Bound (95% Confidence)	Spill Rate	Upper Bound (95% Confidence)
Including Hurricane Spills						
≥1,000 bbl	0.00	0.22	0.56	0.00	0.25	0.63
≥10,000 bbl	0.00	0.06	0.17	0.00	0.13	0.38
Excluding Hurricane Spills						
≥1,000 bbl	0.00	0.11	0.28	0.00	0.13	0.38
≥10,000 bbl	0.00	0.06	0.17	0.00	0.13	0.38

4.4.2. Supplementary Hurricane Spill Rate

Table 10 estimates rates of hurricane spills per structure year. This assumes that hurricane spills are more plausibly linked to the number of facilities than to the volume of production since platforms are shut in during hurricanes to minimize damage. In addition, the table converts the rate to an equivalent rate per Bbbl using the current ratio[10] of 10,000s of structure years to Bbbl: 0.633. This conversion is trivial for the 15-year rate since the conversion factor is calculated during the same 15-year time period as for the 15-year rate per oil handled. However, it is included to demonstrate the difference between the traditional rate calculation method and one that calculates the hurricane spill rate on a structure year basis. No hurricane spills ≥10,000 bbl were observed; therefore, rates were only calculated for hurricane spills ≥1,000 bbl.

Table 10. Platform Structure Years Hurricane Spill Rate Comparison (Full Record and 15-year Rate)

Spill Size and Source	Full Record Rate: 1974 - 2015				15-year Rate: 2001 to 2015			
	Structure Years (10,000s)	# of Spills	Spill Rate	Spill Rate (Converted to Bbbl)	Structure Years (10,000s)	# of Spills	Spill Rate	Spill Rate (Converted to Bbbl)
Including Only Hurricane Spills								
≥1,000 bbl	13.7	2	0.15	0.09	5.1	1	0.20	0.13
Sources: U.S. DOI/BSEE OCS Spill Database, December 2015 (spills); U.S. DOI/BSEE Data Center, December 2015 (https://www.data.bsee.gov/homepg/data_center/platform/platform.asp) (Structure Years)								

---

[10] Calculated using oil handled and structure year exposure data from 2001 to 2015.

Table 11 aggregates the hurricane spill rate with the no-hurricane spill rate and includes confidence intervals for the sum of the two rates. These intervals are calculated using a simultaneous bootstrap method for both rate distributions.

Table 11. Platform Aggregated Spill Rates Confidence Intervals (Full Record and 15-year Rate)

	Full Record Rate: 1974 - 2015			15-year Rate: 2001 to 2015		
Spill Size and Source	Lower Bound (95% Confidence)	Spill Rate	Upper Bound (95% Confidence)	Volume Handled (Bbbl)	Spill Rate	Spill Rate per 10,000 Structure Years
≥1,000 bbl						
Rate Excluding Hurricanes	0.00	0.11	0.28	0.00	0.13	0.38
Hurricane Rate (per Bbbl)	0.00	0.09	0.23	0.00	0.13	0.37
Aggregate	0.05	0.20	0.48	0.00	0.25	0.76

The key finding in Table 11 is that the aggregate spill rate (0.20 spills per Bbbl) calculated by analyzing hurricane spills on a structure year basis and operational spills on an oil handled basis is lower than the spill rate that is calculated using traditional methods (0.22 spills per Bbbl). This is because the split approach adjusts for the fact that the current platform count per oil handled is lower than in the past. Therefore, the current exposure to hurricane-related spills as measured by structure years is lower than the current exposure to hurricane-related spills as measured by oil handled.

4.4.3. Platform Alternative Exposure Variable Rate

Table 12 provides base rate calculations using the structure years alternative exposure variable. These rates include all spills, regardless of association with a hurricane. The primary weakness of these rates arises when applying the rate to a single platform. If a deep water complex has one large structure supporting a dozen wells, it will have the same assumed spill rate as a small, single-well platform in shallow water. This is not true of the oil handled variable, which prescribes spill rates on the basis of the magnitude of production.

Table 12. Platform Structure Years Spill Rate Comparison (Full Record and 15-year Rate)

	Full Record Rate: 1974 - 2015			15-year Rate: 2001 - 2015		
Spill Size and Source	Structure Years (10,000s)	Number of Spills	Spill Rate	Structure Years (10,000s)	Number of Spills	Spill Rate
≥1,000 bbl	13.7	4	0.29	5.1	2	0.40
≥10,000 bbl	13.7	1	0.07	5.1	1	0.20

Sources: U.S. DOI/BSEE OCS Spill Database, December 2015) (Spills); U.S. DOI/BSEE Data Center, December 2015 (https://www.data.bsee.gov/homepg/data_center/platform/platform.asp) (Structure Years)

4.5. Platform Spill Distributions

This report also considers the expected spill volume for spills in the various spill size categories. In recent years, the expected range of expected spill volumes has been shifted by the DWH incident. Any review of spill volume distributions must understand the magnitude of this spill and its significance to this work.

4.5.1. DWH

The DWH disaster presents a statistical dilemma when considering the distribution of potential spill sizes. On the one hand, it was a rare occurrence. On the other hand, all other OCS platform spills appear relatively insignificant in magnitude. In the remaining analysis, this spill is excluded, not because it is irrelevant, but because it obscures the estimates related to other, typical spills. Figure 19 depicts the volume of the DWH spill compared to all other recorded OCS platform spills of 1 bbl or more in the OCS since 1964.

It is beyond the scope of this report to analyze the implications of this event for today's oil spill risk analysis. However, there is research surrounding this important spill. Ji, Johnson, and Wikel (2014) have conducted statistical analysis of this and other rare events and their application to oil spill risk analysis.

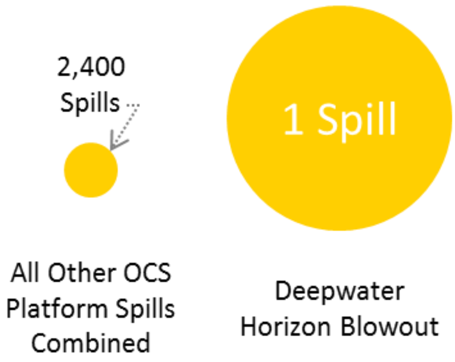

Figure 19. DWH – A Statistical Dilemma

4.5.2. Platform Spill Volume Estimates

Table 13 calculates expected spill volumes for large spills using both the average (mean) and median as estimates. The average spill size varies dramatically depending on whether the DWH spill is included. Whenever the DWH spill is included in the data, it dominates the estimate. Median spill estimates remove the impact of this outlier. Based on this estimate, hurricane spills can clearly be seen to be smaller than other operational spills ≥1,000 bbl.

Table 13. Comparison of Average and Median Platform Spills With and Without DWH and Hurricanes

Spill Source	1974 - 2015			Last 15 years		
	Number of Spills	**Average Spill Size (bbl)**	**Median Spill Size (bbl)**	**Number of Spills**	**Average Spill Size (bbl)**	**Median Spill Size (bbl)**
All Spills	4	1,227,006	3,283	2	2,452,533	2,452,533
Excluding DWH	3	2,674	1,500	1	5,066	5,066
Excluding Hurricanes	2	2,450,750	2,450,750	1	4,900,000	4,900,000
Excluding DWH and Hurricanes	1	1,500	1,500	0	N/A	N/A
Hurricanes Only	2	3,261	3,261	1	5,066	5,066

Source: U.S. DOI/BSEE OCS Spill Database, December 2015

Table 14 provides additional information by spill size category. Expectedly, the average and mean for each category lies between the bounds of the categories, nearer to the lower bound. For OCS spills ≥1 bbl, 57% are <5 bbl.

Table 14. Platform Spill Size Empirical Distribution 2001-2015

Spill Size	Number of Spills	bbl Spilled	Average Spill Size (bbl)	Median Spill Size (bbl)
≥1 to <5 bbl	333	670.5	2.0	2.5
≥5 to <10 bbl	62	431.0	7.0	
≥10 to <20 bbl	48	641.2	13.4	
≥20 to <50 bbl	50	1,624.1	32.5	
≥50 to <100 bbl	32	2,082	65.0	127.4
≥100 to <500 bbl	50	10,372	207.4	
≥500 to <1,000 bbl	10	6,266	626.6	
≥1,000 to <2,000 bbl	2	3,066	1,533	1,572
≥2,000 to <3,000 bbl	1	2,000	2,000	
≥3,000 to <10,000 bbl	—	—	—	
≥10,000 bbl	1	4,900,000	4,900,000	4,900,000
All Spills	**589**	**4,927,151**	**8,365.3**	**3.4**

Source: U.S. DOI/BSEE OCS Spill Database, December 2015

4.5.3. Changes in the Platform Spill Volume Distribution

This section examines and compares the portion of the number and volume of spills that are represented in the full record and 15-year rates. The DWH spill is excluded from these. Figure 20 compares the spill counts to the spill volumes of various spill size categories in the full record time period. While large spills are not even observable on the spill count diagram, they make up 40% of the spill volume diagram. The full record period includes a large range span of time in the 1970s and 1980s where small production spills dominated the spill record. Table 15 lists the numeric values for these charts.

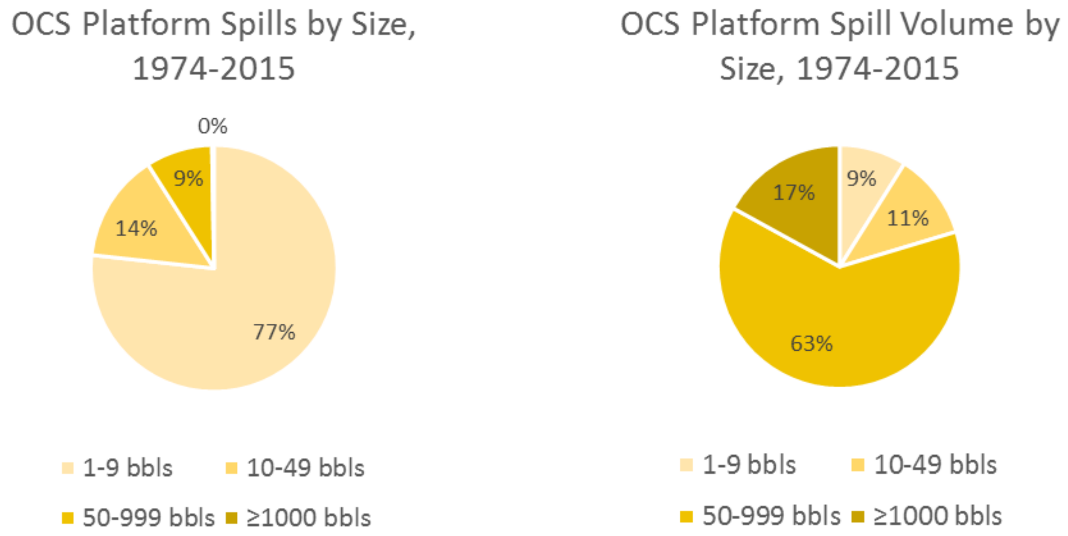

Figure 20. Platform Spill Distribution (Number and Volume) by Spill Size Category, 1974-2015

Table 15. Platform Spill Distribution by Spill Size Category, 1974-2015

Spill Size Category	Number of Spills	bbl Spilled	Average Spill Size (bbl)	% Spills ≥1 bbl	% Volume ≥1 bbl
1-9 bbl	1,412	4,213.6	3.0	76.7%	8.9%
10-49 bbl	262	5,393.6	20.6	14.2%	11.4%
50-999 bbl	161	29,566.0	183.6	8.8%	62.6%
≥1,000 bbl	5	8,021.7	1,604.3	0.3%	17.0%
Total	1,840	47,194.9	1,811.6	100.0%	100.0%
Source: U.S. DOI/BSEE OCS Spill Database, December 2015					

Figure 21 shows these charts for the 15-year spill rate period. During this time, there was a relative decrease in the number of spills <10 bbl. The 50-999 bbl category made up much of the difference, accounting for over half of the spilled fluid volume (removing DWH). This increase may be attributable to the increased number of minor hurricane-related spills during that time and the change in reporting of passive spills. Table 16 lists the numeric values for these charts.

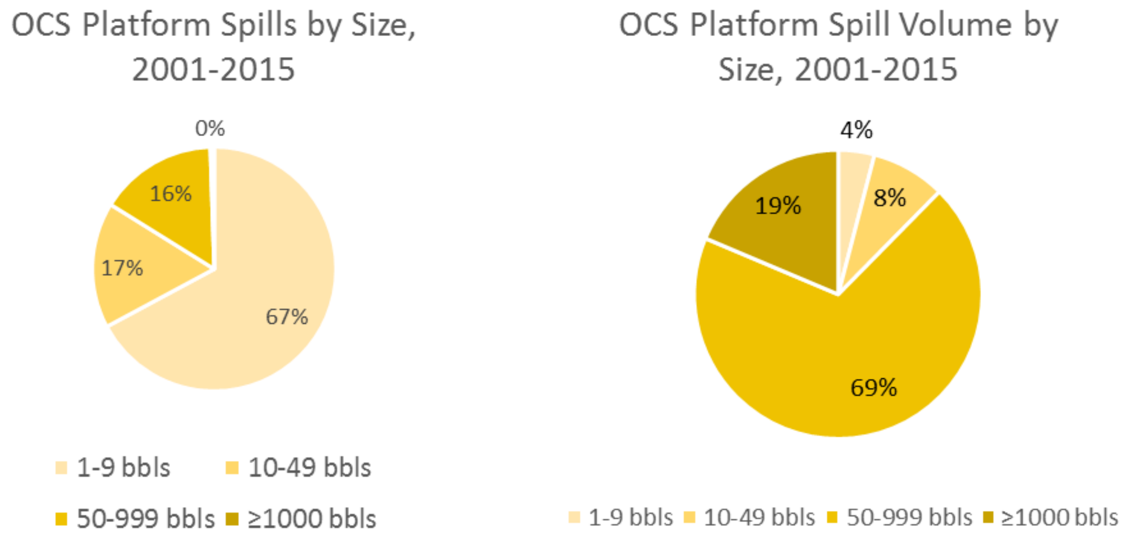

Figure 21. Platform Spill Distribution (Number and Volume) by Spill Size Category, 2001-2015

Table 16. Platform Spill Distribution by Spill Size Category, 2001-2015

Spill Size 2001-2015	Number of Spills	bbl Spilled	Average Spill Size (bbl)	% Spills ≥1 bbl	% Volume ≥1 bbl
1-9 bbl	395	1,101.5	2.8	67.2%	4.1%
10-49 bbl	98	2,265.3	23.1	16.7%	8.3%
50-999 bbl	92	18,718.8	203.5	15.6%	68.9%
≥1000 bbl	3	5,065.7	1,688.6	0.5%	18.7%
Total	588	27,151.3	1,917.9	100.0%	100.0%
Source: U.S. DOI/BSEE OCS Spill Database, December 2015					

5. Pipeline Spill Analysis

From 1964 to 2015, the O&G industry produced over 20.6 Bbbl of crude oil in the U.S. OCS. In addition, Anderson *et al*. estimate that 95% of all crude oil produced in the OCS each year was transported by pipeline (p. 10, 2012). This section summarizes the pipeline spill incidents from the updated spill record; discusses potential exposure variables and causal factors; and presents analysis results of updated spill trends, spill rates, and spill distributions.

5.1. Pipeline Spill Occurrences and Oil Handled

Pipeline spills on the OCS may occur due to corrosion, equipment failure, severe weather, damage to the pipeline by external objects (e.g., anchors), or human error. With updated spill data for the years 2010 to 2015, the analysis team found that OCS pipeline spill rates for large spills have decreased, continuing a trend noted in Anderson *et al*., (2012). Between 2010 and 2015, production on the OCS increased by approximately 3.1 Bbbl of crude oil while no large spills occurred.

A total of 19 OCS pipeline large spills occurred from 1964 to 2015. Figure 22 illustrates that OCS production volume and the number of large spills from OCS pipelines may not have a strong correlation, as production rates per year have tended to increase, while the number of large spills per year has fluctuated. No large spills occurred between 2010 and 2015; however, 16 spills with volumes ≤1,000 bbl did occur, with a total spill volume of about 1,078 bbl.

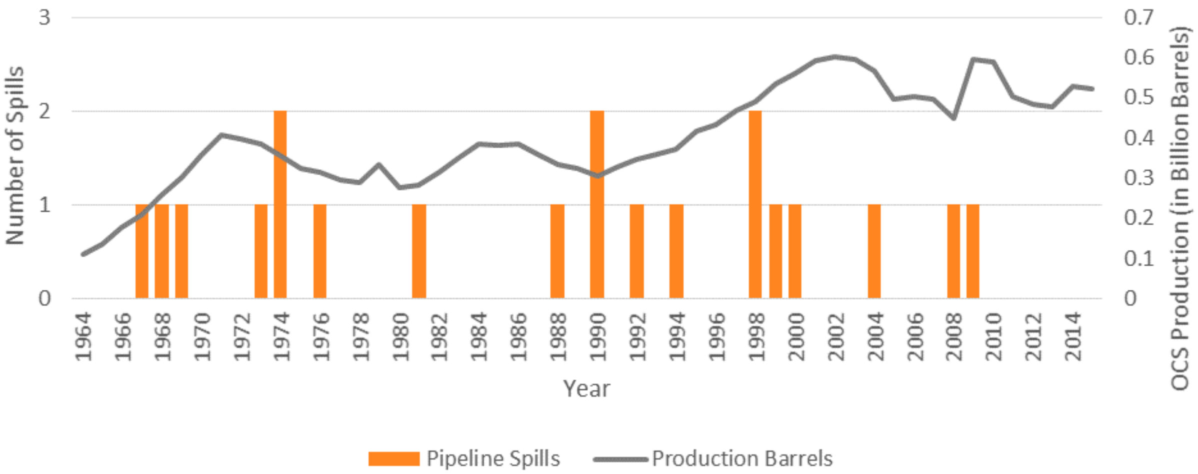

Figure 22. OCS Oil Production vs. OCS Pipeline Large Spills, 1964-2015

The analysis team examined these 16 spills with volumes ≤1,000 bbl, and all had spill volumes between 1 and 400 bbl, with an average spill volume of 46.16 bbl and a median spill volume of 9.25 bbl.

Of the 16 spills, 3 were attributed to Hurricane Ivan, which occurred in the GOM region in 2004. These spills may have been recorded for the years 2010 to 2015 as they were not discovered or corrected until then. It is feasible that Hurricane Ivan damaged the pipelines in 2004, but oil leaked continuously until the pipelines were repaired several years later. The total volume spilled represents an aggregate of all oil spilled over that period of time. This could also be a data quality issue, in which the spills were inaccurately attributed to Hurricane Ivan. Spills caused by Hurricane Ivan accounted for only 13.6 bbl, or 1.26%, of the 1,078 bbl spilled from 2010 to 2015. If these data are inaccurate, the analysis team believes that their effect on the findings of this section will be minimal.

Table 17 provides greater detail on the large spills from OCS pipelines from 1964 to 2015. The majority of these spills were caused by vessels or hurricanes. Spills that involved a platform toppling and disconnecting from a pipeline were typically labeled as platform spills, not pipeline spills; therefore, the analysis team did not focus on that type of spill incident. Corrosion and equipment failure caused 2 of the 19 spills, while hurricanes caused 4, and vessel-induced damages caused the remaining 13.

Table 17. Large (≥1,000 bbl) OCS Pipeline Spills, 1964-2015

Spill Date	Planning Area[1] Block Number	Water Depth (feet)	Miles to Shore	Volume Spilled (bbl)	Operator	Pipeline Segment (Pipeline Authority[2]) Cause/Consequences of Spill
10/15/1967	WD 73	168	22	160,638	Humble Pipe Line	12" oil pipeline Seg #7791 (DOT), anchor kinked, corrosion, leak
3/12/1968	ST 131	160	28	6,000	Gulf Oil	18" oil pipeline Seg #3573 (DOT), barge anchor damage
2/11/1969	MP 299	210	17	7,532	Chevron Oil	4" crude/gas pipeline Seg #3469 (DOT), anchor damage
5/12/1973	WD 73	168	22	5,000	Exxon Pipeline	16" gas and oil pipeline Seg #807 (DOT), internal corrosion, leak
4/17/1974	EI 317	240	75	19,833	Pennzoil	14" oil Bonita pipeline Seg #1128 (DOI), anchor damage
9/11/1974	MP 73	141	9	3,500	Shell Oil	8" oil pipeline Seg #36 (DOI), Hurricane Carmen broke tie-in to 12" pipeline, minor contacts to shoreline, brief cleanup response in Chandeleur Area
12/18/1976	EI 297	210	17	4,000	Placid Oil	10" oil pipeline Seg #1184 (DOI), trawl damage to tie-in to 14" pipeline
12/11/1981	SP 60	190	4	5,100	Atlantic Richfield	8" oil pipeline Seg #4715 (DOT), workboat anchor damage
2/7/1988	GA A002	75	34	15,576	Amoco Pipeline	14" oil pipeline Seg #4879 (DOT), damage from illegally anchored vessel
1/24/1990	SS 281	197	60	14,423[3]	Shell Offshore	4" condensate pipeline Seg #8324 (DOI), anchor damage to subsea tie-in
5/6/1990	EI 314	230	78	4,569	Exxon	8" oil pipeline Seg #4030 (DOI), trawl damage
8/31/1992	PL 8	30	6	2,000	Texaco	20" oil pipeline Seg #4006 (DOT), Hurricane Andrew, loose rig Treasure 75 anchor damage, minor contacts to shoreline, brief cleanup response
11/16/1994	SS 281	197	60	4,533[3]	Shell Offshore	4" condensate pipeline Seg #8324 (DOI), trawl damage to subsea tie-in

Spill Date	Planning Area[1] Block Number	Water Depth (feet)	Miles to Shore	Volume Spilled (bbl)	Operator	Pipeline Segment (Pipeline Authority[2]) Cause/Consequences of Spill
1/26/1998	EC 334	264	105	1,211[3]	Pennzoil E & P	16" gas and condensate pipeline Seg #11007 (DOT), anchor damage to tie-in to 30" pipeline, anchor dragged by vessel in man overboard response
9/29/1998	SP 38	108	6	8,212	Chevron Pipe Line	10" gas and oil pipeline Seg #5625 (DOT), Hurricane Georges, mudslide damage, small amount of oil contacted shoreline
7/23/1999	SS 241	133	50	3,200	Seashell Pipeline	12" oil pipeline Seg #6462 and Seg #6463 (DOT), "Luke David" jack-up rig barge crushed pipeline when sat down on it
1/21/2000	SS 332	435	75	2,240	Equilon Pipeline	24" oil pipeline Seg #10903 (DOT), anchor damage from MODU under tow
9/15/2004	MC 20	479	19	1,720	Taylor Energy	Passive spill - 6" oil pipeline Seg #7296 (DOI), Hurricane Ivan, mudslide damage
9/13/2008	HI A264	150	73	1,316	HI Offshore System	Passive spill - 42" gas/condensate pipeline Seg #7364 (DOT), Hurricane Ike, anchor damage parted pipeline
7/25/2009	SS 142	60	30	1,500	Shell Pipe Line	20" oil pipeline Seg #4006 (DOT), micro-fractures from chronic contacts at pipeline crossing caused failure (separators between pipelines missing)

NOTES: Crude oil release unless otherwise noted; no spill contacts to land unless otherwise noted. OCS - submerged lands, subsoil, and seabed administered by U.S. Federal Government

[1] Planning Area in GOM unless otherwise noted. GOM Planning Areas: EC East Cameron, EI Eugene Island, GA Galveston, HI High Island, MC Mississippi Canyon, MP Main Pass, PL South Pelto, SS Ship Shoal, SP South Pass, ST South Timbalier, WD West Delta. GOM Planning Area Maps http://www.boem.gov/GOMR-GIS-Data-and-Maps/

[2] Pipeline Authority: DOI, BSEE/BOEM; DOT, PHMSA

[3] Condensate

Source: U.S. DOI/BSEE OCS Spill Database, December 2015

Table 18 shows spill rates over 5-year to 10-year periods from the start of the OCS pipeline spill record. From 1964 to 1970, spill data were only available for spills ≥50 bbl. By 1971, comprehensive data for spills ≥1 barrel were incorporated into the spill record. The analysis team studied spill rates for intervals for 1964 to 1970 and 1971 to 1975 to reflect these points in the spill record. After 1975, all spill rate intervals are for 10-year periods until 2015.

The second column in Table 18 (bbl spilled per Bbbl produced) shows a downward trend across the three intervals from 1964 to 1985, followed by an increase from 1986 to 1995. The last two intervals from 1996 to 2015 show another downward trend, with the final interval from 2006 to 2015 reaching the lowest spill rate of 1,108 bbl spilled per Bbbl produced. Over the entire OCS pipeline spill record, an average of 13,894 bbl of oil have been spilled for every Bbbl of oil produced. The volume of bbl spilled across the time intervals displayed a similar trend.

Table 18. OCS Pipeline Spill Rate and Spill Volume Trends Based on Oil Produced, 1964-2015

Years	bbl Spilled per Bbbl Produced	bbl Produced per bbl Spilled	Production (Bbbl)	bbl Spilled by Spill Size			Number of Spills by Spill Size		
				1-999 bbl	≥1,000 bbl	Total	1-999 bbl	≥1,000 bbl	Total
1964-1970[1]	113,246	8,830	1.54	741	174,170	174,911	12	3	15
1971-1975	15,682	63,766	1.87	958	28,333	29,291	94	3	97
1976-1985	3,894	256,780	3.22	3,443	9,100	12,543	144	2	146
1986-1995	12,232	81,752	3.53	2,036	41,101	43,137	75	5	80
1996-2005	4,227	236,549	5.34	5,990	16,583	22,573	119	5	124
2006-2015	937	1,067,233	5.14	2,002	2,816	4,818	50	2	52
Total[2]	**13,918**	**71,850**	**20.6**	**15,170**	**272,103**	**287,273**	**494**	**20**	**514**

[1] Spill data for 1964 to 1970 are for spills ≥50 bbl. Spill data for spills ≥1 bbl begin in 1970 but are more robust starting in 1971.

Sources: U.S. DOI/BSEE OCS Spill Database, December 2015 (Spills); U.S. DOI/ONRR OCS Production Data, December 2015 (Production)

5.2. Pipeline Exposure Units and Causal Factors

This section presents analyses of alternative exposure variables and causal factors. Table 19 introduces and describes potential alternative exposure variables for assessing pipeline spill frequencies.

Table 19. Pipeline Exposure Metrics

Exposure Metric	Feasibility	Relevance	Comments
Oil Volume Produced	**High**	**Medium**	Existing metric. Estimated from BSEE production data. Does not exclude production sent to shore via tanker.
Pipeline Segment-years	**High**	**High**	Estimated from BSEE pipeline data. Comparable interpretation to other count metrics such as platform or rig counts.
Pipeline Foot-years	**High**	**High**	Estimated from BSEE pipeline data. Intuitive physical risk interpretation.
Oil Volume Transported	**Low**	**Medium**	The analysis team did not locate sufficient data to estimate this metric.

The pipelines segment years variable can be interpreted similarly to the platform's structure years variable. They both are physical objects associated with OCS O&G activity that can be counted: platforms for production and pipelines for transport. Table 20 lists spill rates for all spill sizes over 1 bbl using pipeline segment year as its exposure variable. The bbl per segment-year column indicates a dramatic decrease in the volume spill rate. However, the number of segment-years also grows substantially during this time, suggesting a noncausal confounding effect as many unused pipelines deflate the estimate of rates.

Table 20. OCS Pipeline Spill Rate and Spill Volume Trends Based on Segment Years, 1964-2015

Years	bbl Spilled per Segment Years (10,000s)	Segment Years (10,000s)	bbl Spilled by Spill Size			Number of Spills by Spill Size		
			1-999 bbl	≥1,000 bbl	Total	1-999 bbl	≥1,000 bbl	Total
1964-1970[1]	734,612	0.24	741	174,170	174,911	12	3	15
1971-1975	47,504	0.62	958	28,333	29,291	94	3	97
1976-1985	4,293	2.92	3,443	9,100	12,543	144	2	146
1986-1995	7,556	5.71	2,036	41,101	43,137	75	5	80
1996-2005	2,793	8.08	5,990	16,583	22,573	119	5	124
2006-2015	573	8.41	2,002	2,816	4,818	50	2	52
Total[2]	**11,057**	**26.0**	**15,170**	**272,103**	**287,273**	**494**	**20**	**514**

[1] Spill data for 1964 to 1970 are for spills ≥50 bbl. Spill data for spills ≥1 bbl begin in 1970 but are more robust starting in 1971.

Sources: U.S. DOI/BSEE OCS Spill Database, December 2015 (Spills); U.S. DOI/BSEE Data Center, December 2015 (https://www.data.bsee.gov/homepg/data_center/pipeline/pipeline.asp) (Pipeline Years)

5.2.1. Causal Factors

Pipeline spills can be attributed to causal factors such as corrosion, equipment failure, severe weather, or human error. The analysis team developed five categories to summarize causal factors of OCS pipeline spills:

- **Equipment Failure.** Spills caused by mechanical or structural failure of equipment used to control or contain oil in a pipeline
- **External Forces.** Spills caused by non-natural forces, such as human errors or failures in attached platform equipment
- **Corrosion**. Spills caused by parts of the pipeline corroding to the extent that they fail to contain oil
- **Weather/Natural Causes.** Spills caused by severe weather, such as hurricanes, or other natural phenomenon such as mud slides
- **Vessel/Anchor/Trawl Damage.** Spills caused by any part of a vessel or its equipment striking a pipeline and damaging equipment or systems responsible for controlling or containing oil in the pipeline

There may be some overlap between the defined categories. For example, a piece of equipment corroding over time may cause it to fail and spill oil from the pipeline. Such incident descriptions in the data would most likely include both the key words “corrosion” and “equipment failure.” For larger spills (≥1,000 bbl), the analysis team reviewed each spill description and categorized the spill appropriately. There are spills without incident descriptions or that were labeled as unknown. These were excluded from the causal factor analysis.

The analysis team examined large spills in detail. Figure 23 illustrates the percentage of the total OCS pipeline spill volume for large spills by incident type. External forces caused 37% of large spills, the highest proportion of the causal factors. Equipment failure and vessel-induced damages caused the next highest proportions of spills, with each factor responsible for around one-quarter of large spills. Weather, natural causes, and corrosion cumulatively caused less than 15% of large spills.

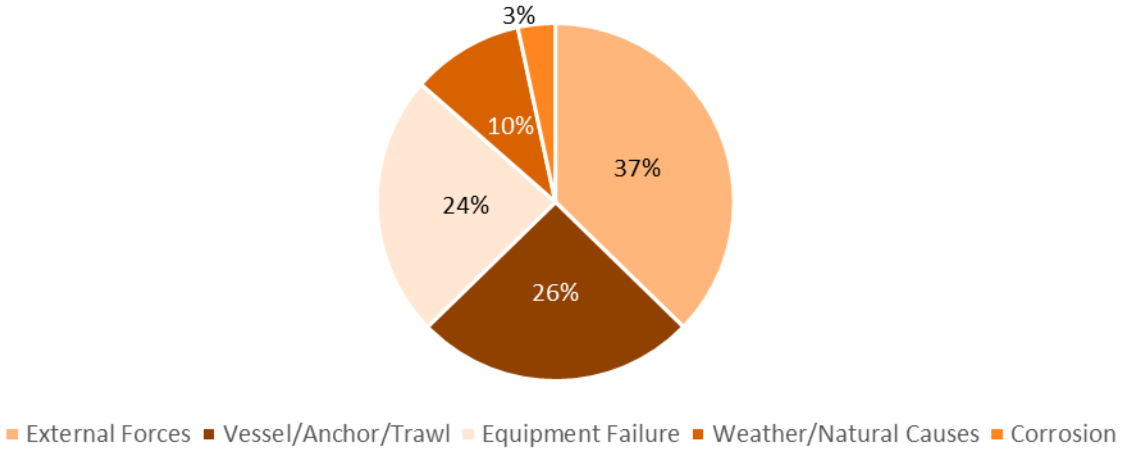

Figure 23. OCS Pipeline Large Spill Causal Factor Summary

Figure 24 details the changing pattern of causal factors over time for all spills ≥1 bbl. To maintain the one-to-one relationship between causal factor values in Figure 24 and the number of spills recorded for each year, the figure normalizes the counts so that the aggregate causal factor counts are equal to the spill counts each year. The analysis also found that for all spills ≥1 bbl, equipment failures tended to cause the most spills early in the record while weather and external force causes became more prevalent late in the record.

Figure 24 also shows that the number of spills caused by weather or natural phenomenon increases substantially around the years 2004, 2005, and 2008. The 2004 and 2005 spikes can be attributed to GOM hurricanes: Ivan (2004), Katrina (2005), and Rita (2005). The spikes for spills caused by external forces for these same years may correlate to the occurrences of the hurricanes. Operators may have accidently spilled oil while attempting to prepare a pipeline for severe weather, or platform equipment may have failed and affected the pipeline as a result of the severe weather.

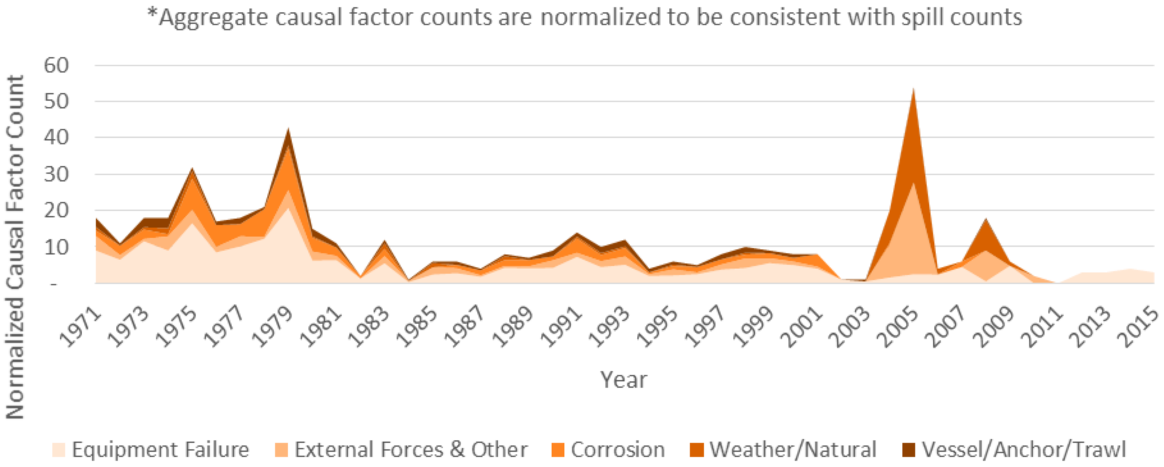

Figure 24. OCS Pipeline Spill Causal Factor Summary

Figure 25 illustrates the percentage of spills attributed to each casual factor across different spill size categories. No discernable trends for equipment failures, external forces, corrosion, or weather and natural phenomenon can be seen as spill volumes increase. The percentages of spills for each of these factors tend to change as spill volume increases. Alternatively, the percentage of spills caused by vessel-induced damage tends to increase as spill volume increases.

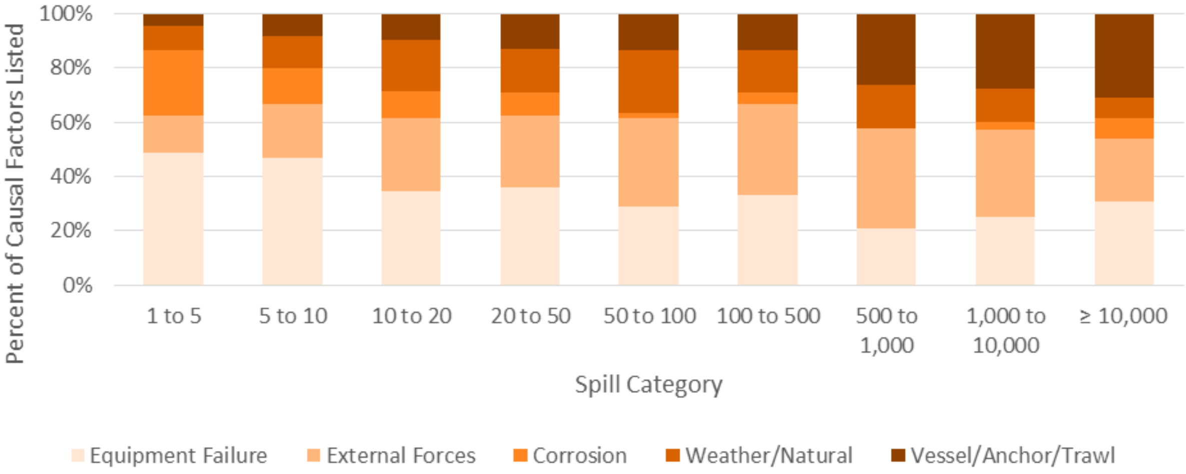

Figure 25. OCS Pipeline Spill Casual Factor Summary by Spill Size Category

5.2.2. Hurricanes

The analysis team studied the impact that hurricanes had on spill frequency and spill volume. Hurricanes caused 3 of the 19 large spills that occurred from 1964 to 2015. Figure 26 depicts the number of spills >1 barrel that have occurred from 1971 to 2015, with the spills categorized as either operational or hurricane. Confirming the findings in Figure 24, pipeline spills caused by hurricanes increased in frequency for the years 2004, 2005, and 2008. While the number of spills caused by hurricanes each year appears random, the number of operational spills per year appears to follow a downward trend. The majority of spills in the last 15 years were caused by hurricanes.

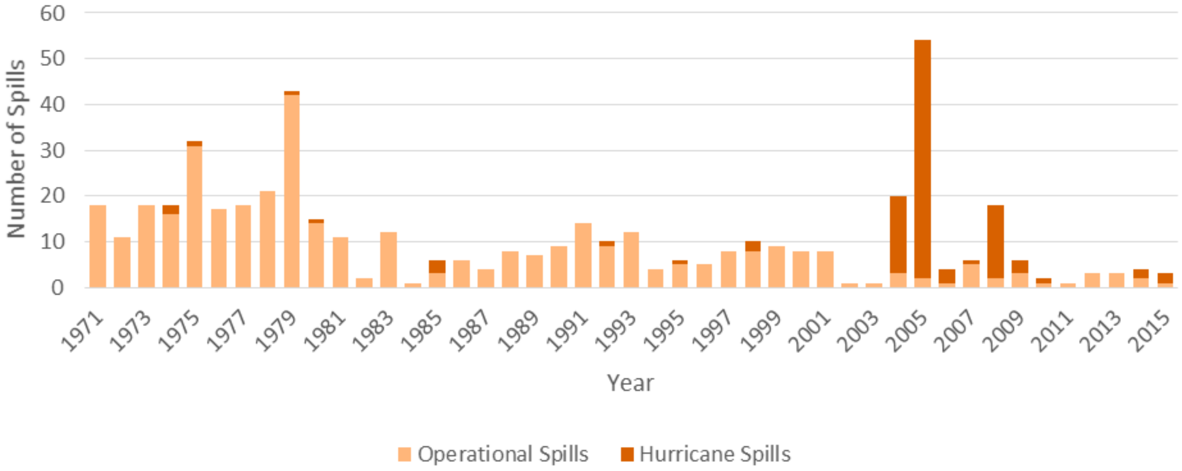

Figure 26. OCS Pipeline Spill Hurricane and Operational Summary

Figure 27 shows the percentage of spills caused by operational or hurricane incidents for different spill size categories. Based on spill size, no clear trend appears to exist for the percentages of spills caused by hurricanes. Hurricanes tend to cause a greater percentage of spills in larger spill size categories than smaller ones; however, the fluctuations across all spill size categories indicate that a strong relationship does not exist.

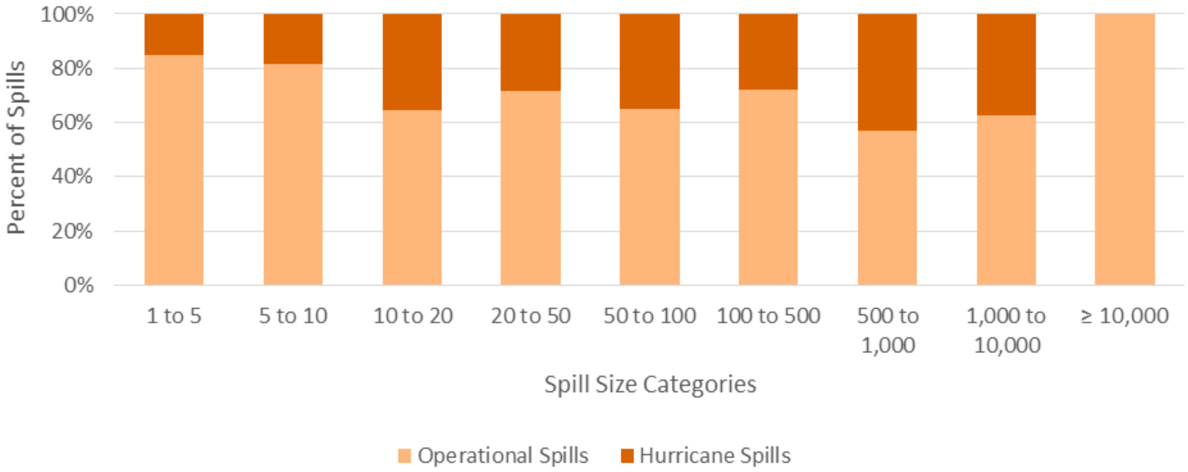

Figure 27. OCS Pipeline Spill Hurricane and Operational Summary by Spill Size Category

The analysis team excluded the pipeline spills caused by hurricanes to examine trends in the other causal factors. Hurricane damage to pipelines can be difficult to predict and control for. Studying causal factors that can be regulated, such as equipment failures, may provide new insights in pipeline spill trends.

Figure 28 illustrates that equipment failures caused a majority of spills over the years. From 1971 until 2002, equipment failures and corrosion were responsible for almost all spill incidents. From 2002 to 2015, equipment failures were responsible for most of the spill incidents. The overall number of spill incidents per year trended downward after an increase in 1979.

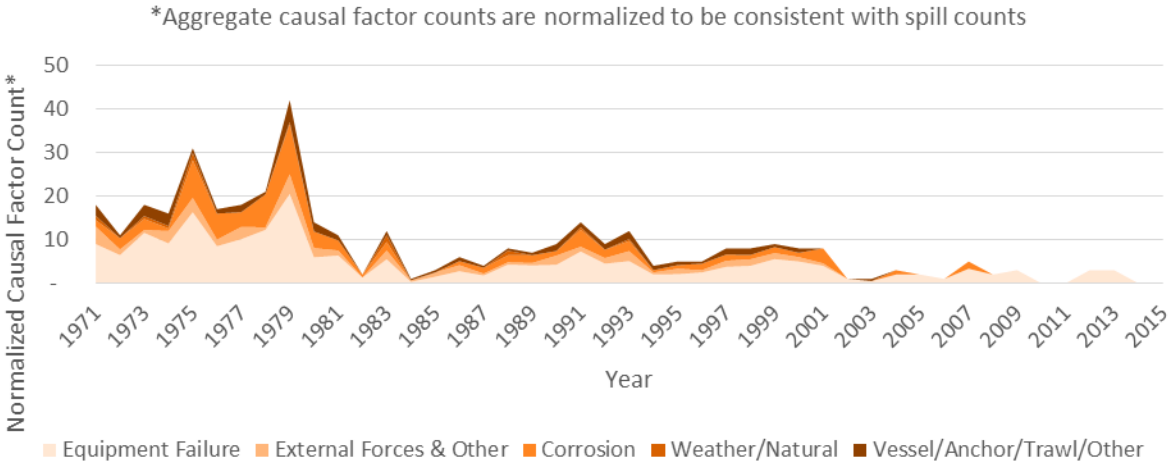

Figure 28. OCS Pipeline Spill Causal Factors Summary – Excluding Hurricanes

5.3. Pipeline Trend Analysis

The section will identify periods of time over the entire pipeline spill record in which significant trends in spill rates can be detected. An accurate trend analysis can illustrate how spill rates have changed over time and can inform how they may continue to behave. Figure 29 illustrates OCS pipeline spill occurrences for every 0.5 Bbbl of OCS oil production. The 2012 spill rates report noted that roughly 95% of all oil produced on the OCS each year was transported via pipeline (Anderson, Mayes and LaBelle). Therefore, studying the number of spills that occur over fixed production volumes may better inform increases or decreases in pipeline spill rates.

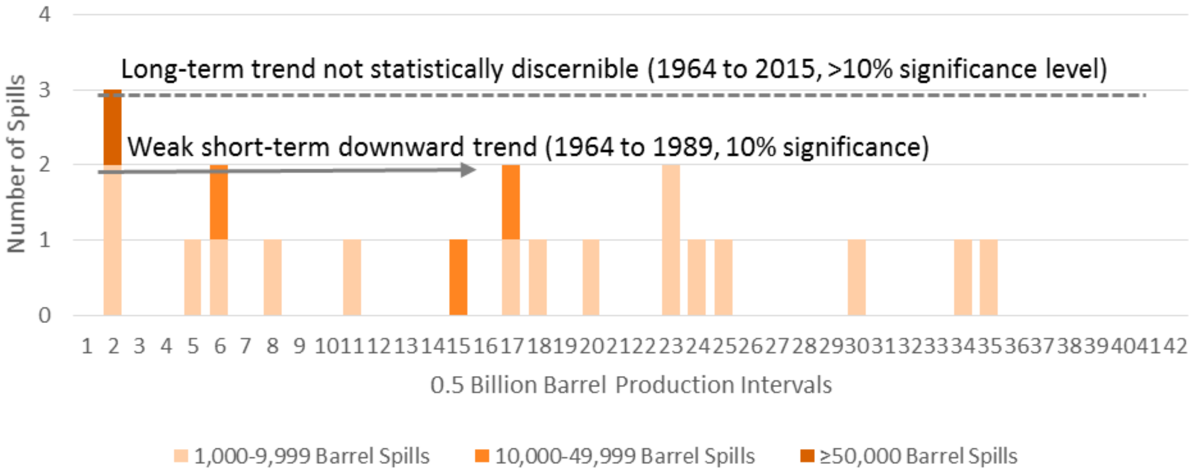

Figure 29. OCS Pipeline Spills over 0.5 Bbbl Production Intervals

Figure 29 shows that the number of spills per 0.5 Bbbl of oil produced has exhibited very little trend since 1964. Applying Kendall's test iteratively across many different intervals did not identify any major trends. Over the whole period, no statistical trend was discernible. The interval with the strongest trend identified using Kendall's test was from 1964 to 1989. Although this might imply that the remaining period, from 1990 to 2015, is the best period to use for calculating rates, the general conclusion of this analysis was that the pipeline data exhibited no compelling trends.

This conclusion was also supported by the results of the runs-up, runs-down test and the Spearman Rank correlation tests, which confirmed that the spills appeared to be independent. The test statistic for the runs-up, runs-down test was 11 runs among 20 observations. The Spearman rank correlation was 0.269. Both of this statistics suggested that the spills were independent events.

5.4. Pipeline Spill Rates

This section includes calculated rates based on the oil handled exposure variable as well as an alternative exposure variable (pipeline segment years).

5.4.1. Pipeline Base Spill Rates

The analysis team studied previous pipeline spills rates from the 2012 report, which included data from 1990 to 2010, and updated the production volumes, spill occurrences, and spill rates with data through 2015. Over the past five years, the spill rate has decreased since 2.5 Bbbl of additional oil were handled without any large spill occurrences.

Table 21 summarizes the pipeline spill rates from the previous report, the current report, and the last 15 years. Anderson *et al*. (2012) estimated the spill rate to be 0.94 large spills per Bbbl, while the updated spill rate estimates 0.89 spills ≥1,000 bbl per Bbbl produced. For pipeline spills ≥10,000 bbl, the spill rate decreased between the previous rate and the updated rate, with no such spills occurring between 2010 and 2015. Over the last 15 years, from 2001 to 2015, the spill rate for spills ≥1,000 bbl was estimated at 0.38 spills per Bbbl produced.

Table 21. OCS Pipeline Spill Rate Estimates for Updated Spill Record

	Previous Rate: 1990-2010[1,2]			**Updated Rate: 1974-2015**			**15-year Rate: 2001-2015**		
Spill Size and Source	**Volume Handled (Bbbl)**	**# of Spills**	**Spill Rate**	**Volume Handled (Bbbl)**	**# of Spills**	**Spill Rate**	**Volume Handled (Bbbl)**	**# of Spills**	**Spill Rate**
Including Hurricanes									
≥1,000 bbl	9.6	9	0.94	17.9	16	0.89	8.00	3	0.38
≥10,000 bbl	9.6	0	0.19	17.9	3	0.17	8.00	0	0.07[3]
Excluding Hurricanes									
≥1,000 bbl				17.9	10	0.56	8.0	0	--.--
≥10,000 bbl				17.9	3	0.17	8.0	0	--.--
[1] Anderson *et al*. (2012)									
[2] The previous report uses production intervals 18 through 37 (Figure 29) as the rate period. This is approximately 1991 to 2010.									
[3] Assume that the same ratio of spills ≥10,000 bbl to spills ≥1,000 bbl applies to this period as to the full record.									
Sources: U.S. DOI/BSEE OCS Spill Database, December 2015 (Spills); U.S. DOI/ONRR OCS Production Data, December 2015 (Production)									

Without records attributed to hurricanes, the spill rate for large spills drops from 0.84 to 0.58 spills per Bbbl produced. The rate of spills ≥10,000 bbl was not affected by excluding hurricane-caused spills, as no such incidents occurred in the spill record.

Table 22 lists confidence intervals for these rates. The intervals are calculated using the bootstrap method due to the small number of spills.

Table 22. OCS Pipeline Spill Rate Confidence Intervals for Updated Spill Record

Spill Size and Source	Full Record Rate: 1974-2015			15-year Rate: 2001-2015		
	Lower Bound (95% Confidence)	Spill Rate	Upper Bound (95% Confidence)	Lower Bound (95% Confidence)	Spill Rate	Upper Bound (95% Confidence)
Including Hurricanes						
≥1,000 bbl	0.50	0.89	1.28	0.00	0.38	0.88
≥10,000 bbl	0.00	0.17	0.34		0.07[1]	
Excluding Hurricanes						
≥1,000 bbl	0.28	0.56	0.89	--.--	--.--	--.--
≥10,000 bbl	0.00	0.17	0.34	--.--	--.--	--.--

[1] Data do not support confidence interval calculation for spills ≥10,000 bbl.

5.4.2. Pipeline Alternative Exposure Variable Rate

Table 23 provides updated rate calculations using the segment years alternative exposure variable, comparing the updated rate with the 15-year. The rates are shown for ≥1,000 bbl and ≥10,000 bbl, including and excluding hurricane spills.

Table 23. OCS Pipeline Spill Rate Estimates for Updated Spill Record

Spill Size and Source	Updated Rate: 1974-2015			15-year Rate: 2001-2015		
	Segment-years (10,000s)	# of Spills	Spill Rate	Segment-years (10,000s)	# of Spills	Spill Rate
Including Hurricanes						
≥1,000 bbl	25.4	16	0.63	12.7	3	0.24
≥10,000 bbl	25.4	3	0.12	12.7	0	--.--
Excluding Hurricanes						
≥1,000 bbl	25.4	10	0.39	12.7	0	--.--
≥10,000 bbl	25.4	3	0.12	12.7	0	--.--

Source: U.S. DOI/BSEE OCS Spill Database, December 2015 (Spills); U.S. DOI/BSEE Data Center, December 2015 (https://www.data.bsee.gov/homepg/data_center/pipeline/pipeline.asp) (Pipeline Years)

5.5. Pipeline Spill Distributions

The analysis team mapped pipeline spills into spill size categories to study the distribution of a sufficient number of spills with relatively uniform spill volumes. For example, small spills with many occurrences in the spill record could be grouped together in a spill size category with a range of 1 to 10 bbl. For larger spills with fewer occurrences in the spill record, the analysis team had to widen the range of spill volumes for the spill size category, such as spills within a range of 50 to 1,000 bbl. This ensured that a sufficient number of spills were grouped into these categories for a statistically reliable analysis.

5.5.1. Pipeline Spill Volume Estimates

The spill rates calculated in section 5.4 are based on 16 spills occurring since 1974. Table 24 describes the magnitude of these spills, providing the average and median spill sizes. Pipeline spills in recent history have been smaller on average.

Table 24. OCS Pipeline Spill Counts and Average and Median Spill Sizes

Spill Source	Entire Record			Last 15 Years		
	# of Spills	Average Spill Size (bbl)	Median Spill Size (bbl)	# of Spills	Average Spill Size (bbl)	Median Spill Size (bbl)
All Spills	16	5,808	3,750	3	1,512	1,500
Excluding Hurricanes	10	7,469	4,551	0	N/A	N/A
Hurricanes Only	6	3,041	1,860	3	1,512	1,500
Source: U.S. DOI/BSEE OCS Spill Database, December						

Table 25 provides estimates of the average and median spills over the last 15 years for each spill size category. The pipeline spill distribution is slightly less skewed toward small spills. While about 65% of platform spills are between 1 and 5 bbl, only 53% of pipeline spills fall within this range. Expected spill amounts within each spill size category are similar.

Table 25. OCS Pipeline Spill Distribution Statistics by Spill Size Category, 2001-2015

Spill Size	# of Spills	bbl Spilled	Average Spill Size (bbl)	Median Spill Size (bbl)
≥1 to <5 bbl	59	137.2	2.33	4.3
≥5 to <10 bbl	18	121.1	6.73	
≥10 to <20 bbl	22	284.8	12.95	
≥20 to <50 bbl	13	365.4	28.11	
≥50 to <100 bbl	8	565	70.66	108
≥100 to <500 bbl	10	1,952	195.24	
≥500 to <1,000 bbl	3	2,493	831.00	
≥1,000 to <2,000 bbl	3	4,536	1,512.00	1,500
≥2,000 to <3,000 bbl	-	-	--.--	
≥3,000 to <10,000 bbl	-	-	--.--	
≥10,000 bbl	-	-	--.--	None
All Spills	**136**	**10,455**	**76.88**	**5.0**
Source: U.S. DOI/BSEE OCS Spill Database, December				

5.5.2. Changes in the Pipeline Spill Volume Distribution

This section compares the distribution of spills observed in the full record versus the 15-year rate. Figure 30 compares the spill counts to the spill volumes of various spill size categories in the full record time period. The total spilled volume during the full record time period is dominated by large spills. Of the 107,000 bbl spilled from 1974 to 2015, roughly 86.5% came from the 16 spills that were ≥1,000 bbl in size. Conversely, only about 1% of that total volume came from the 305 spills between 1 and 9 bbl in size. Table 26 lists the numerical values presented in these charts.

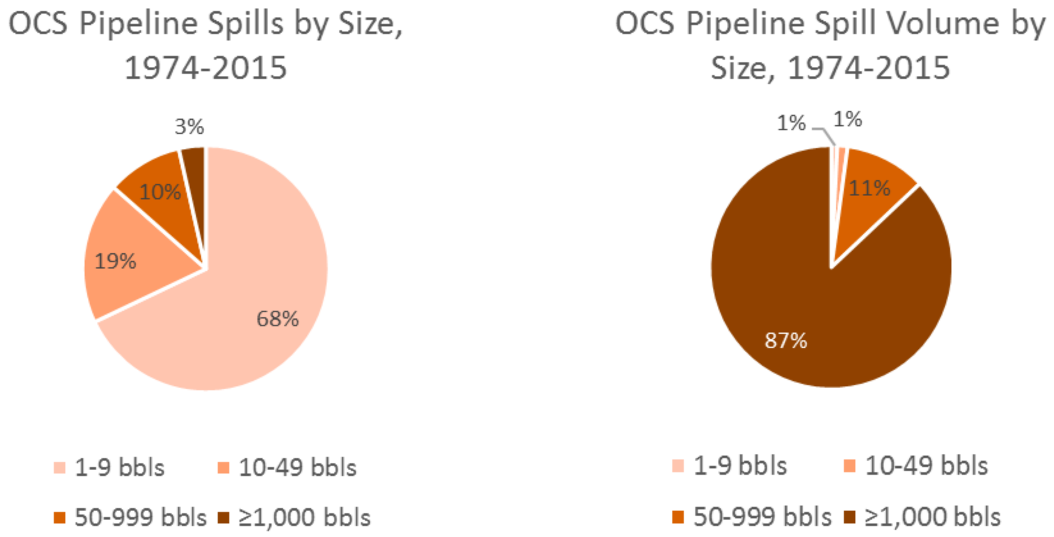

Figure 30. OCS Pipeline Spill Distribution (Number and Volume) by Spill Size Category, 1974-2015

Table 26. OCS Pipeline Spill Distribution by Spill Size Category, 1974-2015

Spill Size 1971-2015	# of Spills	bbl Spilled	Average Spill Size (bbl)	% Spills >=1 bbl	%Volume >=1 bbl
1-9 bbl	307	835.4	2.7	67.9%	0.8%
10-49 bbl	84	1,455.9	17.3	18.6%	1.4%
50-999 bbl	45	11,534.2	256.3	10.0%	10.8%
≥1000 bbl	16	92,933.0	5,808.3	3.5%	87.0%
Total	452	106,758.5	6,084.7	100.0%	100.0%

Source: U.S. DOI/BSEE OCS Spill Database, December 2015

Comparing Figure 31 for the 15-year rate to the full record rate, the number of large spill occurrences and the total volume dropped significantly as a percent of total. When compared to the 1974 to 2015 distribution, the 50-999 category makes up a much larger percentage of the spilled volume. This primarily is due to the absence of large spills in recent history and may signify the impact of improved technology on modern pipelines. Table 27 lists the numerical values for the charts.

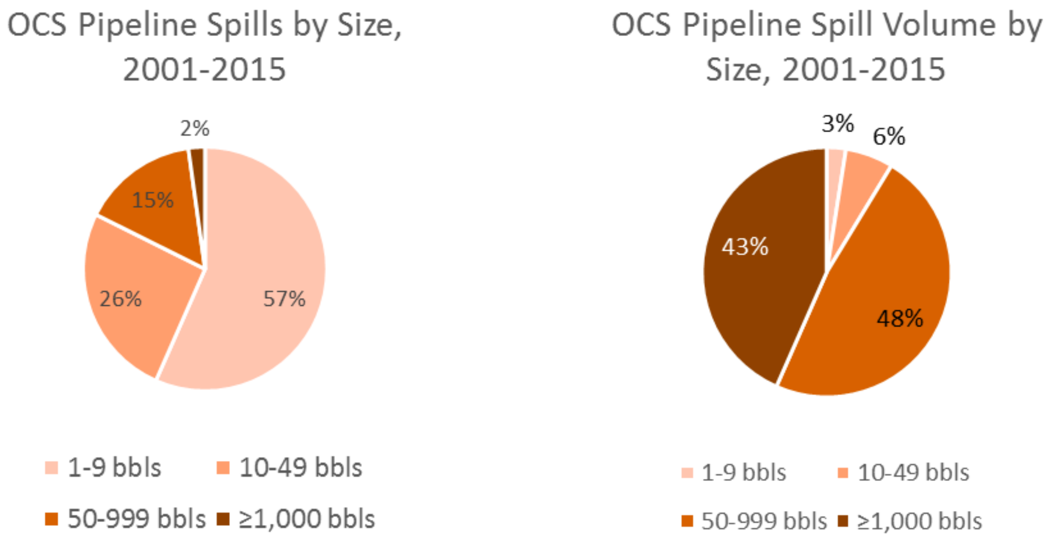

Figure 31. OCS Pipeline Spill Distribution (Number and Volume) by Spill Size Category, 2001-2015

Table 27. OCS Pipeline Spill Distribution by Spill Size Category, 2001-2015

Spill Size 2001-2015	# of Spills	bbl Spilled	Average Spill Size (bbl)	% Spills ≥1 bbl	%Volume ≥1 bbl
1-9 bbl	77	258.3	3.4	56.6%	2.5%
10-49 bbl	35	650.2	18.6	25.7%	6.2%
50-999 bbl	21	5,010.7	238.6	15.4%	47.9%
≥1000 bbl	3	4,536.0	1,512.0	2.2%	43.4%
Total	**136**	**10,455.2**	**1,772.5**	**100.0%**	**100.0%**
Source: U.S. DOI/BSEE OCS Spill Database, December 2015					

6. Tanker and Barge Spill Analysis

The portion of offshore production that is not shipped to shore via pipeline is transported via tanker or barge. This is a small portion of total crude traffic and is difficult to isolate for the purpose of developing spill rates. Instead this report considers several different tanker and barge populations worldwide and their spill records. Worldwide tanker and barge oil handled levels are far higher than those on the OCS. From 1974 to 2014, tankers worldwide handled almost 360 Bbbl of crude oil. In the U.S. alone, tankers transported about 70 Bbbl in that same timeframe. Petroleum barges transported about 11 Bbbl of crude oil in the U.S. from 1974 to 2014. This section examines spills, identifies trends, and develops spill rates for tankers and barges.

6.1. Tanker and Barge Spill Occurrences and Oil Handled

This section reviews the spill data for worldwide tankers, tankers operating in U.S. waters, ANS tankers, and barges operating in U.S. waters.

6.1.1. Worldwide Tanker Spills

Oil spills from tankers or barges may be caused by groundings, collisions, or other incidents in which the hull of the vessel is damaged and leaks oil. They may also be caused when oil is improperly handled as it is loaded or unloaded. The analysis team collected international exposure data and tanker spill data from 2009 to 2014 and limited the scope to include crude oil only. The analysis team then analyzed the worldwide tanker spill record to eliminate duplicate entries and ensure data quality. During this process, the analysis team discovered a small number of duplicate spills. For example, spills that occurred when two vessels collided could be logged in the spill record twice – one record for each vessel involved. To maintain an assumed Poisson distribution, these spills are considered as a single spill.

Table 28 summarizes worldwide tanker spills from 1974 to 2014 based on spill size category and spill location spill: in port or at sea. A total of 301 large spills occurred from 1974 to 2014, although the number of spills per year has decreased in the last 15 years. For the updated spill record from 2009 to 2014, four additional spills were identified and the annual volume of oil handled remained relatively consistent (between 13.7 and 14.2 Bbbl per year). The mode and size of the three newly identified 2014 spills could not be determined in the source data. As such they are assumed to be between 1,000 and 10,000 bbl. The new average spill rate over the entire record was 0.679 spills per Bbbl handled.

Across all spill size categories, spills tended to occur more frequently at sea than in port, except for spills between 1,000 and 9,999 bbl in volume. Overall, 163 of those occurred at sea, and 138 occurred in port. For spills with a volume between 10,000 and 99,999 bbl, a total of 93 spills occurred. About 67% occurred at sea, while about 33% occurred in port. Spills ≥100,000 bbl in volume followed a similar pattern. Of the 60 total spills ≥100,000 bbl, 67% occurred at sea and 33% occurred in port. For spills between 1,000 and 9,999 bbl in volume, the pattern was almost reversed. Only 61 of the 145 spills, or 41% of the total, occurred at sea, and the remaining 87 spills, or 59% of the total, occurred in port.

Table 28. Worldwide Tanker Spill Summary, 1974-2014

		Spills In Port			Spills At Sea			Crude Oil Handled (Bbbl)	Spills per Bbbl
Year	Spills	1K-9.99K bbl	10K-99.99K bbl	≥100K bbl	1K-9.99K bbl	10K-99.99K bbl	≥100K bbl		
1974	20	8	2	1	5	2	2	10.165	1.968
1975	19	1	1	3	7	4	3	9.330	2.036
1976	20	6	3	1	2	2	6	10.510	1.903
1977	16	2	2	1	3	3	5	10.692	1.496
1978	16	3	1	2	3	4	3	10.480	1.527
1979	22	4	2	3	4	5	4	10.956	2.008
1980	10	1	1	1	3	2	2	9.657	1.036
1981	7	3	1	0	3	0	0	8.535	0.820
1982	8	3	1	1	3	0	0	7.318	1.093
1983	13	4	1	0	1	4	3	6.860	1.895
1984	8	3	3	0	1	1	0	6.845	1.169
1985	5	1	2	0	0	1	1	6.353	0.787
1986	6	3	0	0	0	3	0	7.191	0.834
1987	11	4	1	0	3	3	0	6.762	1.627

		Spills In Port			Spills At Sea				
Year	Spills	1K-9.99K bbl	10K-99.99K bbl	≥100K bbl	1K-9.99K bbl	10K-99.99K bbl	≥100K bbl	Crude Oil Handled (Bbbl)	Spills per Bbbl
1988	10	3	3	0	2	1	1	7.412	1.349
1989	12	2	1	0	1	5	3	8.041	1.492
1990	13	5	0	0	2	5	1	8.707	1.493
1991	10	3	0	2	2	1	2	9.183	1.089
1992	7	2	1	1	2	1	0	9.301	0.753
1993	6	0	1	0	2	1	2	9.873	0.608
1994	8	1	1	1	1	2	2	10.083	0.793
1995	6	3	0	0	2	1	0	10.287	0.583
1996	7	4	0	1	2	0	0	10.618	0.659
1997	7	2	0	1	2	2	0	11.316	0.619
1998	3	3	0	0	0	0	0	11.617	0.258
1999	6	4	0	0	1	1	0	11.567	0.519
2000	2	0	2	0	0	0	0	12.173	0.164
2001	2	1	0	0	1	0	0	12.344	0.162
2002	3	2	0	0	1	0	0	12.217	0.246
2003	1	0	0	1	0	0	0	12.974	0.077
2004	5	3	0	0	1	1	0	13.596	0.368
2005	2	1	0	0	0	1	0	13.819	0.145
2006	2	0	0	0	0	2	0	14.166	0.141
2007	2	0	0	0	0	2	0	14.540	0.138
2008	1	0	0	0	0	1	0	14.439	0.069
2009	0	0	0	0	0	0	0	13.872	--.--
2010	1	0	1	0	0	0	0	13.750	0.073
2011	1	0	0	0	0	1	0	13.888	0.072
2012	0	0	0	0	0	0	0	14.127	--.--
2013	0	0	0	0	0	0	0	13.768	--.--
2014	3	2	0	0	1	0	0	13.754	0.218
Total	**301**	**87**	**31**	**20**	**61**	**62**	**40**	**443.086**	**0.679**

Source: U.S. DOI/BSEE OCS Spill Database, December 2015 (Spills); BP Statistical Review of World Energy (1975-2009) (Oil Handled)

Even though worldwide crude oil movements have tended to increase since the 1980s, the number of large spills from tankers has tended to decrease since the early 1990s (see Figure 32). The analysis found that although crude oil movements increased over time, the number of recorded spills has decreased.

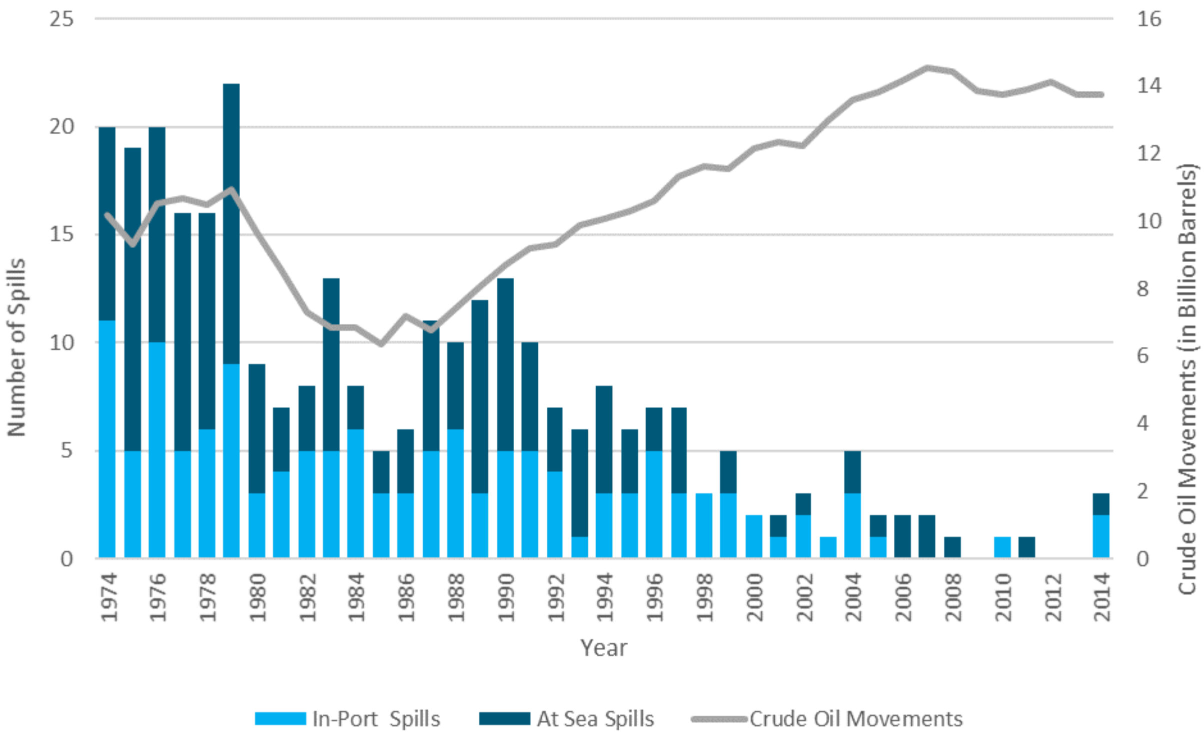

Figure 32. Crude Oil Movements vs. Worldwide Tanker Large Spills

The analysis team found the percentage of spills that occurred at sea or in port each year tended to fluctuate over the entire spill record. Although the total number of spills each year has tended to decrease, the percentage of spills per year based on tanker mode did not appear to change consistently. Overall, more spills have occurred at sea than in port for the entire spill record.

6.1.2. U.S. Waters Tanker Spills

The analysis team next studied the subset of worldwide crude oil spills occurring in U.S. waters. Exposure volumes were estimated based on domestic crude oil transport volumes and crude oil import and export rates, which accounted for foreign tanker transport volumes. The analysis team had only sufficient data to estimate domestic exposure volumes and spill rates through 2013.

Table 29 summarizes domestic tanker spills from the years 1974 to 2013. Import and export volumes were computed by summing the volumes of crude oil imported to and exported from the U.S. The adjusted transport volumes for crude oil were computed by summing the domestic transport volume and 50% of the import and export volume each year. The rationale for this adjustment is that import and export movements spend less than half of their voyage within U.S. waters while domestic movements spend the entire voyage within U.S. waters (Anderson and LaBelle, 2000; Anderson *et al.*, 2012). The analysis team used the adjusted transport volume to calculate the annual spill rates.

The adjusted transport volumes tended to decrease in the last 15 years, with the most rapid rates of decline occurring in the last 5 years. Both the import and export volumes and the domestic transport volumes tended to decrease from 1999 to 2013. From 2008 to 2013, the adjusted transport volume declined by an average of 0.1026 Bbbl per year.

Table 29. Tanker Spills in U.S. Waters Summary, 1974-2013

Year	All Spills	Spills in Port			Spills at Sea			Imports and Exports Bbbl	Domestic Transport Bbbl[1]	Adjusted Transport Bbbl[2]	Spills Per Bbbl
		1K-9.99K bbl	**10K-99.99K bbl**	**≥100K bbl**	**1K-9.99K bbl**	**10K-99.99K bbl**	**≥100K bbl**				
1974	5	3	1	0	1	0	0	1.437	0.221	0.940	5.322
1975	3	1	0	1	1	0	0	1.702	0.173	1.024	2.930
1976	2	2	0	0	0	0	0	2.245	0.149	1.272	1.573
1977	2	1	1	0	0	0	0	2.686	0.204	1.547	1.293
1978	0	0	0	0	0	0	0	2.576	0.594	1.882	0.000
1979	5	3	1	0	0	0	1	2.521	0.639	1.900	2.632
1980	2	0	1	0	1	0	0	2.035	0.842	1.860	1.076
1981	2	1	1	0	0	0	0	1.737	0.875	1.744	1.147
1982	1	0	1	0	0	0	0	1.501	0.937	1.688	0.593
1983	1	1	0	0	0	0	0	1.208	0.990	1.594	0.627
1984	1	0	0	0	0	1	0	1.142	0.922	1.493	0.670
1985	2	1	1	0	0	0	0	1.084	1.002	1.544	1.295
1986	3	3	0	0	0	0	0	1.441	0.994	1.715	1.750
1987	2	0	0	0	1	1	0	1.582	1.061	1.852	1.080
1988	2	1	1	0	0	0	0	1.680	1.004	1.844	1.085
1989	2	1	0	0	0	0	1	1.988	0.879	1.873	1.068
1990	3	1	0	0	0	2	0	2.058	0.816	1.845	1.626
1991	2	2	0	0	0	0	0	1.949	0.817	1.792	1.116
1992	1	1	0	0	0	0	0	2.145	0.760	1.833	0.546
1993	0	0	0	0	0	0	0	2.382	0.663	1.854	--.--
1994	0	0	0	0	0	0	0	2.576	0.649	1.937	--.--
1995	1	1	0	0	0	0	0	2.470	0.595	1.830	0.546
1996	0	0	0	0	0	0	0	2.684	0.558	1.900	--.--
1997	1	1	0	0	0	0	0	2.879	0.513	1.953	0.512
1998	0	0	0	0	0	0	0	2.903	0.424	1.876	--.--
1999	0	0	0	0	0	0	0	2.963	0.344	1.826	--.--
2000	1	0	1	0	0	0	0	3.489	0.317	2.062	0.485
2001	0	0	0	0	0	0	0	3.242	0.348	1.969	--.--
2002	0	0	0	0	0	0	0	3.195	0.341	1.939	--.--
2003	0	0	0	0	0	0	0	3.438	0.339	2.058	--.--
2004	1	1	0	0	0	0	0	3.536	0.319	2.087	0.479
2005	0	0	0	0	0	0	0	3.480	0.298	2.038	--.--
2006	0	0	0	0	0	0	0	3.489	0.245	1.990	--.--
2007	0	0	0	0	0	0	0	3.472	0.254	1.990	--.--
2008	0	0	0	0	0	0	0	3.278	0.242	1.881	--.--
2009	0	0	0	0	0	0	0	3.000	0.234	1.734	--.--
2010	0	0	0	0	0	0	0	2.980	0.221	1.711	--.--
2011	0	0	0	0	0	0	0	2.747	0.205	1.579	--.--
2012	0	0	0	0	0	0	0	2.404	0.231	1.433	--.--
2013	0	0	0	0	0	0	0	2.105	0.315	1.368	--.--
Total	**45**	**25**	**9**	**1**	**4**	**4**	**2**	**97.429**	**21.534**	**70.249**	**0.641**

[1] Coastal and intraterritorial domestic transport of crude oil (excludes inland transport)

[2] Assumes half of exposure from U.S. imports/exports occurs outside U.S. waters. Values = 100% Domestic Transports + 50% Imports & Exports

Source: U.S. DOI/BSEE OCS Spill Database, December 2015 (Spills); U.S. Army Corps of Engineers, Waterborne Commerce of the United States, Part 5, National Summaries, 1975-2009 (Oil Handled)

From 1974 to 2014, 45 large crude oil tanker spills occurred in the U.S. The findings for domestic tanker spills did not conform to the worldwide pattern of spills occurring more often at sea than in port. Thirty-five of the 45 total domestic spills occurred in port while only 10 occurred at sea.

These observations may be due to the methods the analysis team used to filter the international tanker spill record for domestic spill data. The analysis team defined domestic tanker spills as those occurring within U.S. federal jurisdiction, specifically on the U.S. OCS and in coastal U.S. waters. The U.S. OCS extends roughly 200 nautical miles from the coast, and the analysis team controlled for domestic tanker spills based on this projection. Compared to the entire international tanker spill record, the domestic spill record encompassed a smaller area in which at sea spills would occur versus the area in which in port spills would occur. It may have been more likely for a spill in port to occur than a spill at sea given these geographical constraints.

Figure 33 illustrates the number of tanker spills in U.S waters that occurred each year, along with crude oil import and export rates, domestic movements, and adjusted movements. The analysis team found that the number of large spills per year may follow one of these possible trends:

- Spill counts tended to decrease in spite of an increasing number of adjusted crude oil movements around the mid-1980s, which then decreased in the mid-2000s.
- Spill counts decreased along with decreasing domestic crude oil movements during the mid-1980s.

The high spill counts in the 1970s do not correlate with high domestic movements during that same period, suggesting that the downward spill trend is a rate improvement and not caused by changes in exposure.

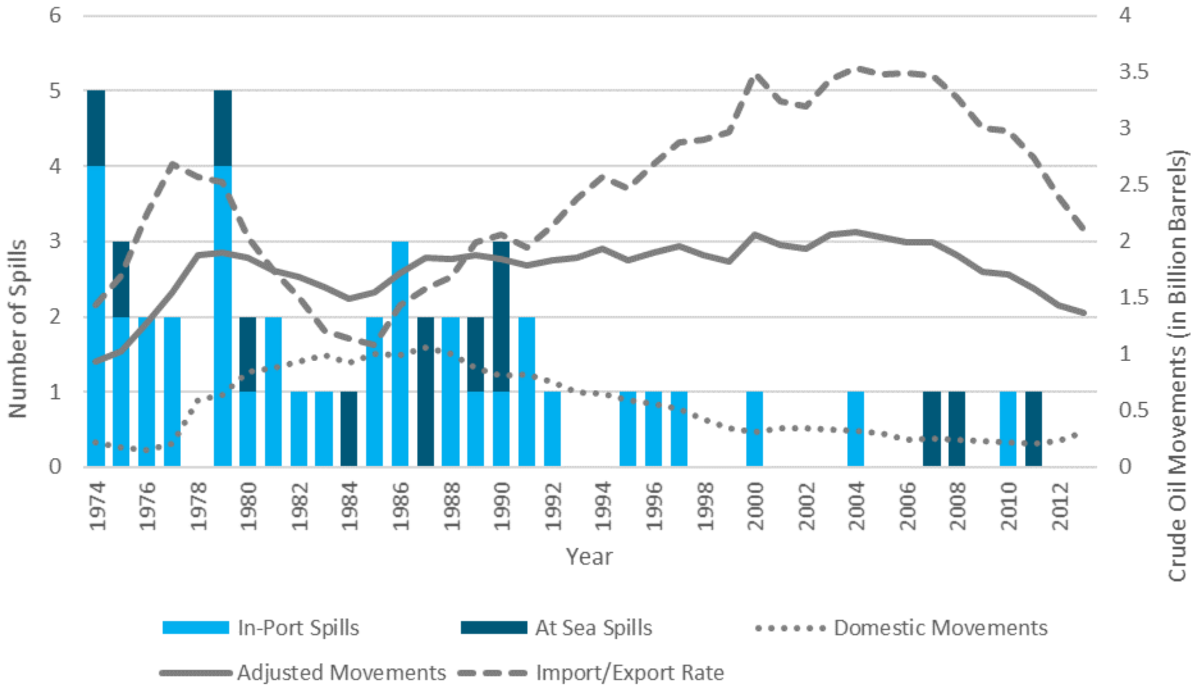

Figure 33. Crude Oil Movements and Import/Export Rate vs. Domestic Tanker Large Spills

Although the analysis team computed the domestic tanker spill rates using the adjusted crude oil movements, the observed number of spills appeared to follow trends in the domestic crude oil movements in Figure 33. Specific information on the oil spilled in each incident, such as whether the oil was foreign or domestic, was not available in the data. Categorizing spills based on the origin of the oil (foreign or domestic) could provide more insight on the trends in spill rates.

6.1.3. ANS Tanker Spills

ANS oil being shipped from Valdez, Alaska, is a highly traceable selection of tankers with a well understood spill record and oil handled volumes. Historical spill incidents are relatively few in number and include the Exxon Valdez spill, three spills by the tanker Stuyvesant, and seven others. No spills of ANS crude were identified since the 1991 spill by the Exxon San Francisco.

Figure 34 presents these 11 spills along with the oil handled exposure variables. TAPS pipeline throughput is used under the assumption that the vast majority of the TAPS pipeline oil is loaded on tankers at Valdez. Since 2009, it is assumed that almost all volume of ANS crude has been shipped to a U.S. west coast destination.

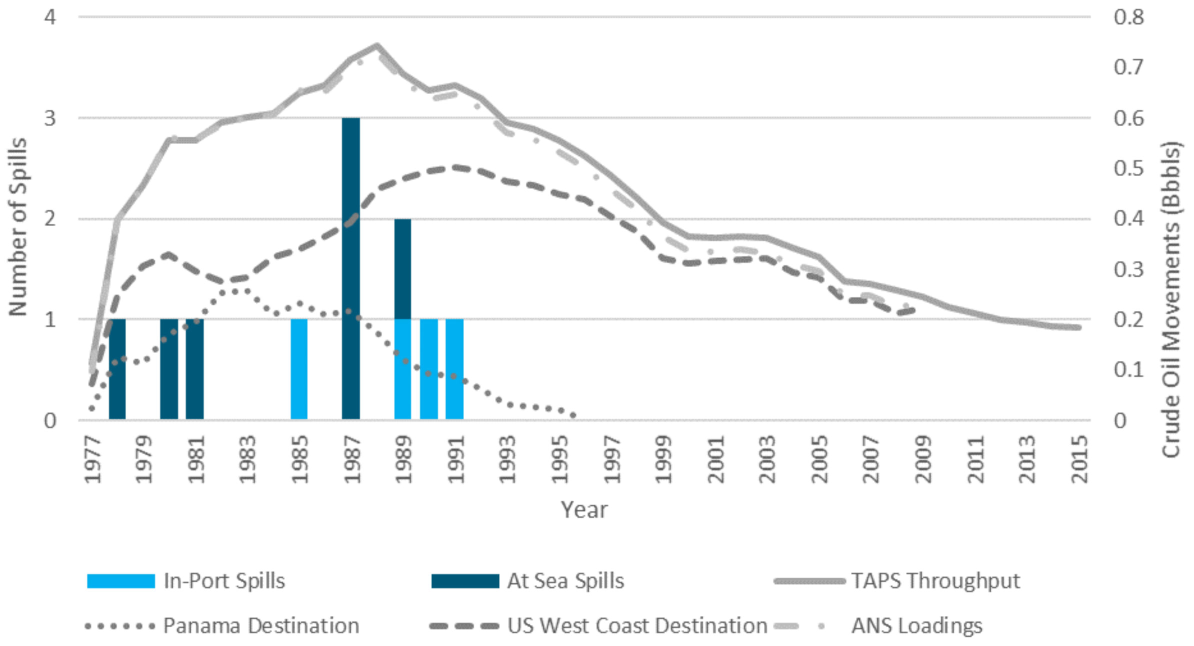

Figure 34. Crude Oil Movements vs. ANS Tanker Large Spills

6.1.4. U.S. Waters Barge Spills

Petroleum barges transported over 70 Bbbl of petroleum in U.S. coastal and inland waters from 1974 to 2013, 11 Bbbl of which was crude oil. The volume of oil spilled by barges tended to be less than the volume of oil spilled by tankers, as oil tankers generally transport significantly larger volumes of oil per vessel than barges. Over the entire spill record, 183 oil spills from barges occurred in U.S. waters, with 28 of those spills involving crude oil.

Table 30 summarizes the number of petroleum and crude oil spills from barges in U.S. waters from 1974 to 2013. It shows that the volume of petroleum transported by barge remained fairly constant in U.S waters from 1974 to 2013. The annual volume transported ranged between 1.54 and 1.85 Bbbl and did not tend to increase or decrease over time. The volume of crude oil transported by barge appeared to follow a similar pattern from 1974 to 2011, with no significant periods of increase or decrease over time. In the years 2012 to 2013, however, the volume of crude oil transported grew more rapidly than in previous years. In 2012, the volume increased by 39% over the previous year and grew by another 27% in 2013.

While transport volumes remained fairly constant, spill rates for both petroleum and crude oil barge spills decreased rapidly after 1990. Of the 183 total spills recorded from 1974 to 2013, only 35 occurred between the years 1991 and 2013. The first 17 years of the 40-year spill record, from 1974 to 1990, accounted for almost 81% of the total number of barge spills, while the latter 23 years, from 1991 to 2013, accounted for just over 19% of the spills.

Table 30. Barge Spills in U.S. Waters (Including Inland Waters) Summary, 1974-2013

		All Petroleum Spills (Including Crude Oil)					Crude Oil Spills Only					
Year	All Spills	1K-9.99K bbl	10K-24.99K bbl	≥25K bbl	Trans-ported Volume Bbbl	Spills Per Bbbl	All Spills	1K-9.99K bbl	10K-24.99K bbl	≥25K bbl	Trans-ported Volume Bbbl	Spills Per Bbbl
1974	13	10	0	3	1.616	8.045	5	4	0	1	0.321	15.576
1975	10	8	2	0	1.607	6.223	4	3	1	0	0.331	12.085
1976	9	9	0	0	1.746	5.155	3	3	0	0	0.339	8.850
1977	12	11	1	0	1.785	6.723	0	0	0	0	0.327	0.000
1978	13	11	2	0	1.850	7.027	2	2	0	0	0.359	5.571
1979	10	10	0	0	1.707	5.858	1	1	0	0	0.319	3.135
1980	10	10	0	0	1.716	5.828	2	2	0	0	0.270	7.407
1981	5	3	0	2	1.675	2.985	0	0	0	0	0.219	0.000
1982	4	3	0	1	1.569	2.549	0	0	0	0	0.227	0.000
1983	5	1	3	1	1.537	3.253	1	0	1	0	0.251	3.984
1984	8	5	2	1	1.640	4.878	1	0	1	0	0.275	3.636
1985	9	7	2	0	1.580	5.696	2	2	0	0	0.300	6.667
1986	6	5	1	0	1.642	3.654	1	1	0	0	0.296	3.378
1987	4	4	0	0	1.666	2.401	0	0	0	0	0.270	0.000
1988	9	8	0	1	1.738	5.178	1	1	0	0	0.305	3.279
1989	7	7	0	0	1.715	4.082	0	0	0	0	0.283	0.000
1990	12	10	2	0	1.744	6.881	2	2	0	0	0.311	6.431
1991	3	3	0	0	1.649	1.819	0	0	0	0	0.282	0.000
1992	1	1	0	0	1.601	0.625	0	0	0	0	0.279	0.000
1993	2	2	0	0	1.638	1.221	0	0	0	0	0.284	0.000
1994	0	0	0	0	1.637	0.000	0	0	0	0	0.269	0.000
1995	2	1	1	0	1.600	1.250	0	0	0	0	0.257	0.000
1996	4	3	1	0	1.613	2.480	0	0	0	0	0.262	0.000
1997	2	2	0	0	1.734	1.153	0	0	0	0	0.262	0.000
1998	1	1	0	0	1.702	0.588	1	1	0	0	0.215	4.651
1999	2	2	0	0	1.649	1.213	0	0	0	0	0.202	0.000
2000	2	2	0	0	1.670	1.198	0	0	0	0	0.195	0.000

2001	2	2	0	0	1.684	1.188	0	0	0	0	0.183	0.000
2002	0	0	0	0	1.600	0.000	0	0	0	0	0.191	0.000
2003	1	0	0	1	1.634	0.612	0	0	0	0	0.209	0.000
2004	2	2	0	0	1.688	1.185	0	0	0	0	0.210	0.000
2005	2	1	0	1	1.709	1.170	1	1	0	0	0.205	4.878
2006	2	2	0	0	1.753	1.141	0	0	0	0	0.191	0.000
2007	0	0	0	0	1.795	0.000	0	0	0	0	0.187	0.000
2008	1	1	0	0	1.636	0.611	0	0	0	0	0.169	0.000
2009	0	0	0	0	1.570	0.000	0	0	0	0	0.164	0.000
2010	0	0	0	0	1.575	0.000	0	0	0	0	0.171	0.000
2011	0	0	0	0	1.542	0.000	0	0	0	0	0.198	0.000
2012	2	1	1	0	1.678	1.192	1	1	0	0	0.326	3.067
2013	1	1	0	0	1.816	0.551	0	0	0	0	0.451	0.000
Total	**178**	**149**	**18**	**11**	**66.706**	**2.668**	**28**	**24**	**3**	**1**	**10.365**	**2.701**
Source: U.S. DOI/BSEE OCS Spill Database, December 2015 (Spills); U.S. Army Corps of Engineers, Waterborne Commerce of the United States, Part 5, National Summaries, 1975-2009 (Oil Handled)												

Figure 35 illustrates the data summarized in Table 30, in addition to the total product movements, which were computed as the total petroleum movements minus the crude oil movements. The analysis team found that few barge spills in U.S. waters involved crude oil. Over the entire spill record, the number crude oil spills tended to decrease, while crude oil movements remained fairly constant until around 2012 and 2013. The number of product spills tended to fluctuate from 1974 to 1990, then decreased rapidly after 1990, while product movements remained fairly constant. As a result of the steep drop off in spills after 1990, the analysis team identified the period from 1991 to 2013 as a potential date range to conduct a trend analysis.

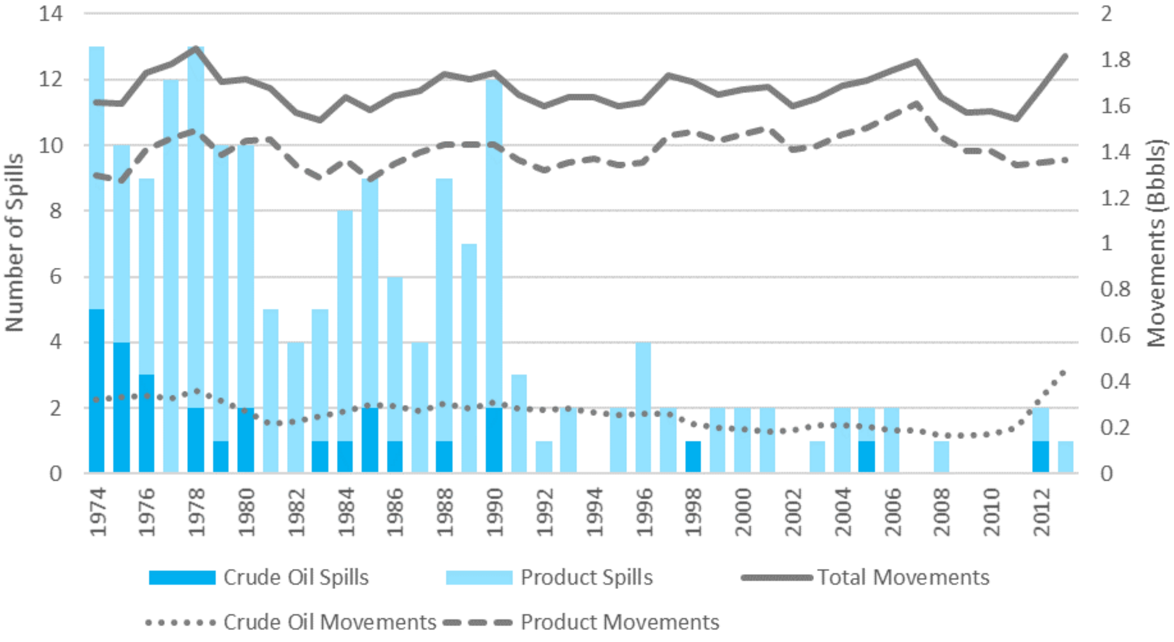

Figure 35. Movements vs. Domestic Barge Large Spills

6.2. Tanker and Barge Exposure Units

The analysis for this report included review of many potential alternative exposure variables for tankers and barges. Unlike offshore facilities and pipelines, tankers and barges are not geographically bound to a given region. This makes it difficult to assign exposure to a specific region. Worldwide spill rates bypass this issue by not regarding any regional boundaries, but are also less relevant for evaluating activity in U.S. waters.

Table 31 lists a selection of potential alternative exposure variables.

Table 31. Tanker and Barge Exposure Metrics

Exposure Metric	Feasibility	Relevance	Comments
Worldwide Crude Imports	**High**	**Medium**	Existing metric. Applies to worldwide tanker spills.
ANS Loadings	**Medium**	**Medium**	Existing metric. Applies to ANS tanker spills.
U.S. Crude Commerce	**High**	**Medium**	Existing metric. Applies to U.S. waters tanker spills and interior barge spills.
Number of Tankers	**Medium**	**Medium**	Estimated from IHS Maritime and Trade data. Relevant only to worldwide tanker spill rates.
Tanker Transit Miles	**Low**	**High**	The analysis team did not locate sufficient data to estimate this metric.
Average Daily Count of Tankers	**Low**	**High**	The analysis team did not locate sufficient data to estimate this metric.
Average Daily Volume of Oil	**Low**	**High**	The analysis team did not locate sufficient data to estimate this metric.

The only feasible alternative exposure variable that was defined was tanker years. These data were available from IHS Maritime and Trade on a worldwide basis. The most interesting feature of these exposure data is the split between tankers meeting the 1992 MARPOL double hull requirement[11] and other tankers.

---

[11] MARPOL is an international convention about maritime pollution. http://www.imo.org/en/About/conventions/listofconventions/pages/international-convention-for-the-prevention-of-pollution-from-ships-(marpol).aspx

Figure 36 plots this exposure data against the number of large spills. Unlike platforms and pipelines, for which the improved spill trend is not easily attributable to the exposure variables considered, tanker spills are easily attributable to the number of non-MARPOL compliant tankers.

Since single-hull tankers are being phased out worldwide, the number of non-MARPOL tankers is a poor exposure variable for projection purposes. Representative spill rates for the new MARPOL double hull tankers may not be calculable until more years of data are collected.

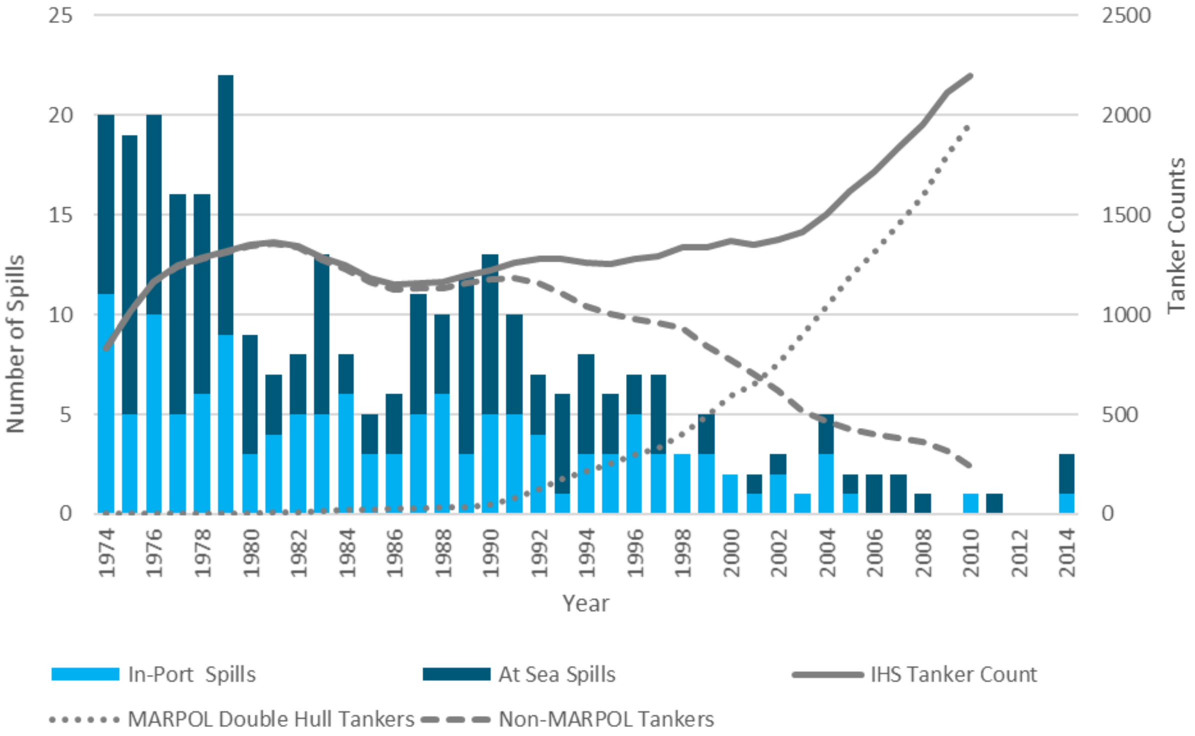

Figure 36. MARPOL and Non-MARPOL Tankers vs. Worldwide Tanker Spills

6.3. Tanker and Barge Trend Analysis

Large tanker and barge spills occur relatively frequently compared to platform and OCS pipeline spills. Practically, this enables the calculation of annual spill rates (normalized by the exposure level) for trend analysis instead of constructing oil handled intervals, as done for platforms and pipelines.

Figure 37 plots the annual spill rates for worldwide tankers and tankers in U.S. waters. Recent portions of the data were tested for trend to identify stable periods for spill rate estimation. Although the spill rate for tankers worldwide has greatly decreased, it still maintains a statistically significant downward trend for any reasonable segment of the data.

For tanker spills in U.S. waters, the period from 1992 to 2013 appears to be nearly trendless. Linear regression of year onto the annual spill rate over this period produces a coefficient of -0.0018, suggesting that the slope of the trend is sufficiently close to zero to allow for a reasonable spill rate calculation over this period. As in the case of the platform small and large spill trend analysis, these regression findings are not suitable for forecasting purposes.

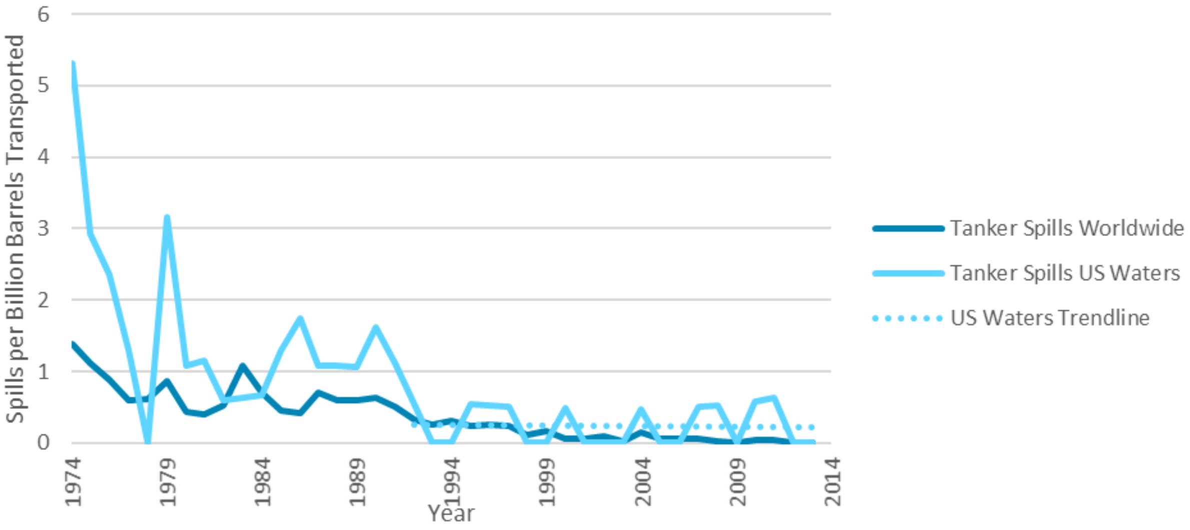

Figure 37. Worldwide and U.S. Waters Tanker Spill Trends, 1974-2014

Figure 38 considers a similar period for all barge spills of petroleum (including crude). The trend line for the period from 1992 to 2013 has a slope of -0.0364. Although this slope is higher than for U.S. Waters tankers, it is still relatively low when compared to the slope that would be calculated if spills prior to 1992 were included in the regression.

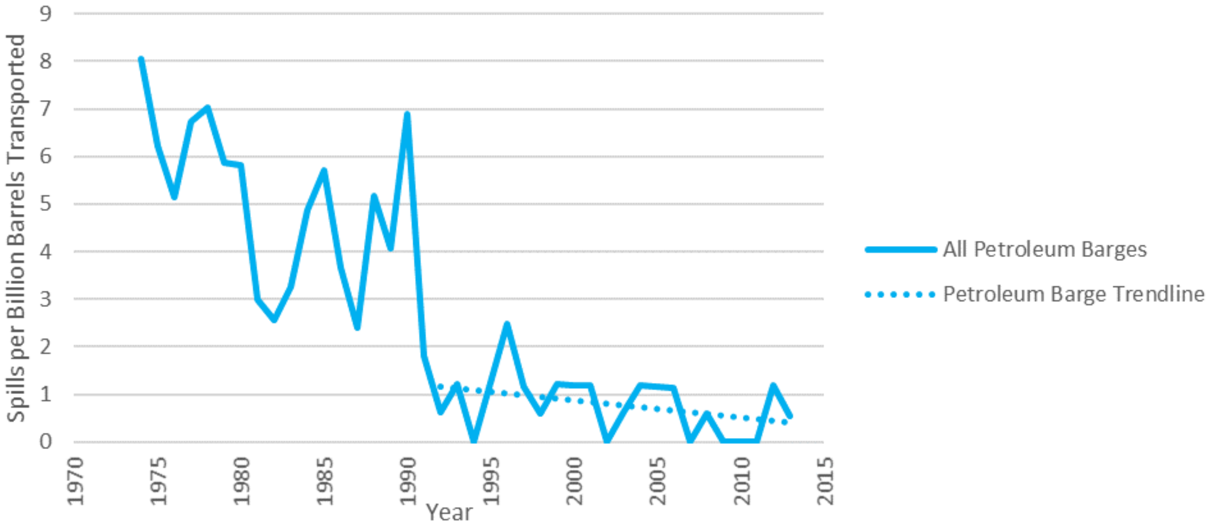

Figure 38. Petroleum Barge Spill Trends, 1974-2014

The absence of any recent spills by ANS tankers makes trend analysis of these spills impossible.

6.4. Tanker and Barge Spill Rates

This section develops a wide variety of rates for each of the major tanker and barge populations split by operating mode: at sea and in port, spill size categories, and spill fluid. As in the prior sections, this section reports rates based on the full record and for a recent 15-year period. The trend analysis identified the period from 1992 to present as a relevant spill rate setting period for tankers and barges in U.S. waters. Although this is a period of 23 years, this data range is used for calculating the recent spill rates, and is still referred to as the 15-year rate, in keeping with Anderson *et al.* (2012).

6.4.1. Worldwide Tanker Spill Rates

The frequency of worldwide tanker spills has declined dramatically (see Table 32). There is no ideal period for rate setting due to the continued downward trend in spill rates. For other tanker types, the period from 1992 to 2013 appeared to be relatively trendless. The updated tanker rates will use this period as well. Aside from the observed gradual decrease in spill rates since 1992, the date marks the initial MARPOL regulations for single hull tanker phase out.[12]

Table 32. Worldwide Tanker Unadjusted Spill Rates (Crude)

Spill Size and Location	Previous Rate 1974-2008[1]			Updated Rate 1974-2014			15-year Rate 1992-2014		
	Volume Transported (Bbbl)	**# of Spills**	**Spill Rate[2]**	**Volume Transported (Bbbl)**	**# of Spills**	**Spill Rate[2]**	**Volume Transported (Bbbl)**	**# of Spills**	**Spill Rate[2]**
≥1,000 bbl									
All Spills	**359.9**	**303**	**0.84**	**443.1**	**301**	**0.68**	**288.1**	**75**	**0.26**
In Port		137	0.38		138	0.31		39	0.14
At Sea		166	0.46		163	0.37		36	0.12
≥10,000 bbl									
All Spills	**359.9**	**151**	**0.42**	**443.1**	**153**	**0.35**	**288.1**	**31**	**0.11**
In Port		50	0.14		51	0.12		11	0.04
At Sea		101	0.28		102	0.23		20	0.07
≥100,000 bbl									
All Spills	**359.9**	**62**	**0.17**	**443.1**	**60**	**0.14**	**288.1**	**9**	**0.03**
In Port		20	0.05		20	0.05		5	0.02
At Sea		42	0.12		40	0.09		4	0.01

[1] Anderson and LaBelle (2012)

[2] Spill rate = number of spills ≥1,000 bbl (or 10,000 bbl or 100,000 bbl) per Bbbl handled

Sources: U.S. DOI/BSEE OCS Spill Database, December 2015 (Spills); BP Statistical Review of World Energy (1975-2009) (Oil Handled)

The slight decrease in the number of spills in the full record since the prior report is due to increased screening of duplicates and the absence of recent large spills.

---

[12] http://www.imo.org/en/OurWork/Environment/PollutionPrevention/OilPollution/Pages/constructionrequirements.aspx

6.4.2. U.S. Waters Tanker Spill Rates

Tanker Spills in U.S. Waters uses 1992 to 2013 as its 15-year rate period (see Table 33). The trend analysis identified this data range as relatively trendless. A range broader than 15 years will only make the estimate more robust if there is no observable trend during the period.

Table 33. Tankers in U.S. Waters Unadjusted Spill Rates (Crude)

Spill Size and Location	Previous Rate 1974-2008[1]			Updated Rate 1974-2013			Last 15-year Rate 1992-2013		
	Volume Transported (Bbbl)[3]	# of Spills	Spill Rate[2]	Volume Transported (Bbbl)[3]	# of Spills	Spill Rate[2]	Volume Transported (Bbbl)[3]	# of Spills	Spill Rate[2]
≥1,000 bbl									
All Spills	**62.4**	**53**	**0.85**	**70.3**	**45**	**0.64**	**40.8**	**5**	**0.12**
In Port		37	0.59		35	0.50		5	0.12
At Sea		16	0.26		10	0.14		0	0.03[3]
≥10,000 bbl									
All Spills	**62.4**	**20**	**0.32**	**70.3**	**16**	**0.23**	**40.8**	**1**	**0.02**
In Port		10	0.16		10	0.14		1	0.02
At Sea		10	0.16		6	0.09		0	0.01[3]

[1] Anderson and LaBelle (2000)

[2] Spill rate = number spills ≥1,000 bbl (or 10,000 bbl or 100,000 bbl) in size per Bbbl handled

[3] Assume that the same ratio of at sea to all spills applies to this period as to the full record.

Sources: U.S. DOI/BSEE OCS Spill Database, December 2015 (Spills); U.S. Army Corps of Engineers, Waterborne Commerce of the United States, Part 5, National Summaries, 1975-2009 (Oil Handled)

The updated rates are lower than previously estimated for two reasons. First, the new period of data has a low spill rate when compared to the prior full record. Additionally, the data underwent minor changes as the analysis process meticulously removed duplicate events, screened spills by fluid type, and geospatially reviewed the occurrences within U.S. waters. Even with these refinements, the full record rate is still highly conservative when compared to recent experience.

6.4.3. ANS Crude Tanker Spill Rates

Spill rates for tankers transporting ANS crude are particularly difficult given the limited number of historical spills and the absence of a spill in the record since 1991. Table 34 includes full record rates. Fifteen-year rates are not calculated, given the lack of data.

Table 34. ANS Crude Tankers Unadjusted Spill Rates (Crude)

Spill Source: U.S. Flag Ships[1]	**Previous Rate 1977-2008[2]**			**Updated Rate 1977-2015**			**Last 15-year Rate 2001-2015[4]**		
	Volume Transported (Bbbl)	**# of Spills**	**Spill Rate[3]**	**Volume Transported (Bbbl)**	**# of Spills**	**Spill Rate[3]**	**Volume Transported (Bbbl)**	**# of Spills**	**Spill Rate[3]**
≥1,000 bbl[4]									
All Spills	**15.3**	**11**	**0.72**	**17.3**	**11**	**0.64**	**4.0**	**0**	--.--
In Port		4	0.26		4	0.23		0	--.--
At Sea		7	0.46		7	0.41		0	--.--
≥10,000 bbl[4]									
All Spills	**15.3**	**3**	**0.20**	**17.3**	**3**	**0.17**	**4.0**	**0**	--.--
In Port		0	--.--		0	--.--		0	--.--
At Sea		3	0.20		3	0.17		0	--.--

[1] The Jones Act, part of the Merchant Marine Act of 1920, requires that goods transported by water between U.S. ports, such as North Slope Crude Oil from Valdez, Alaska, to U.S. coastal ports in Alaska, Hawaii, California, and the GOM, be carried by U.S. Flag Ships. U.S. Flag Ships must be constructed (or rebuilt) in the U.S., owned by U.S. citizens, crewed by U.S. citizens, and registered in the U.S.

[2] Anderson and LaBelle (2000)

[3] Spill rate = number of spills ≥1,000 bbl (or ≥10,000 bbl or ≥100,000 bbl) in size per Bbbl handled

[4] Zero spills ≥1,000 bbl for ANS crude oil tankers in last 15 years (2001-2015).

Source: U.S. DOI/BSEE OCS Spill Database, December 2015 (Spills); Alyeska Pipeline Service Company, 2016 (http://www.alyeska-pipe.com/TAPS/PipelineOperations/Throughput) (Oil Handled)

The updated rates have decreased as the volume of oil handled has increased. No new spill events were identified.

6.4.4. Barges in U.S. Waters Spill Rates

Barge Spills in U.S. Waters uses 1992 to 2013 as its 15-year rate period (see Table 35). The trend analysis identified this data range as relatively trendless. A range broader than 15 years will make the estimate more robust if there is no observable trend during the period.

Table 35. Barges in U.S. Waters Unadjusted Spill Rates

	Previous Rate 1974-2008[1]			**Updated Rate 1974-2013**			**Last 15-year Rate 1992-2013**		
Spill Source	**Volume Handled (Bbbl)**[3]	**# of Spills**	**Spill Rate**[2]	**Volume Handled (Bbbl)**	**# of Spills**	**Spill Rate**[2]	**Volume Handled (Bbbl)**	**# of Spills**	**Spill Rate**[2]
≥1,000 bbl									
All Petroleum Products	58.53	197	3.37	66.7	178	2.67	36.5	29	0.79
Crude Oil Only	9.06	28	3.09	10.4	28	2.70	5.1	3	0.59
≥10,000 bbl									
All Petroleum Products	58.53	33	0.56	66.7	29	0.43	36.5	5	0.14
Crude Oil Only	9.06	5	0.55	10.4	4	0.39	5.1	0	0.08[3]

[1] Anderson and LaBelle (2000)

[2] Spill rate = number of spills ≥1,000 bbl (or ≥10,000 bbl) in size per Bbbl handled

[3] Assume that the ratio of the ≥10,000 bbl rate to the ≥1,000 bbl rate is the same for the 15-year rate as for the updated rate

Source: U.S. DOI/BSEE OCS Spill Database, December 2015 (Spills); U.S. Army Corps of Engineers, Waterborne Commerce of the United States, Part 5, National Summaries, 1975-2009 (Oil Handled)

Table 36 lists confidence intervals for these rates. Because no exposure period analysis was performed for tankers, the bootstrap could not be applied by treating exposure periods as separate statistical observations. Consequently, the confidence intervals below are calculated using the normal approximation to the Poisson distributed rate. In a few instances, the approximation led to the lower bound of the interval being negative. In these cases, a value of 0 replaced the calculated lower bound. The symbol "--.--" indicates that the confidence interval could not be computed.

Table 36. Tanker and Barge Spill Rate Confidence Intervals Summary by Spill Location and Spill Size

Entities	Spill Size (Lower Bound)	All Spills			In Port			At Sea		
		Lower Bound	Selected Spill Rate	Upper Bound	Lower Bound	Selected Spill Rate	Upper Bound	Lower Bound	Selected Spill Rate	Upper Bound
Crude Oil Spills										
Worldwide Tankers (1992-2010)[1]	1,000	--.--	0.26	--.--	--.--	0.14	--.--	--.--	0.12	--.--
	10,000	--.--	0.11	--.--	--.--	0.04	--.--	--.--	0.07	--.--
	100,000	--.--	0.03	--.--	--.--	0.02	--.--	--.--	0.01	--.--
Tankers in U.S. Waters (1992-2013)	1,000	0.02	0.12	0.23	0.02	0.12	0.23	--.--	0.03	--.--
	10,000	0.00	0.02	0.07	0.00	0.02	0.07	--.--	0.01	--.--
ANS Tankers (1977-2015)	1,000	0.26	0.64	1.01	0.00	0.23	0.46	0.11	0.41	0.71
	10,000	0.00	0.17	0.37	--.--	0.00	--.--	0.00	0.17	0.37
Barges in U.S. Waters (1992-2013)	1,000	0.00	0.59	1.26	--.--	N/A	--.--	--.--	N/A	--.--
	10,000	0.00	0.08	0.34	--.--	N/A	--.--	--.--	N/A	--.--
Petroleum Spills										
Barges in U.S. Waters (1992-2013)	1,000	0.51	0.79	1.08	--.--	N/A	--.--	--.--	N/A	--.--
	10,000	0.02	0.14	0.26	--.--	N/A	--.--	--.--	N/A	--.--

[1] Because of the downward trend in worldwide tanker spill rates, these rates include spills from a period of higher spill rates than are currently being experienced. Therefore, the rates are highly conservative. Confidence intervals cannot be reasonably calculated for significantly biased rate estimates.

Source: U.S. DOI/BSEE OCS Spill Database, December 2015

6.5. Tanker and Barge Spill Distributions

On average, tankers and barges have larger spills than platforms and pipelines. Table 37 provides the average and median spill sizes for each of the tanker and barge groups that were analyzed in this report. These spill distributions correspond with the spill rates calculated in Section 6.4.

Table 37. Tanker and Barge Spill Counts and Average and Median Spill Sizes (Spills ≥1,000 bbl)

	Entire Record			Last 15 Years		
Spill Source	**# of Spills**	**Average Spill Size (bbl)**	**Median Spill Size (bbl)**	**# of Spills**	**Average Spill Size (bbl)**	**Median Spill Size (bbl)**
Tankers Worldwide, Total (1974-2014)	**301**	**96,654**	**11,114**	**75**	**50,313**	**8,184**
In Port	138	68,103	6,305	39	52,984	5,600
At Sea	163	120,624	19,530	36	47,489	11,900
Tankers in U.S. Waters, Total (1974-2013)	**45**	**28,246**	**6,300**	**5**	**5,050**	**2,400**
In Port	35	15,617	5,690	5	5,050	2,400
At Sea	10	72,445	16,024	0	--.--	
Tankers Alaska North Slope Crude, Total (1977-2016)	**11**	**29,495**	**4,950**	**0**	**--.--**	**--.--**
In Port	4	4,712	3,845	0	--.--	--.--
At Sea	7	43,657	4,950	0	--.--	--.--
Barges in U.S. Waters Including Inland Waters (1974-2013)						
Petroleum Spills	178	6,655	2,954	29	8,468	3,000
Crude Oil Only	28	6,653	3,709	3	2,889	3,000

Source: U.S. DOI/BSEE OCS Spill Database, December 2015

Table 38 summarizes the subset of these spills which exceeded 10,000 bbl in volume.

Table 38. Tanker and Barge Spill Counts and Average and Median Spill Sizes (Spills ≥10,000 bbl)

Spill Source	Entire Record			Last 15 Years		
	# of Spills	Average Spill Size (bbl)	Median Spill Size (bbl)	# of Spills	Average Spill Size (bbl)	Median Spill Size (bbl)
Tankers Worldwide, Total (1974-2014)	**153**	**184,408**	**50,833**	**31**	**111,530**	**37,740**
In Port	51	175,387	49,020	11	169,155	91,000
At Sea	102	188,919	53,887	20	79,837	34,167
Tankers in U.S. Waters, Total (1974-2013)	**16**	**72,520**	**22,905**	**1**	**12,800**	**12,800**
In Port	10	45,232	21,000	1	12,800	12,800
At Sea	6	118,000	79,651	0	--.--	--.--
Tankers Alaska North Slope Crude, Total (1977-2016)	**3**	**97,062**	**15,000**	**0**	**--.--**	**--.--**
In Port	0	--.--	--.--	0	--.--	--.--
At Sea	3	97,062	15,000	0	--.--	--.--
Barges in U.S. Waters Including Inland Waters (1974-2013)						
Petroleum Spills	29	25,073	20,000	5	34,920	20,000
Crude Oil Only	4	24,180	20,326	0	--.--	--.--
Source: U.S. DOI/BSEE OCS Spill Database, December 2015						

7. Results Summary

This section compares quantitative results from each of the analysis sections of the report.

7.1. Spill Occurrence Rate Summaries

For each entity type, two spill rates were developed. The full record rate includes data over a long period of time and is a less volatile estimate. In prior reports, there also is a 15-year rate that is calculated using a short, recent time period. Table 39 lists the time frames used for the development of both rates for each entity type. For the tanker and barge rates, the analysis used a longer exposure period than 15 years for calculating the “15-year” rate. This was deemed appropriate in order to improve the accuracy of the estimates since there did not appear to be a significant change in the level of spill occurrences over the longer period. For reference, Table 40 lists the oil handled volumes and the sources for these data, as used in the calculation of the spill rates.

Table 39. Selected Date Ranges for Full Record and 15-year Rates

	Date Range of Record		
Spill Source	**Full Record**	**15-year**	**Data Availability for Spill Occurrence Rate Calculations**
OCS Platform Spills	1974 to 2015	2001 to 2015	Strong trend prior to 1971 makes the period of data from 1964 to 1970 irrelevant for rate calculations.
OCS Pipeline Spills	1974 to 2015	2001 to 2015	No major trends identified that would limit the applicable data.
Worldwide Tankers	1974 to 2014	1992 to 2014	Exposure data stops at 2014.
Tankers in U.S. Waters	1974 to 2013	1992 to 2013	Exposure data stops at 2013. Strong downward shift in rates, starting in 1992.
ANS Tankers	1977 to 2015	N/A	TAPS began operations in 1977. No large ANS Crude spills since 1991.
Barges in U.S. Waters	1974 to 2013	1992 to 2013	Moderate shift in rates, starting in 1992. Exposure data stops at 2013.

Table 40. Exposure Values for Full Record and 15-year Rates

	Oil Handled Volume (Bbbl)		
Spill Source	**Full Record**	**15-year**	**Data Source**
OCS Platform Spills	17.9	8.0	BSEE Production Data
OCS Pipeline Spills	17.9	8.0	BSEE Production Data
Worldwide Tankers	443.1	288.1	BP World Energy Review
Tankers in U.S. Waters	70.3	40.8	USACE Waterborne Commerce Statistics
ANS Tankers	17.3	4.0	Alyeska Pipeline Throughput Data
Barges in U.S. Waters (Petroleum)	66.7	36.5	USACE Waterborne Commerce Statistics
Barges in U.S. Waters (Crude)	10.4	5.1	USACE Waterborne Commerce Statistics

Table 41 identifies a selection of the optimal rate for current spill modeling purposes and provides an explanation for this selection.

Table 41. Best-estimate Spill Rates

Spill Source	Selected Rate Period	Explanation
OCS Platform Spills	Full Record	15-year rate does not include a credible amount of data.
OCS Pipeline Spills	Full Record	15-year rate does not include a credible amount of data.
Worldwide Tankers	15-year Rate	Single hull rates are irrelevant.
Tankers in U.S. Waters	15-year Rate	Significant shift in rates, starting in 1992.
ANS Tankers	Full Record	No large spills since 1991.
Barges in U.S. Waters	15-year Rate	Significant shift in rates, starting in 1992.

Figure 39 and Figure 40 summarize the full record rate and the 15-year rate for large spills and spills ≥10,000 bbl, and compares them to spill rates recorded by the five previous versions of this report. While the analysis team performed several additional analyses to isolate the impact of hurricanes for OCS platform spills and consider alternative exposure variables, the rates shown in these figures are calculated using all spills on a per-Bbbl basis, making them comparable to previous spill rates.

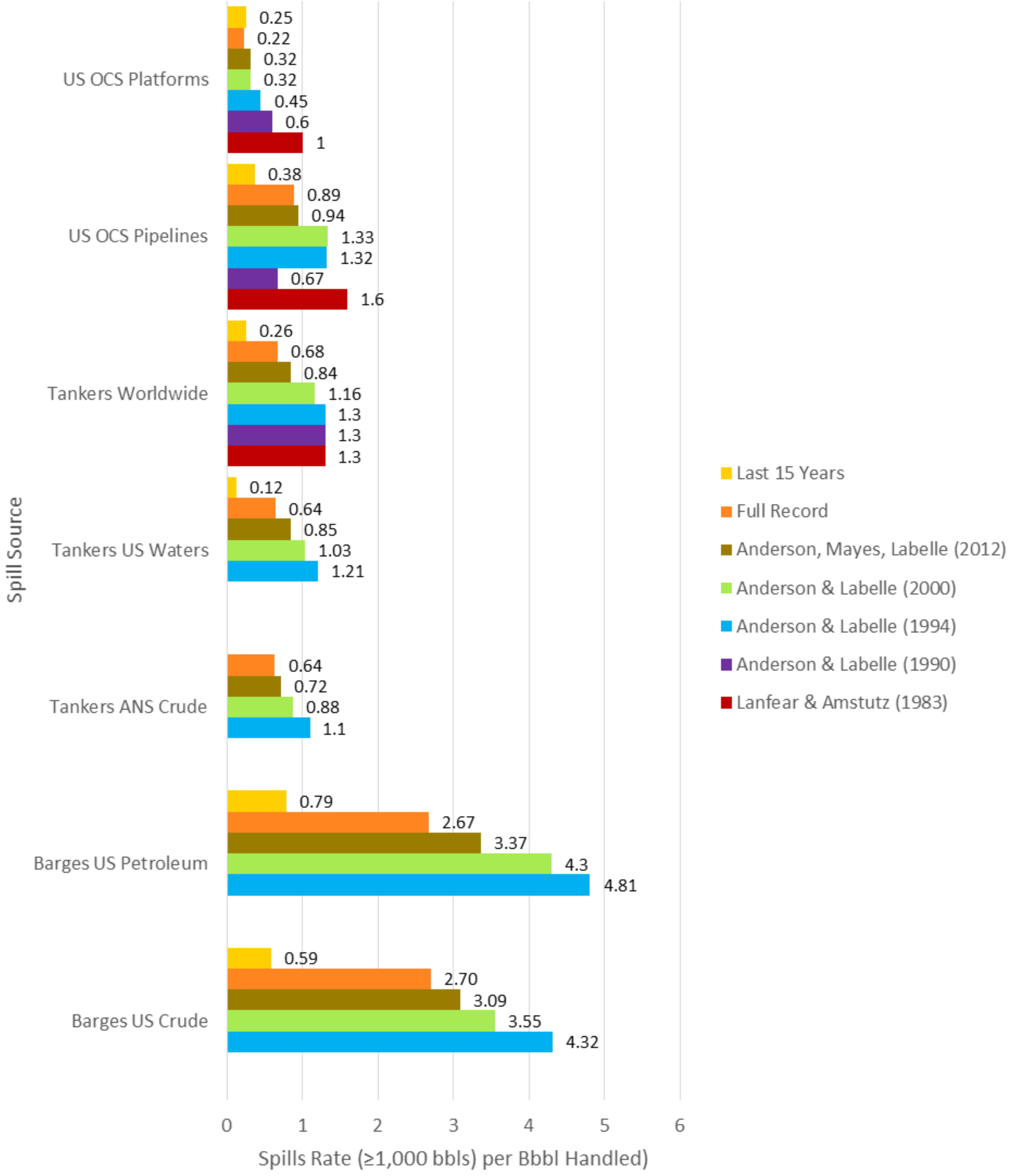

Figure 39. Comparison of Historical Spill Rate Estimates for Spills ≥1,000 bbl

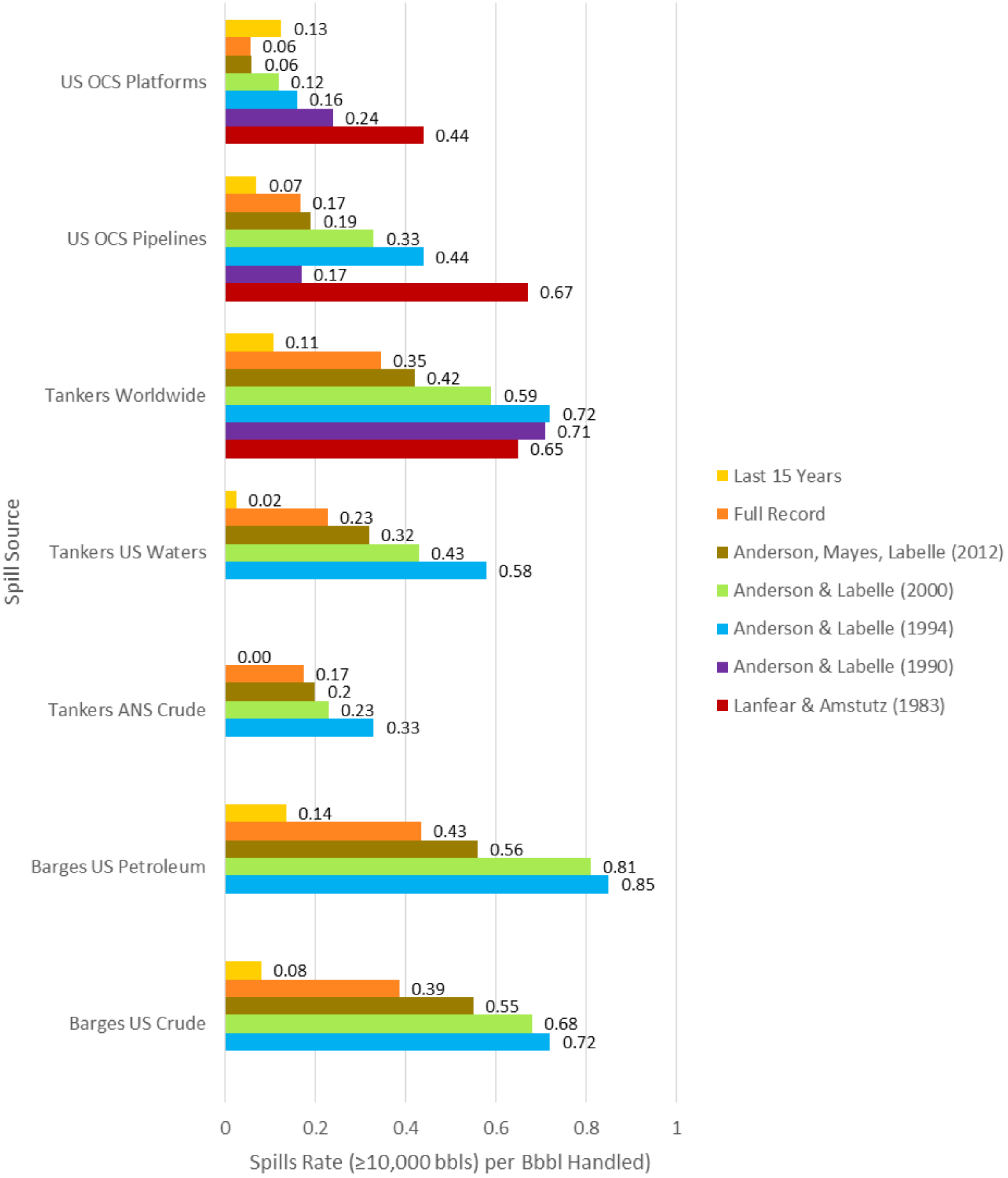

Figure 40. Comparison of Historical Spill Rate Estimates for Spills ≥10,000 bbl

7.1.1. U.S. OCS Platforms

The spill occurrence rates for large spills from OCS platforms are slightly lower than historical rates. This is solely due to the increase in the exposure period to account for spill risk since 2010. The spills used in the calculation of the rate are identical to those included by Anderson *et al.* (2012).

7.1.2. U.S. OCS Pipelines

The full record rate for pipelines is on par with the results presented by Anderson *et al.* (2012). The 15-year rate, however, is greatly impacted by the small number of large pipeline spills and is less than half of the full record rate.

7.1.3. Tankers Worldwide

Overall, worldwide tanker rates are comparable to prior analyses. Although there was no new spill data available, the slight decrease in the rates is attributable to the change in the date range used for the rate. The full record rate is a conservative spill rate, given the significant difference between it and the 15-year rate.

7.1.4. Tankers in U.S. Waters

Although this report used new spill data for tankers in U.S. waters, no new large spills were identified for the period from 2010 to 2015. The inclusion of additional exposure for recent history resulted in a reduction of the spill rates.

7.1.5. Tankers Carrying ANS Crude

No new spills were identified for tankers carrying ANS crude. The 15-year rate is no longer reasonable to calculate, so it is not listed. The decrease in the spill rate is attributable to an increase in the amount of exposure applied in the rate calculation.

7.1.6. Barges Carrying Petroleum in U.S. Waters

The number of large barge spills continues to decline, as in prior reports. Although the data collection methods employed were able to identify more barge spills than have historically been included in the analysis, large barge spills continue to decline in frequency. This should be expected given the very low 15-year rate listed in Anderson *et al.* (2012).

7.1.7. Barges Carrying Crude in U.S. Waters

The same declining spill rates are evident for crude barges as well. The number of large barge spills continues to decline, as in prior reports. Although the data collection methods employed were able to identify more barge spills than have historically been included in the analysis, large barge spills continue to decline in frequency. This should be expected given the very low 15-year rate listed in Anderson *et al.* (2012).

7.2. OCS Spill Size Empirical Distribution

Table 42 summarizes platform and pipeline spill sizes over the last 15 years. Overall, the number of platform spills increased from 510 to 564, while the number of pipeline spills decreased from 207 to

141. This drop in pipeline spills is consistent with the year-to-year spill charts presented earlier. Notably, the number of large pipeline spills has also decreased. The combined spill occurrence rate also decreased in each category.

Table 42. Combined Empirical Size Distribution of Platform and Pipeline Spills, 2001-2015

Spill Size (bbl)	Number of Spills			bbl Spilled			Spill Rate[2]			Average Spill Size Barrels			Median Spill Size Barrels		
	Platforms	Pipelines	Total	Platforms	Pipelines	Total	Platform	Pipeline	Total	Platforms	Pipelines	Total	Platforms	Pipelines	Total
≥1 to <5	333	59	392	670.5	137.2	807.7	49.4	9.6	59.0	2.0	2.33	2.1	2.5	4.3	2.8
≥5 to <10	62	18	80	431.0	121.1	552.1				7.0	6.73	6.9			
≥10 to <20	48	22	70	641.2	284.8	926.0	12.3	4.4	16.6	13.4	12.9	13.2			
≥20 to <50	50	13	63	1,624.1	365.4	1,989.5				32.5	28.1	31.6			
≥50 to <100	32	8	40	2,082	565.3	2,647	10.3	2.3	12.5	65.0	70.7	66.2	127	108	125
≥100 to <500	50	10	60	10,372	1,952.4	12,324				207.4	195.2	205.4			
≥500 to <1,000	10	3	13	6,266	2,493.0	8,759	1.3	0.4	1.6	626.6	831.0	673.7			
≥1,000 to <2,000[1]	2	3	5	3,066	4,536.0	7,602	0.4	0.4	0.8	1,533	1,512	1,520	1,572	1,500	1,536
≥2,000 to <3,000	1	-	1	2,000	-	2,000				2,000	--.--	2,000			
≥3,000 to <10,000[1]	-	-	-	-	-	-				--.--	--.--	--.--			
≥10,000	1	-	1	4,900,000	-	4,900,000	0.1	-	0.1	4,900,000	--.--	4,900,000	4,900,000	None	4,900,000
All Spills	589	136	725	4,927,151	10,455	4,937,607	73.6	17.0	90.7	8,365	77	6,810	3.4	6.0	4.0

[1] The three spills from Hurricane Rita in 2005 are counted separately.

[2] Spill rates based on 8 Bbbl production.

Source: U.S. DOI/BSEE OCS Spill Database, December 2015

8. Conclusions

For all entity types, platforms, pipelines, tankers and barges, the long-term trend of improving spill rates continued. In many instances, there were a low number of new large spills in the data, despite systematic and detailed review of the available data sources. The following sections explore these improvement trends in detail.

More than prior reports, this report sought to differentiate between spills caused by hurricanes and those resulting from operational causes. While hurricanes have historically been a point of concern as it relates to understanding trends and utilizing the Poisson distribution to describe spills, this report presents spill rate estimates for entities with and without including hurricane spills. The major hurricanes of the 2000s had a significant impact on OCS platform and pipeline spill occurrence levels and provided the impetus for this distinction.

This report frequently includes confidence intervals to help the reader understand the level of uncertainty in each estimate. In many cases, the estimates are highly uncertain, especially when the data period is relatively short.

8.1. Findings

8.1.1. OCS Platform Spill Conclusions

The platform spill record has been improving. The trend analysis on large spills, excluding hurricane spills, did not reveal any disruption of this improvement. Furthermore, analysis of the minor spill size categories showed a matching trend, with spill rates gradually reducing over the past several decades. At worst, after conducting the Kendall's test, the analysis identified no change in large spill frequency over the years 1971 to 2015. Most of the data analysis was confined to that timeframe.

Causal factor analysis reveals some of the underlying reasons for the improvement. Equipment failures caused the greatest number of platform spills from 1971 to 2015, but the number of spills attributed to equipment failures has been steadily decreasing since 1975. Over the same time, spills associated with production operations have dramatically declined. The data clearly suggests that the intersection of equipment failure and production operations was a major source of spills in the past, but that improved significantly in later years.

DWH presented the analysis team with a dilemma when computing platform spill rates and studying the platform spill distribution. Although it is an outlier in the spill record, DWH represented a worst-case scenario for platform oil spills that could provide valuable insight on the potential impacts of other similar disasters. However, its sheer magnitude skewed any estimates the analysis team made for more typical platform spills. In order to develop more realistic estimates for operational spills, the analysis team decided to exclude DWH from several summary statistics. Excluding DWH, the analysis found that platform spill rates decreased, continuing a trend noted in the 2012 report (Anderson *et al.*). DWH was the only major spill in the data since 2010 and the only spill ≥10,000 bbl in over 30 years.

LOWC events are an interesting subset of large spills from platforms. While they were analyzed separately from the other causal factors, the data clearly indicated that larger spills are increasingly likely to be associated with a LOWC. Each of the ≥10,000 bbl spills in the record are due to LOWC.

This spill record also provides insights into the changes in the operating modes that drive spill events. Just as the decrease in equipment failures has contributed to the overall frequency of spills, Figure 6 illustrates a major decline in production spills since the 1970s and 1980s. In the 2000s, the operating mode during hurricanes was often not indicated in the data, resulting in a swell in unknown operations during that time.

8.1.2. OCS Pipeline Spill Conclusions

The analysis team found that the number of large pipeline spills tended to decrease from 1971 to 2015. Vessel-induced damages, such as an anchor striking a pipeline, tended to be the main causal factor for these spills. For spills including minor spills, equipment failures caused the majority of spills from 1971 to 2015. The results from Kendall's test on large spills indicated that over the entire spill record, no discernable trend existed. The analysis did find that for the first part of the record, from 1964 to 1989, there appeared to be a downward trend in pipeline spill rates, but it did not last. Furthermore, although the pipeline trend analysis was inconclusive, this may be because the trend analysis is based on patterns in spill occurrences. Since there have not been any large OCS pipeline spills in recent history, the trend analysis process does not recognize the potential decrease in the spill occurrence rate since the last spill in 2009.

The analysis also studied the impact that hurricanes had on pipeline spill frequency and spill volume. Hurricanes caused 4 of the 20 large spills that occurred from 1974 to 2015. Over the entire record, the number of pipeline spills fluctuates, with spills caused by hurricanes peaking for the years 2004, 2005, and 2008. Moreover, the majority of spills in the last 15 years were caused by hurricanes. The analysis team excluded pipeline spills caused by hurricanes for some analyses to examine trends in other causal factors, finding that all other spills per year followed a downward trend.

8.1.3. Tanker and Barge Conclusions

The number of spills worldwide and in U.S. waters for tankers and barges dramatically decreased after 1990 and has continued to gradually drop, even though crude oil movements have increased since the 1980s. The key finding related to tankers and barges is the correlation of improved spill rates with the phasing out of single-hull tankers and barges.

Worldwide tanker spills also tended to occur more often at sea than in port. The analysis team did not find any trends in the percentages of spills at each location by year. Over the entire record the percentage of spills that occurred at sea or in port each year tended to fluctuate. Spills involving ANS crude oil also tended to occur more often at sea than in port. Alternatively, tanker spills in U.S. waters tended to occur in port much more frequently than at sea. This trend reversal may be due to the geographical constraints the analysis team placed on tanker spills in U.S. waters. Compared to the worldwide tanker spill record, the spill record in U.S. waters encompassed a smaller area in which at sea spills would occur versus the area in which in port spills would occur.

A low number of new large spills were observed in the data since 2010. While this might suggest that the data are insufficient, it is interesting to note that there were large increases in the amounts of data available for some incidents of smaller size. The data processing stages carefully processed the most recent data, and additional supplementary sources were identified and analyzed to validate the small number of large spills. This was true for platforms and pipelines as well as for crude tankers and petroleum barges in U.S. waters.

8.2. Recommendations

Overall, the methodology used in this report is consistent with prior reports. This methodology is straightforward and conservative. The use of a relatively large date range for rate setting makes the rates more stable against fluctuations in emergent data. As a product of the key findings above, and difficulties encountered during the construction of these estimates, this analysis recommends the consideration of the following improvements for future versions of this report:

1. Consider conducting measurement and modeling of the correlation between the frequency of small and large spills. If correlation exists, it could help smooth the rates for less frequent, large spills.
2. Consider simulation techniques to estimate the likelihood of future worst-case scenario events. Current rates for spills ≥10,000 bbl have relatively little recent data upon which to be based, but the distribution of spill sizes, along with an understanding of current spill occurrence rates, could be used to simulate outcomes that are possible, but have never occurred.
3. Consider the cost of maintaining the international tanker spill database and determine whether rates for the U.S. waters are sufficient.
4. Consider whether ANS tanker spills analysis is still a sufficiently large exposure source for analysis.
5. Consider using international data for estimating rare spill frequencies and understanding their causal factors. Although less relevant to the OCS, the current data are insufficient at the highest spill size categories for developing robust estimates.

9. References

Alyeska Pipeline Service Company. (2016). *Throughput* [Dataset]. Retrieved from http://www.alyeska-pipe.com/TAPS/PipelineOperations/Throughput

Anderson, C.M. and LaBelle, R.P. (1990). Estimated occurrence rates for analysis of accidental oil spills on the U.S. Outer Continental Shelf. *Oil & Chem. Pollut.* 6, 21-35. Retrieved from http://www.boemre.gov/eppd/sciences/osmp/pdfs/AndersonAndLaBelle/AndersonAndLaBelle1990.pdf

Anderson, C.M. and LaBelle, R.P. (1994). Comparative Occurrence Rates for Offshore Oil Spills. *Spill Science & Technology Bulletin*, Vol.1 No. 2, 131-141. Retrieved from http://www.boemre.gov/eppd/sciences/osmp/pdfs/AndersonAndLaBelle/Anderson_LaBelle1944.pdf

Anderson, C.M. and LaBelle, R.P. (2000). Update of Comparative Occurrence Rates for Offshore Oil Spills. *Spill Science & Technology Bulletin*, Vol.6 No. 5/6, 303-321. Retrieved from http://www.boemre.gov/eppd/sciences/osmp/pdfs/AndersonAndLaBelle/AndersonAndLaBelle2000.pdf

Anderson, C.M. Mayes, M., and LaBelle, R.P. (2012). Update of Occurrence Rates for Offshore Oil Spills. Bureau of Ocean Energy Management OCS Report 2012-069. Herndon, VA: Bureau of Ocean Energy Management. Retrieved from http://www.boem.gov/uploadedFiles/BOEM/Environmental_Stewardship/Environmental_Assessment/Oil_Spill_Modeling/AndersonMayesLabelle2012.pdf

BP. (1975-2015). *BP Statistical Review of World Energy (1975-2015, annual reports)*. London: Whitehouse Associates. Retrieved from http://www.bp.com/statisticalreview

Efron, B. (1979). Bootstrap methods: Another look at jackknife. *Annals of Statistics* 7, 1-26. Retrieved from http://www.stat.cmu.edu/~fienberg/Statistics36-756/Efron1979.pdf

Federal Interagency Solutions Group. (2010). *Oil budget calculator: Deepwater horizon technical documentation*. Retrieved from http://www.restorethegulf.gov/sites/default/files/documents/pdf/OilBudgetCalc_Full_HQ-Print_111110.pdf

Ji, Z-G., W. Johnson and G. Wikel. (2014). Statistics of Extremes in Oil Spill Risk Analysis. *Environmental Science and Technology*. Published Online: August 9, 2014 DOI: 10.1021/es501515j.

Ji, Z.-G., W. Johnson, and Li, Z. (2011). Oil Spill Risk Analysis Model and Its Application to the Deepwater Horizon Oil Spill Using Historical Current and Wind Data, in Monitoring and Modeling the Deepwater Horizon Oil Spill: A Record-Breaking Enterprise. *Geophysical Monograph Series*, doi:10.1029/2011GM001117, pp. 227-236.

Kanji, G.K. (2006). *100 Statistical Tests* (3rd ed.). London, UK: SAGE Publications. Retrieved from https://www.researchgate.net/file.PostFileLoader.html?id=54928025d4c1180c708b478f&assetKey=AS%3A273654322008065%401442255683016

LaBelle, R.P. and Anderson, C.M. (1985). The Application of Oceanography to Oil-Spill Modeling for the Outer Continental Shelf Oil and Gas Leasing Program, *Marine Technology Society Journal*, Vol. 19, No. 2, 19-26. http://www.boemre.gov/eppd/sciences/osmp/pdfs/AndersonLabelle1985.pdf

Lanfear, K.J. and Amstutz, D.E. 1983. *A Reexamination of Occurrence Rates for Accidental Oil Spills on the U.S. Outer Continental Shelf*, 1983 Oil Spill Conference, American Petroleum Institute, Washington, DC

Ross, S.M. (1985). *Introduction to Probability Models*. Academic Press, Orlando, FL.

Smith, R.A., Slack, J.R., Wyant, T. and Lanfear, K. J. (1982). *The Oil Spill Risk Analysis Model of the U.S. Geological Survey*. USGS Professional Paper 1227, U.S. Geological Survey, Reston, VA. Retrieved from http://www.boemre.gov/eppd/PDF/smithetal.pdf

Table of Critical Values: Pearson Correlation [Dataset]. Retrieved from http://www.statisticssolutions.com/table-of-critical-values-pearson-correlation/

U.S. Army, Corps of Engineers (USACE). (2014). *Waterborne Commerce of the United States* [1974 to 2014, annual report]. U.S. Department of the Army Corps of Engineers, Waterborne Commerce Statistics Center, New Orleans, LA. Retrieved from http://www.navigationdatacenter.us/wcsc/wcsc.htm

U.S. Department of Commerce (DOC). (2000). *Annual Summaries of Alaskan North Slope Crude Oil Loadings (1977-1998).* U.S. Department of Commerce, Maritime Administration, Office of Policy and Plans, Washington, DC.

Zar, J. H. (2005). Spearman Rank Correlation. *Encyclopedia of Biostatistics*. http://onlinelibrary.wiley.com/doi/10.1002/0470011815.b2a15150/abstract

A. Trend Analysis

As in previous versions of this report, three different correlation analyses were used to identify trends in rare, large spill occurrences. All three tests involve the null hypothesis that a string or group of numbers is randomly generated. Under this assumption, the tests provide a means of comparing a calculated statistic to the expected distribution in order to determine whether the statistic reaches the critical value at which the null hypothesis can be rejected. If the statistic reaches a critical value, then the initial assumption of data randomness can be rejected—implying a trend.

Tests in which the desired result is the opposite of the null hypothesis are considered strong tests – the data must significantly conflict with the null hypothesis in order to conclude the alternative hypothesis. In this report, the null hypothesis is often the desired outcome since this implies the independence of the observations and the applicability of the Poisson distribution for spill estimates.

Each of the processes described below assumes the context in which these tests were applied in this report.

Kendall’s Rank Correlation Test

Process:

1. List the relevant incidents in order of occurrence (top to bottom).
2. Calculate the amount of exposure between each incident and the incident preceding it. (For the first incident, calculate the exposure since the start of the study, or the beginning of the exposure data.)
3. Transpose the exposure amounts to create a matrix with the original list on the left axis and the transposed list along to top axis.
4. For the lower left half (triangle) of the matrix, indicate with a “T” if the exposure amount along the left axis is larger than the exposure amount along the top axis. Indicate with an “I” if it is smaller. Do not fill in the central diagonal.
5. Count the number of “T”s and subtract the number of “I”s. This is the test statistic.

To illustrate:

Table A1. Kendall’s Rank Correlation Test Example

Incident #	Exposure Quantities	Transposed Exposure Quantities				
		0.3	**0.1**	**0.2**	**0.4**	**0.5**
1	**0.3**					
2	**0.1**	I				
3	**0.2**	I	T			
4	**0.4**	T	T	T		
5	**0.5**	T	T	T	T	

There are eight “T”s and two “I”s. There are five observations and the test statistic is 6. Further details on this test are available in Test 59, and the critical values table is Table 27 in: https://www.researchgate.net/file.PostFileLoader.html?id=54928025d4c1180c708b478f&assetKey=AS%3A273654322008065%401442255683016

The tests become weaker when there are equivalent exposure levels such as when events can occur simultaneously. It is hard to order. For this reason, the trend analyses performed for this report either removed hurricane spills or combined simultaneous hurricane spills in order to eliminate this issue.

The trend analysis presented in Anderson, Mayes, Labelle (2012) tracks the volume of crude produced between large spills. Three simultaneous spills would have resulted in two production volumes of 0 bbl, since production stops during hurricanes. This is confusing for performing the interpretation of the trend analysis statistics employed.

Runs-up, Runs-down Test

Process:

1. List incidents in order of occurrence.
2. Calculate the amount of exposure between each incident and the incident preceding it. (For the first incident, calculate the exposure since the start of the study, or the beginning of the exposure data, if relevant.)
3. Starting with the second incident, mark whether its associated exposure period is larger or smaller than the prior exposure period. Mark increases with a "+" and decreases with a "-".
4. Complete this for the set of incidents and count the number of "runs" of "+"s and "-"s.

The number of incidents and the number of runs are the necessary components for looking up the critical values and determining whether the runs indicate that the incident sequence is random or not. Table A2 provides an example.

Table A2. Runs Up, Runs Down Example

Incident Number	Preceding Exposure Amount	Marker
1	0.1	
2	0.34	+
3	0.75	+
4	1.1	+
5	0.5	-
6	0.6	+
7	0.5	-

A "run" is a string of incidents where the marker does not change signs. In this example, there are seven incidents and four runs.

Further details on this test are available in Test 67, and the critical values table is Table 30 in:

https://www.researchgate.net/file.PostFileLoader.html?id=54928025d4c1180c708b478f&assetKey=AS%3A273654322008065%401442255683016

Spearman Rank Correlation Test

This is equivalent to the Hotelling and Pabst's test, but uses an easier test statistic (the Pearson's correlation coefficient).

Process:

1. List incidents in order of occurrence and assign an ordinal rank.
2. Calculate the amount of exposure between each incident and the incident preceding it. (For the first incident, calculate the exposure since the start of the study, or the beginning of the exposure data, if relevant.)
3. Then, assign a rank to each of the exposure amounts, from least to greatest.
4. Compute the Pearson's Correlation Coefficient for the Incident Ordinal Rank.
5. Using that statistic, the number of observations, and this table, identify the significance level of the statistic.

The number of incidents and the number of runs are the necessary components for looking up the critical values and determining whether the runs indicate that the incident sequence is random or not.

Table A3 provides a Spearman rank correlation test example.

Table A3. Spearman Rank Correlation Test Example

Incident Ordinal Rank	Preceding Exposure Amount	Exposure Rank
1	0.1	1
2	0.3	2
3	0.8	6
4	1.1	7
5	0.7	5
6	0.6	4
7	0.5	3

To reiterate: with each of these tests, the original assumption (null hypothesis) is that the data are random. In the case of setting rates, this kind of randomness is good in that in implies the appropriateness of using the Poisson distribution and suggests that no significant trends are present.

For further details on this technique:

http://onlinelibrary.wiley.com/doi/10.1002/0470011815.b2a15150/abstract

Critical values table is available at:

http://www.statisticssolutions.com/table-of-critical-values-pearson-correlation/

B. The Bootstrap Method

The bootstrap method (Efron, 1979) is a statistical method for estimating a sampling distribution for a set of observations, especially when the underlying distribution of those observations is unknown. Consider this simplified example using familiar terms in this paper. Table B1 presents three exposure intervals for which the number of spill incidents is known.

Table B1. Exposure Interval Example

Exposure Interval	Number of Spills
1	0
2	1
3	2

Given this information, the best estimate spill rate is:

$$\frac{(0+1+2)\ incidents}{3\ units\ of\ exposure} = 1\ spill\ per\ exposure\ unit$$

Given this information, it would be possible to calculate the sample variance of the results and to construct a confidence interval using a standard bell curve distribution. However, because the sample size is so small and the sample variance somewhat large, the 95% confidence interval may well extend below zero and underestimate the lower bound.

The bootstrap method uses a simulation to identify the sampling distribution. To do this, a large number of 3-exposure unit trials are conducted, randomly selecting one of the spill counts from the distribution above. In this case, the distribution is that 0, 1, and 2 can each be picked with equal probability. Table B2 presents example results for the first several simulations.

Table B2. Example Simulation Results

	Observation #			
Trial Number	**1**	**2**	**3**	**Rate Estimate**
1	0	1	0	0.33
2	2	0	0	0.67
3	1	1	0	0.67
4	1	2	2	1.67
5	1	1	0	0.67
6	0	2	1	1.00
7	2	2	1	1.67

Finally, to calculate the upper and lower confidence interval bounds, simply take the appropriate percentiles of the randomly generated rate estimates:

For a two-sided 95% confidence interval, take the 0.025th and 0.975th percentiles.

For a 90% confidence interval, take the 0.05th and 0.95th percentiles.

This simulation technique requires many iterations for the percentiles to be able to converge to a stable confidence interval. The analyses in this report used 1,000 simulated trials and randomly generated observations for up to 20 exposure intervals.