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Persistence Of Crude Oil Spills On Open Water

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Final Report

for:
U.S. Department of the Interior
Minerals Management Service
Alaska Outer Continental Shelf Region
Anchorage, AK

by:

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

The Department of the Interior Mission

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

The Minerals Management Service Mission

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

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

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

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by:
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EXECUTIVE SUMMARY

The primary objective of this study was to develop mathematical descriptions of the persistence of crude oil spills at sea, as a function of spill size, based on a statistical analysis of historical spill data. These results could be used by the Minerals Management Service (MMS) to estimate defensible durations for spill trajectories in the MMS Oil Spill Risk Analysis for Alaska Outer Continental Shelf (OCS) waters.

The following definition of oil slick persistence was used for this study:

"An oil slick is considered to be persisting on the sea surface when it can be observed to be a coherent slick, or perceptible segments of a coherent slick, by normal methods of slick detection, such as aerial surveillance."

A survey of reports of oil spill incidents throughout the world was completed. Major oil spill incidents from the Torrey Canyon in 1967 to the Erika in 1999/2000 have generated an immense amount of literature, but the information on oil slick persistence (the critical parameter to this study) has seldom been detailed. The number of useable incidents was reduced, from an initial 154 to 84, by first removing the spills that occurred in inland or restricted waters (ports and harbors) then reduced further to 20 by applying other criteria (information availability, crude oil only). Of the final incident list, 13 were releases from tankers and 7 were oil well blowouts. In addition to these, a database of 12 experimental spills was compiled, for which good persistence data existed. These experimental spills all involved much smaller oil volumes.

Correlation analyses were carried out on three data sets and, although they by no means gave definitive results because of the small size of the sets, they did indicate the relative importance of different variables and their dependencies for each of the three data sets. Regression analysis with the three data sets showed that:

1. Wind speed did not have a statistically significant effect on persistence.
2. Countermeasures effort did not have a statistically significant effect on persistence.
3. The following regressions of historic spill data should be used by MMS to estimate the mean persistence of slicks on open water for modeling purposes:

For spills greater than or equal to 1000 barrels in size:

$$PD_{\geq 1000bbl} = 0.0001S - 1.32T + 33.1$$

Where,

- PD = Spill persistence in days
- S = Spill size in barrels
- T = Water temperature in degrees Celsius

For spills less than 1000 barrels in size:

$$PD_{<1000bbl} = 0.0034S + 2.02$$

Estimates of the statistical significance and 95% confidence intervals for these predictors are given in the report. Cumulative distribution function plots were prepared for several different discrete spill sizes.

The above conclusions apply to spills of most crude oils. Some crude oils (or more specifically, condensates) are very light, with an API Gravity exceeding 45.5°. Some of these very light crudes, or condensates have high Pour Points, and these would persist if they were spilled on water colder than their Pour Point. Many very light crudes, or condensates, have Pour Points that are less than ambient temperature and these will not persist as slicks on the open ocean. These very light crude slicks are likely to dissipate in less than one day.

To improve the data set for future statistical studies of oil persistence it is recommended that spill responders be encouraged to conduct frequent over-flights of large slicks and monitor weather and sea state conditions in the vicinity of the slicks until they dissipate offshore. As well, consideration should be given to studies of the basic mechanisms of slick dissipation at sea. The processes that eventually render persistent slicks undetectable may be the continuous fragmentation of the oil down to small particle sizes combined with horizontal dispersion of the "slick" over the sea surface, rather than conventional natural dispersion of small droplets into the water column. Until the mechanisms that control dissipation of a slick are understood, computer modeling cannot reasonably be expected to predict slick persistence or impacts.

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1. PROJECT BACKGROUND

The Minerals Management Service (MMS) has environmental impact assessment responsibilities under both the National Environmental Policy Act (NEPA) and the Outer Continental Shelf Lands Act (OCSLA), which are partially addressed through the use of oil spill modeling. In such modeling, the MMS typically uses standard time periods such as 1, 3, 10, and 30 days to analyze the effects of open water crude oil slicks. The analytical approach used by MMS includes a combination of trajectory modeling, oil-weathering modeling, and the results of a study completed for MMS in 1985 entitled *"Oil Slick Sizes and Length of Coastline Affected: A Literature Survey and Statistical Analysis"* (Ford, 1985). In this study, correlations are derived between spill size and length of coastline affected. Unfortunately, the correlations do not take into account spill persistence, and small spills, even far offshore, are presumed to be as likely to reach shorelines, as are large spills. This does not make intuitive sense and goes against the commonly held views of spill experts. The MMS in Alaska is particularly concerned about the issue because scenarios currently considered in Lease Sale Environmental Impact Statements (EISs) involve relatively small spills in the size range of 500 to 1000 barrels. MMS scientists may be asked in a court of law to defend statements regarding spill persistence and impact, and cannot easily defend their approach, especially as it related to relatively small spills.

Hypothetical spill trajectory shoreline contacts are collated and reported in the MMS oil spill trajectory model analysis, but the model analysis does not take into account the oil spill behavior processes of spreading, evaporation, emulsification and natural dispersion. These processes are dealt with separately by the use of a spill-behavior, or spill-weathering, model. There are a number of oil spill behavior models available internationally, but none is considered accurate in predicting the long-term fate of spills at sea. Knowing how long it takes for spills to dissipate at sea is crucial in accurately determining spill impact.

State-of-the-art oil weathering models are believed to be reasonably accurate in predicting the short-term behavior of marine spills (within hours or a day or two). This is because modelers can draw from a broad database on the short-term behavior of spills, actual or experimental. This is not true for the long-term behavior of spills. Consequently, most modelers today must arbitrarily select a point at which an oil spill finally “dissipates”. This is usually the point at which the effective thickness of the spill (meaning the volume of the oil on the surface, whether in slick or particle form, divided by the area of coverage) reaches some, low arbitrary value, such as 1 μm (1 x 10^{-3} mm) or 10 μm. None of the existing models predict surface-oil breakup and diffusion on the basis of empirical oil spill evidence, nor do databases for existing weathering models and other databases maintained by MMS and others compile the necessary spill information as to when slicks visibly dissipate as function of time and spill size. Spill size ranges of interest to MMS include 500 to 999 bbl; 1,000 to 9,999 bbl; 10,000 to 50,000 bbl; 50,000 to 150,000 bbl; and >150,000 bbl.

2. GENERAL DESCRIPTION, OBJECTIVE AND GOALS OF PROJECT

The primary objective of the study was to develop mathematical descriptions of the persistence of crude oil spills at sea, as a function of spill size, based on a statistical analysis of historical spill data. These results would then be used by MMS to estimate reasonable durations for spill trajectories in the MMS Oil Spill Risk Analysis for Alaska Outer Continental Shelf (OCS) waters. The correlation must be defensible in a court of law and must be based on actual spill experience and not theory. A secondary objective of the study was to refine the spill-size/spill-persistence correlation in terms of other variables such as oil type, weather and sea conditions, and spill type (e.g., batch spill versus blowout). It was recognized by MMS that satisfying this objective would be very difficult because of a perceived dearth of good historical spill data.

The goals of the project were to:

1. Compile and collate historical data on the persistence of crude oil slicks on open water;
2. Apply statistical methods to analyze persistence of crude oil slicks as a function of initial spill volume, environmental conditions, crude oil properties, and response effort; and,
3. Develop correlations, equations, or other empirical predictors of slick duration for the size categories used by MMS.

2.1 Discussions with Client

A post-award conference/teleconference was held in Anchorage with Alaska OCS Region and other MMS staff to ensure a clear understanding by all of study tasks, concerns, availability of relevant data and reports, and timelines. A brief summary of the key points discussed and outcomes from the meeting are provided below. These are included here because they guided much of the subsequent research and correlation.

A table of oil persistence factors that would be considered in the analysis of spill databases was presented, discussed and revised. The final table is presented below in the project methods section.

The issue of spill dissipation was discussed at length. Its definition was of obvious importance to the study. MMS was unsure what definition should apply and was open minded about what the project team might decide. It was agreed that spills would be considered "dissipated" even though some oil in fine-particle, or "tar ball", form were still on the surface. It was decided that the project team would derive a definition. The project team subsequently derived the following working definition:

"An oil slick is considered to be persisting on the sea surface when it can be observed to be a coherent slick, or perceptible segments of a coherent slick, by normal methods of slick detection, such as aerial surveillance."

It was further discussed what to do about spilled oil that hits shoreline and then, after some time, washes back to the marine environment. It was agreed that such oil should not be considered as part of the same spill, from a modeling point of view. For the purposes of this study, the persistence of a spill was the time taken for the spill to "dissipate" while still at sea before contacting any shore (note that the project dealt only with spills on open water, not in ice-covered waters).

It was agreed that a rational screening system would have to be developed for eliminating the bulk of reported spills that are of no use to the study. It was agreed to eliminate all spills for which either spill size or some measure of spill persistence could not be determined or estimated. To include as many spills as possible in the screening process, it was decided to define "persistence" or "dissipation" in terms of either discreet ranges or exact times depending on the available data. By choosing to define persistence as spills that persist for greater than 7 days, greater than 34 days, etc., spills could be included in the final data set that survived for at least X days before they were lost to observers. This substantially increased the number of spills in the final database. Without this refinement, a significant number of spills would have been rejected that were tracked for some time but were lost afterwards.

3. PROJECT METHODOLOGY

3.1 Literature/Database Review and Collation of Spill Persistence Parameters

Data Sources

A survey of reports of oil spill incidents throughout the world was completed. Data sources included MMS, NOAA, United States Coast Guard, and Environment Canada reports, Marine Pollution Bulletin, and the Oil Spill Intelligence Report. Sources of international experience and expertise, such as ITOPF, were also consulted. Much of the detail on the spills selected for inclusion in the database was obtained from technical papers published in the AMOP Technical Seminar proceedings and the Proceedings of the biennial Oil Spill Conference. The available information was assessed and is collated in a Microsoft Access database (Spill Database.mdb), which includes the specific references for the source of the data.

The U.S. Coast Guard Report "Past In-Situ Burning Possibilities" (Yoshioka et al. 1999) provided the starting point for the development of the database. The database developed for this report contains considerable information on historical oil spills occurring between the years of 1967 and 1997, for spills of over 10,000 barrels for North America and over 50,000 barrels for Europe and South America. For Europe and South America, this dataset only includes spills within 200 miles of shore for. For North America, spills within 200 miles of shore (including

Alaska, but excluding Hawaii) and spills in the Gulf of Mexico and the Caribbean Sea were included. The report analyses 141 total spills and provides information on such criteria as date, latitude and longitude, state/country, continent, volume spilled, and oil type.

Other oil spill data sources consulted in the search included; NOAA's Historical Incident Database (http://www.incidentnews.gov/incidents/history.htm), which provides details on oil and chemical spills around the world of over 100,000 barrels internationally and 10,000 barrels in US water. NOAA's Oil Spill Case Histories (http://response.restoration.noaa.gov/oilaids/spilldb.pdf) gives information on significant U.S. and international spills between 1967 and 1991. NOAA's Oil and Hazardous Materials Response reports detail oil and chemical incidents in the US coastal zones (http://response.restoration.noaa.gov/oilaids/spillreps/spillreps.html) to which NOAA provided technical or operational assistance. The MMS Spill Incident Database (http://www.mms.gov/incidents/pollution.htm) has information on spills from 1974 through 2003. Environmental Canada's Oil Spill Database (http://www.etcentre.org:8080/cgi-win/TankerSpill_e.exe?Path=\Website\river\) provides details on international tanker oil spills of over 1,000 barrels.

In addition, data from training exercises that have involved the intentional release of oil at sea and the numerous experimental releases of oils at sea that have been conducted during the last 30 years in European and Canadian waters were collected.

A listing of data sources consulted and the type of information they contain is given below.

1) U.S. Coast Guard Report CG-D-17-99 "Past In-Situ Burning Possibilities"

- Name, date
- Location (latitude and longitude)
- Volume (bbls)
- Product
- City, state, country, continent

2) NOAA Historical Incident Database

- Name, date
- Location

- Volume
- Product
- Cause
- Weather information
- Spill summary
- Spill behavior
- Response methods

3) NOAA Oil Spill Case History (US spill >10,000 gallons; International spills <100,000)

- Name, date
- Location
- Volume
- Product
- Cause
- Weather information
- Spill summary
- Spill behavior
- Response methods
- References

4) Environment Canada Spill Database (International ship spills > 1,000 barrels)

- Name, date
- Volume (bbls)
- Oil Type
- Cause
- Location of spill
- Short narrative

5) NRC Database

- Name, date
- Location
- Product
- Cause
- Volume
- Incident Summary

6) MMS Oil Spill Incident Database

- Name, date
- Location
- Product
- Volume
- Cause

- Distance to shore
- Depth of water

7) NOAA Oil & HM Spill Reports (93-99)

- Name, date
- Location
- Product
- Cause
- Volume
- Response methods
- Incident summary
- References

8) MSRC Report: An Analysis of Historical Opportunities for Dispersants and In-Situ Burning Use in the Coastal Waters of the United States, except Alaska

- Name, date
- Cause
- Location
- Product
- Volume
- Spill response methods

9) Oil Spill Intelligence Report

- Name, date
- Location
- Product
- Cause

10) USGC Marine Casualty and Pollution Database

- Name, date
- Product
- Source
- Response Information

11) International Oil Spill Conference Proceedings 1969-97

- Name, date
- Product
- Cause
- Weather Information
- Persistence
- Response Information

12) AMOP Technical Seminar Proceedings (1976 to 2002)

- Name, date
- Product
- Cause
- Weather Information
- Persistence
- Response Information

Sources for environmental data, including such factors as wave height, wave period, wind speed, and air/water temperature, included NOAA's Environmental Buoy Database and the Comprehensive Ocean – Atmosphere Data Set (COADS). The NOAA database contains weather and ocean related information collected from buoys and Coastal-Marine Automated Network stations around the Atlantic Ocean, Gulf of Mexico, central and western Pacific Ocean, North Pacific Ocean above 50°N, and the Eastern Pacific Ocean.

COADS is a joint effort between a NOAA's Climate Diagnostics Center (CDC), the Cooperative Institute for Research in Environmental Sciences (CIRES), the National Center for Atmospheric Research (NCAR), and NOAA's National Climatic Data Center (NCDC). It provides ocean data that has been compiled from ship reports over the global oceans.

1) NOAA Marine Environmental Buoy Database
- Wave height, period, spectra
- Wind speed, direction, gust
- Sea surface temperature
- Air temperature
- Air pressure

2) Comprehensive Ocean-Atmosphere Data Set
- Sea surface temperature
- Wind speed
- Air temperature

Spill Persistence Parameters

The prevailing conditions that influence the drifting, spreading and ultimate break-up of oil slicks can reasonably be expected to include wind speed, current speed, underlying water sediment load and wave conditions. Severe weather events, such as intense storms, will exert large influences on oil slick persistence.

The spilled oil properties that influence persistence likely include volatility, density, viscosity of the (perhaps emulsified) oil, and Pour Point of the spilled oil on the sea surface at a particular time.

Environmental data about a specific accidental oil spill was often sparse. Additional information to fill/fix data gaps was gathered by attempting to access other marine weather data sources. In those cases where weather data was available, it was difficult to determine a number that would adequately characterize a variable, particularly for those spills that persisted for a long time, or drifted for long distances from their origin.

Table 1 is a comprehensive list of the spill characteristics that were of interest for each oil spill. These data items formed the basis for the Access database field structure.

3.2 Oil Spill Database Development

A Microsoft Access Database (Spill Database) was compiled that included the spill information parameters identified in Table 1. Data sources were acquired and the spill information parameters found for each spill were entered into the database. Major oil spill incidents from the Torrey Canyon in 1967 to the Erika in 1999/2000 have generated an immense amount of literature, but the information on oil slick persistence (the critical parameter to this study) was seldom detailed. As well, many of the recorded spills occurred in inland or coastal waters that resulted in the slicks coming ashore, which removed them from consideration in the study. This severely limited the number of recorded spill incidents that could be included in the study.

Table 1: Comprehensive Data List

General	Weather	Sea Conditions	Oil Properties	Cleanup Methods
Date of Spill	Wind Speed	Current Speed	Type	Physical Recovery
Time of Day of Spill	Wind Direction	Current Direction	Flash Point	Dispersant Use
Volume of Spill	Air Temperature	Tides (Ebb/Flood)	Specific/API Gravity	Shoreline Cleanup
Location - Latitude - Longitude	Precipitation	Water Temperature	Viscosity	
	Air Pressure	Water Density	Emulsification Factor	
	Severe Weather Conditions	Water Depth	Pour Point	
Cause	Visibility	Sea State Wave Height Wave Period Wave Spectra	Initial Oil Layout/Distribution	
Spill Source				
City/State/ Country/ Water Body				
Distance from Shore				
Persistence				
Information Source				
Meta Data				

The number of usable spills was reduced based upon location (spills had to be offshore, in open water), information availability (if no information was available from which a persistence meeting the criteria listed above could be determined, the event was rejected) and oil type (only crude oil spills were used for the final statistical analyses). Discussions of why individual spills were rejected are included in the main Access database (Spill Database).

Selection of the spills was accomplished by first compiling a list of spills using the twelve report and database sets listed in Section 3.1, primarily the "Past In-situ Burning Possibilities" report, and any available NOAA and USCG online databases. The Internet was then searched for all spills listed, using several different search engines, noting the availability of spill data for each. Once completed, spills were eliminated where insufficient data was available. Each of the data sources described above was reviewed as possible sources of data. Although there were a number of sources listed, most were discounted for one reason or another. An example would be the Environmental Canada database, which has quite a comprehensive list of spills, but has very limited data fields. Where weather and sea state data were not available, attempts were made to procure that data from the National Weather Service and the NOAA weather buoy archives. This proved successful for spills in North American and European waters; however, additional weather and sea state data were not available for spills in other areas of the world. Overall, wind speed data could not be found for six of the 20 incidents on the final list.

3.3 Statistical and Numerical Analysis of Spill Persistence

The collected data was analyzed to determine statistically significant relationships between spill persistence and spill size, and spill persistence and other factors. A detailed account of the analyses completed can be found in the report accessible digitally through the following link (BerchaGroupFinalReport.pdf) or in separate hard-copy. The primary goal of the statistical assessment was to identify possible relationships between the dissipation times for spills and spill size. These times can be used by MMS as the end points for trajectory modeling. The spill size-range categories most useful to MMS are 500 to 999 bbl; 1,000 to 9,999 bbl; 10,000 to 50,000 bbl; 50,000 to 150,000 bbl; and >150,000 bbl, and these were considered in the analysis.

A secondary goal was to statistically analyze the data set to determine quantitative relationships between on-water spill persistence and (1) associated environmental factors; (2) the physical and chemical properties of the spilled oil; and (3) response effort parameters.

Following a review of the oil spill data sets it was ascertained that certain relationships or correlations are apparent among them. An investigation of these correlations utilizing classical statistical correlation and regression analysis indicated that certain combinations of parameters gave statistically significant relationships. Accordingly, use of statistical correlation and regression, together with appropriate tests of significance was conducted.

Regression Analysis : Overview

Regression analysis is a method of determining how one variable, the dependent variable, is numerically related to other independent variables. Regression analysis can be simple linear regression, logarithmic linear regression, polynomial regression, and multiple linear regression. Each of these methods was applied to various combinations of independent variables and both the regression coefficients and the P values were generated. All calculations were carried out for a 95% common confidence interval, CI. The magnitude of the Pearson's correlation coefficient, R^2, is an indicator of the accuracy of the regression. The P value is the estimated probability that the hypothesis, in this case the regression, is statistically significant. The smaller P values are an indicator of increasing statistical significance. In general, regressions giving P values less than 0.05 may be considered to be statistically significant.

The regression analyses were carried out utilizing a proprietary statistical analysis software package called "Analyse-It". This package provides the Pearson's correlation coefficients, standard error (SE), the slope and intercept values for the best-fit and their bounds within the 95% confidence interval. In addition, several graphical displays are given. The first graphical display is simply a plot of the best-fit regression line for which the coefficients were estimated. Next, the standardized residuals, which are the differences between the observed and predicted values, divided by the standard error are given, together with their histogram and fitted normal distribution. The primary measures utilized from these regression analyses were the values of R^2, the P-value, and the 95% confidence limits for each of the coefficients. All of the detailed regression analysis printouts are given in (BerchaGroupFinalReport.pdf).

Monte Carlo Simulation : Overview

Certain generalized distributions were found to characterize the correlation coefficients among the dependent variable, spill persistence, and one or more of the independent variables. To obtain measures of the probability of exceedence of the spill persistence, numerical or Monte Carlo simulation was applied to evaluate cumulative distribution functions from these probability distributions.

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

Consider the example of the following equation: $X = X_1S + X_2$. Where, X is the dependent variable (such as spill persistence in days), S is the size of the spill in barrels, and X_1 and X_2 are correlation coefficients. Suppose now that X_1 and X_2 are some arbitrary distributions that can be described by a collection of values x_1 and x_2. What is done in the Monte Carlo process, figuratively, is to put the collection of the X_1 values into one hat, the X_1 hat, and the same for the X_2 values – into an X_2 hat. A value is then randomly draw from each of the hats and the resultant value of the dependent variable, X, is computed. This is done several thousand times. Thus, a resultant or dependent variable distribution, X, is estimated from the computations of all valid combinations of the independent variables (X_1 and X_2), for a given S.

The resultant can be viewed as a cumulative distribution function. Such a cumulative distribution function (CDF) is also a measure of the accuracy or, conversely, the variance of the distribution. If the CDF is a vertical line, no matter where one draws on the vertical axis, the same value of the variable will result – that is, the variable is a constant. At the other extreme, if the variable is completely random then the distribution will be represented as a diagonal straight line between the minimum and maximum value.

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

4. RESULTS

4.1 Final Database

The original USCG database (Yoshioka et al. 1999) contains 141 incidents. This was eventually increased to a total of 154 by accessing other spill incident data sources. The number of useable incidents was reduced from 154 to 84 by removing the spills that occurred in inland or restricted waters (rivers, ports and harbors) and then reduced to 20 by applying the other criteria (information availability, crude oil only) listed in Section 3.2. Of the final 20 incidents, 13 were releases from tankers and 7 were oil well blowouts. In addition to these, a database of 12 experimental spills was compiled, for which good persistence data existed. These spills all were much smaller oil volumes than the tanker releases, and were thus kept in a separate database. A listing of all the data included in each of the 32 incidents is in the back of the hard copy version of the Bercha report.

The final data sets used for the analysis are summarized in Table 2, Table 3 and Table 4 for tanker, experimental, and blowout spills respectively. One tanker incident (*Atlantic Empress)* contained in the database was not included in the final list for statistical analysis, because the reported spill volume was highly questionable (likely the entire ship's cargo of 1,000,000 bbls, rather than the unknown amount released at the end of the incident that was tracked until it dissipated). One blowout (Norwuz) was likewise not included in the final list in Table 4 because the only information recorded was the estimated flow rate of the well early in the year-long incident, not the total discharged over the entire time span of the release. Spill #19 in Table 4 is a pipeline spill, but is included with the blowouts because a "live" pipeline spill has a similar release behavior to that of a sub-sea blowout.

Table 2: Tanker Spills

No[1]	Spill Name	Spill Persistence (days)	Year Spill Occurred	Spill Size (bbl)	Oil Specific Gravity	Water Temperature (°C)	Wind Speed (m/s)	Countermeasures Used (Yes/No)
2	Asimi	11	1983	379000	0.851	25.0	8.0	N
3	Texaco Caribbean	9	1987	60000	0.851	23.8	-	N
4	Torrey Canyon	60	1967	366500	0.869	10.3	8.8	Y
6	Kirki	4	1991	135000	0.823	21.1	18.0	N
7	Glacier Bay	18	1987	3800	0.896	4.9	6.6	Y
9	Aragon	21	1989	175000	0.922	19.0	7.6	N
10	Khark 5	18	1989	454000	0.871	18.9	-	Y
11	Burmah Agate	9	1979	254761	0.828	20.0	8.1	Y
12	Exxon Valdez	56	1989	257142	0.894	4.0	7.0	N
15	Stuyvesant (II)	8	1987	14285	0.896	8.0	8.4	N
17	Mega Borg	15	1990	100000	0.832	28.0	4.7	Y
20	Seki	14	1994	47619	0.865	23.8	-	N

[1] Spill number identifier as assigned in Bercha's study for tank vessel and blowout spills.

Table 3: Experimental Spills

No[1]	Spill Name	Spill Persistence (days)	Year Spill Occurred	Spill Size (bbl)	Oil Specific Gravity	Water Temperature (°C)	Wind Speed (m/s)
1		5	1972	840	0.858	10	-
2		1	1976	70	0.850	11	1.3
3		0.5	1977	70	0.850	7	7.5
4	Haltenbanken 82	5	1982	700	0.820	12	7.0
5	Forties 1987	4	1987	140	0.835	15	6.5
6	Haltenbanken 89	4	1989	210	0.850	10	6.5
7		4	1992	105	0.835	11	6.5
8	AEA 94	3	1994	105	0.835	15	2.5
9	Charlie 95	3	1995	105	0.835	15	6.5
10	AEA '97	2	1997	350	0.822	18	5.5
11	AEA '97	2	1997	350	0.822	18	5.5
12	AEA '97	2	1997	230	0.893	18	5.0

[1] Spill number identifier as assigned in Bercha's study for experimental oil spills.

Table 4: Blowout Spills

No[1]	Spill Name	Spill Persistence (days)	Year Spill Occurred	Spill Size (bbl)	Oil Specific Gravity	Water Temperature (°C)	Wind Speed (m/s)	Countermeasures Used (Yes/No)
1	Uniacke Blowout	1	1984	3000	0.802	1	11.0	N
13	Trinimar Well 327	9	1973	36650	0.820	24.6	-	N
14	PEMEX/YUM II	32	1987	56000	0.860	19.7	-	N
16	Chevron Main Pass Block 41	1	1970	65000	0.855	14	7.1	Y
18	Ekofisk Bravo Oil Field	54	1977	202381	0.846	6	8.5	N
19	Piper/ Claymore	12	1986	18000	0.850	3	-	N

[1] Spill number identifier as assigned in Bercha's study for tank vessel and blowout spills.

4.2 Correlation Analysis

The oil spill data sets were delivered to Bercha Group for statistical analysis. An inspection of the data revealed that the main quantitative variables relating to spill persistence were:

- Spill size
- Oil specific (or API) gravity
- Water temperature

Wind speed and countermeasures effects were also considered.

All of the spill records contained spill persistence; however, several records did not include specific gravity and water temperature. Specific gravities for those oils for which these data were not given were estimated from the qualitative description of the oil. Missing water temperatures were estimated using a correlation with spill latitude and water temperature.

An examination of the effects of wind speed and spill countermeasures on spill persistence was carried out. Wind speed, when available, was included in the data sets. The wind speed most often quoted was an average value over the period that the oil slicks persisted. This average value may conceal episodes of high or low wind speed or changes in wind direction that would contribute to slick break-up. For statistical analysis purposes, countermeasures were simply noted as being included (Y) or excluded (N) for tanker and blowout spills.

Tanker Spill Data Correlations

Figure 1 summarizes the values of the coefficient of correlation (R^2) and shows the least squares linear regression straight lines for the relationship between spill persistence in days and each of the three independent variables for the tanker spill data. As can be seen, the highest value of the correlation coefficient occurs for the water temperature, at a value of 0.32, with the next highest occurring for the spill size at a value of 0.17. The wind speed correlation coefficient at 0.07 is very low, indicating virtually no correlation with wind speed.

Experimental Spill Data Correlations

Figure 2 shows the correlation between spill persistence and the independent variables for experimental spill data. Here, clearly, the best correlation with a correlation coefficient of 0.34 occurs for the spill size variable. Again, wind speed correlation is low. Temperature and specific gravity give insignificant correlations.

Blowout Spill Data Correlations

Finally, Figure 3 shows the correlations among spill persistence and the independent variables for blowout spills. Again, the strongest correlation is shown for the spill size variable here. Wind speed correlation is very low; temperature correlation is non-existent.

Summary

Table 5 summarizes the values of the coefficient of correlation (R^2) for the relationships between the spill persistence in days and each of the four main independent variables for the three spill categories. Countermeasures could not be included in this analysis since it was recorded as a Yes/No value only.

Table 5: Coefficient of Correlation Summary

Spill Category	R^2 for Independent Variable			
	Spill Size	Specific Gravity	Temperature	Wind Speed
Tanker Spills	0.167	0.137	0.374	0.069
Experimental	0.344	0.039	0.013	0.133
Blowouts	0.729	0.183	0.000	0.026

Tanker Spills

No	Spill Name	PD	S	SG	T	W	CM
2	Asimi	11	379000	0.851	25.0	8.0	N
3	Texaco Caribbean	9	60000	0.851	23.8	-	N
4	Torrey Canyon	60	366500	0.869	10.3	8.8	Y
6	Kirki	4	135000	0.823	21.1	18.0	N
7	Glacier Bay	18	3800	0.896	4.9	6.6	Y
9	Aragon	21	175000	0.922	19.0	7.6	N
10	Khark 5	18	454000	0.871	18.9	-	Y
11	Burmah Agate	9	254761	0.828	20.0	8.1	Y
12	Exxon Valdez	56	257142	0.894	4.0	7.0	N
15	Stuyvesant (II)	8	14285	0.896	8.0	8.4	N
17	Mega Borg	15	100000	0.832	28.0	4.7	Y
20	Seki	14	47619	0.865	23.8	-	N
		R^2	0.167	0.137	0.324	0.069	

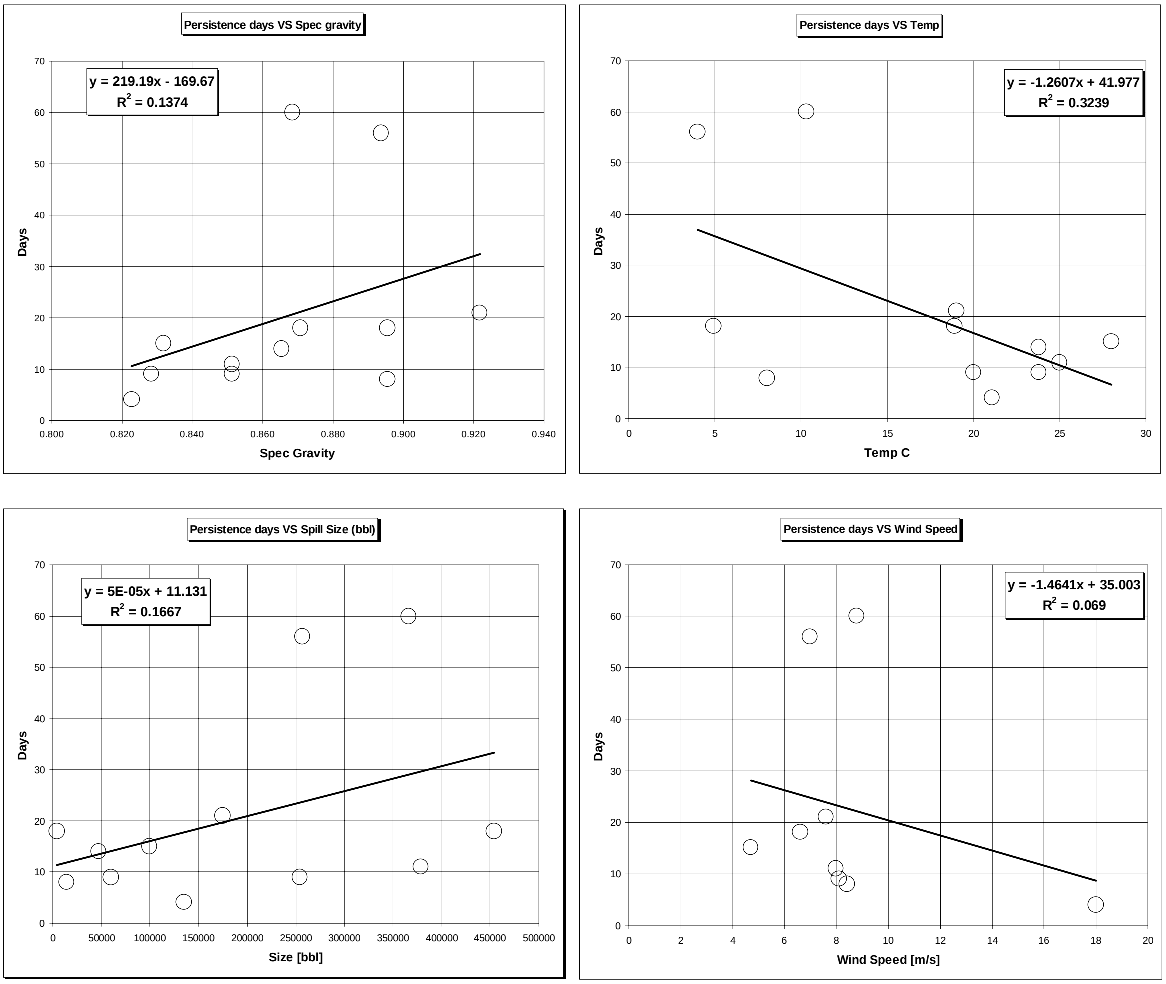


Figure 1: Correlations Among Tanker Spill Persistence Variables

Experimental Spills							
No	**Spill Name**	**PD**	**S**	**SG**	**T**	**W**	**CM**
1		5	840	0.858	10	-	-
2		1	70	0.850	11	1.3	-
3		0.5	70	0.850	7	7.5	-
4	**Haltenbanken 82**	5	700	0.820	12	7.0	-
5	**Forties 1987**	4	140	0.835	15	6.5	-
6	**Haltenbanken 89**	4	210	0.850	10	6.5	-
7		4	105	0.835	11	6.5	-
8	**AEA 94**	3	105	0.835	15	2.5	-
9	**AEA 94**	3	105	0.835	15	6.5	-
10	**AEA '97**	2	350	0.822	18	5.5	-
11	**AEA '97**	2	350	0.822	18	5.5	-
12	**AEA '97**	2	230	0.893	18	5.0	-
		R^2	**0.344**	**0.039**	**0.013**	**0.133**	

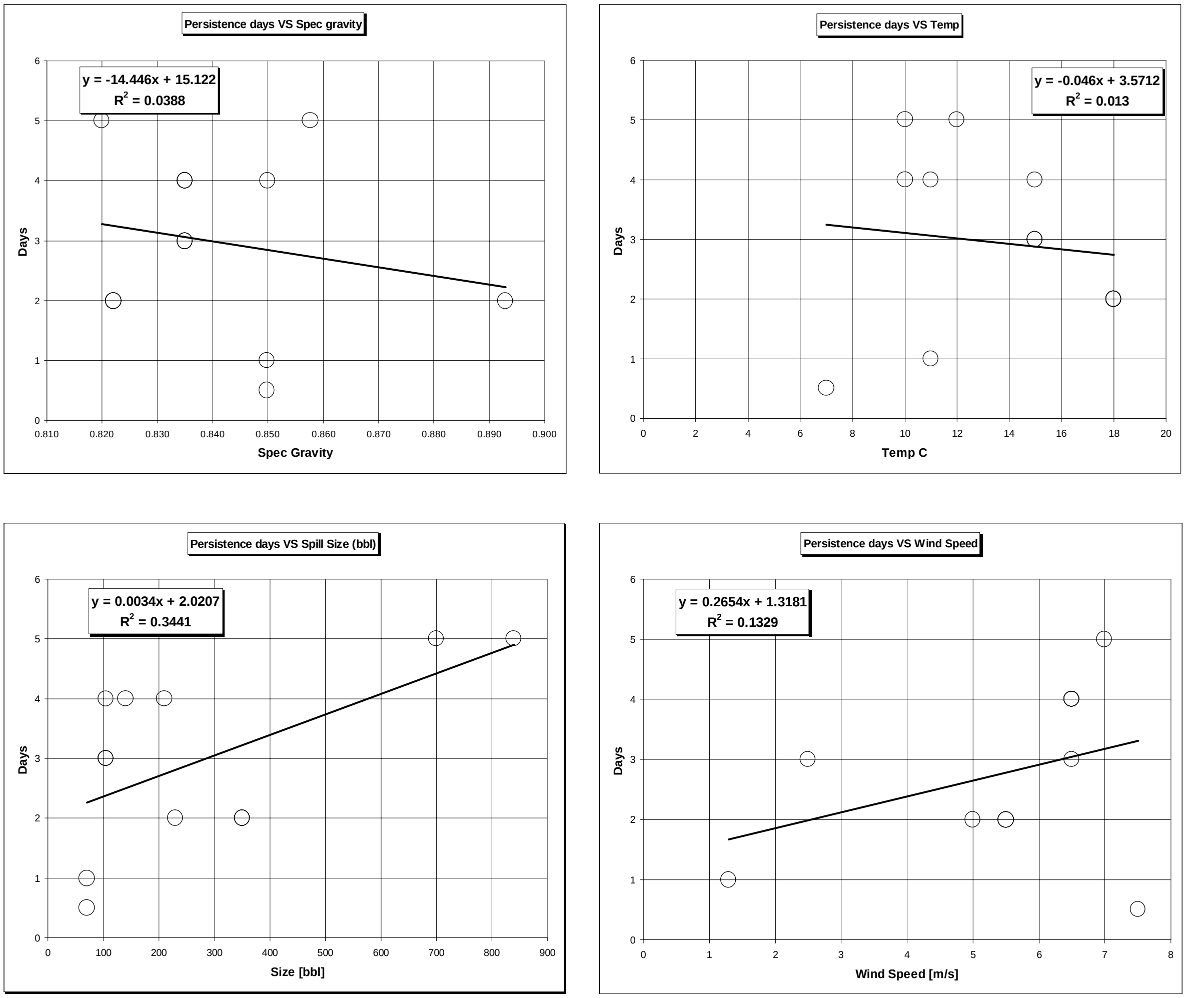


Figure 2: Correlations Among Experimental Spill Persistence Variables

Blowout Spills							
No	**Spill Name**	**PD**	**S**	**SG**	**T**	**W**	**CM**
1	**Uniacke Blowout**	1	3000	0.802	1	11.0	N
13	**Trinimar Well 327**	9	36650	0.820	24.6	-	N
14	**PEMEX/YUM II**	32	56000	0.860	19.7	-	N
16	**Chevron Main Pass Block 41**	1	65000	0.855	14	7.1	Y
18	**Ekofisk Bravo Oil Field**	54	202381	0.846	6	8.5	N
19	**Piper/ Claymore**	12	18000	0.850	3	-	N
		R²	**0.729**	**0.183**	**0.000**	**0.026**	

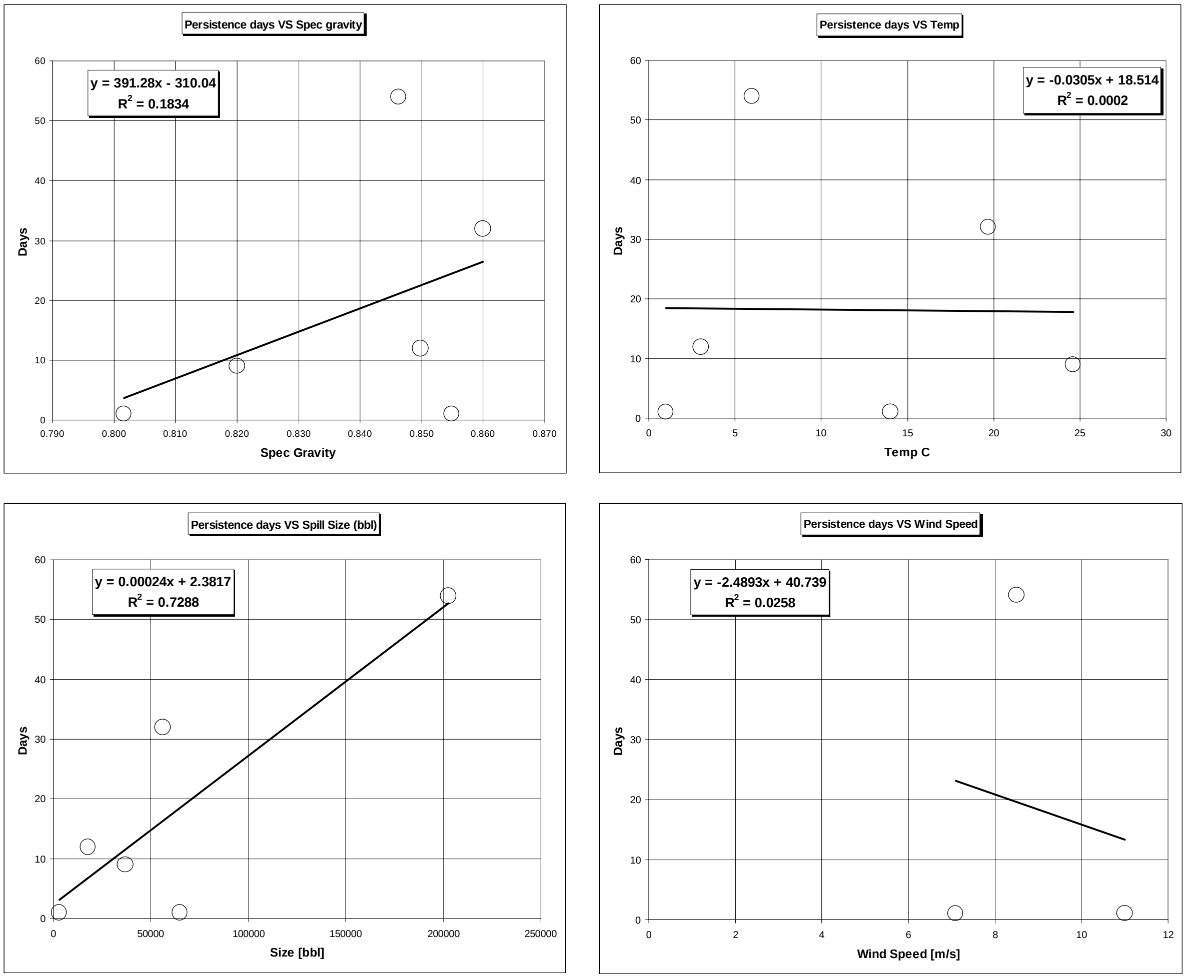


Figure 3: Correlations Among Blowout Spill Persistence Variables

Conclusions from Correlation Analysis

Although these correlation analyses have by no means given definitive results, they do indicate the relative importance of different variables and their dependencies for each of the three data sets. The following preliminary conclusions can be reached from the correlation analyses:

- For tanker spills, correlation between persistence and spill size and water temperature should be investigated further.
- For experimental spills, the only promising correlation is that between spill persistence and spill size.
- For blowout spills, the most promising correlation is also between spill persistence and spill size.
- Although correlations of the effect of wind on spill persistence are very low, the effect of wind could be further investigated by plotting two data subsets of spill persistence for high and low wind speeds.
- A similar approach for the effect of countermeasures on tanker and blowout spills could be attempted.

4.3 Regression Analysis

Regression analyses were completed using five different methods (linear, log linear, polynomial, multiple linear, and log multiple linear) for each of seven combinations of independent variables:

1. Spill size (S);
2. Specific gravity (SG);
3. Temperature (T);
4. S, SG, T;
5. S, SG;
6. S, T; and,
7. SG, T

for the three classes of spills.

Tanker Spill Data Regression Analysis

Table 6 summarizes the results of the regression analyses using four different methods for each of seven combinations of independent variables for tanker spills. As can be seen, the sixth combination, persistence and spill size and water temperature manifests the highest statistical significance. Both the multiple linear regressions and the logarithmic multiple linear regressions show high values (0.52) of the regression coefficient R^2, and values less than 0.05 of the P value, suggesting statistical significance. Accordingly, the multiple linear regression analysis between spill persistence, spill size and temperature (S, T) was selected for further statistical investigation. This additional statistical investigation consisted of plotting the expected spill size variation within the 95% confidence interval for representative water temperatures of 0°, 10°, and 20°C. The multiple regression equation for this combination of variables is given below:

$$\mathbf{PD_{Tv} = 0.0001S - 1.32T + 33.1} \qquad \textbf{(1)}$$

Where,

- PD_{Tv} = Spill persistence in days for tank vessel spills
- S = Spill size in barrels
- T = Water temperature in degrees Celsius

This equation was used as a basis to determine the envelope of spill persistence expectations within the 95% confidence interval. Figures 4, 5, and 6 show graphs of the bounds for these expectations for the 95% confidence interval for temperatures of 0°C, 10°C, and 20°C, respectively. For a spill size of 200,000 barrels, the persistence at 95% confidence interval ranges from approximately 20 to approximately 80 days, for the low temperature case. Although this is quite a large range, it must be kept in mind that the confidence interval is quite significant as this means that there is a 95% chance that the persistence will be within that boundary with an increasing probability that it will be at the predicted value of approximately 50 days for that spill size. A similar interpretation can be given for the higher temperatures.

Table 6: Summary of Different Regression Analysis Results for Tanker Spills (Lowest value of P highlighted)

No	Independent Variable	Method	R^2	P
1	Size (S)	Linear	0.17	0.188
		Log Linear	0.07	0.423
		Polynomial	0.20	0.364
2	Spec. Gravity (SG)	Linear	0.14	0.236
		Log Linear	0.27	0.084
		Polynomial	0.22	0.326
3	Temperature (T)	Linear	0.32	0.054
		Log Linear	0.27	0.082
		Polynomial	0.33	0.164
4	S, SG, T	Multiple Linear	0.53	0.098
		Log M Linear	0.61	0.049
5	S, SG	Multiple Linear	0.34	0.153
		Log M Linear	0.45	0.067
6	S, T	Multiple Linear	0.52	0.036
		Log M Linear	0.52	0.038
7	SG ,T	Multiple Linear	0.32	0.171
		Log M Linear	0.34	0.157

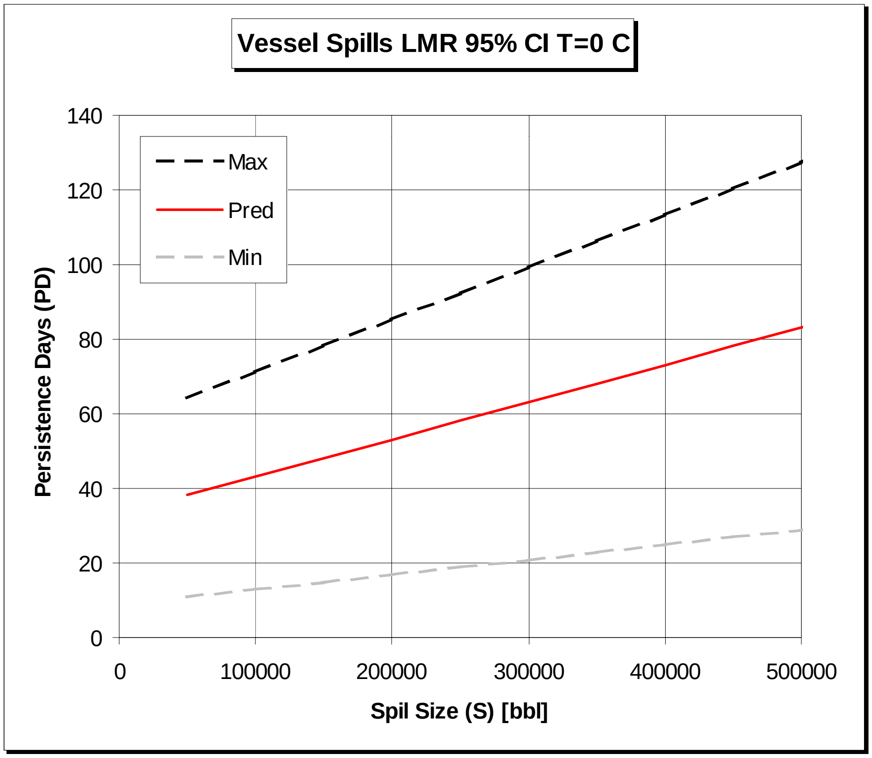


Figure 4: 95% CI Spill Persistence Variation with Spill Size for Water Temperature of 0°C

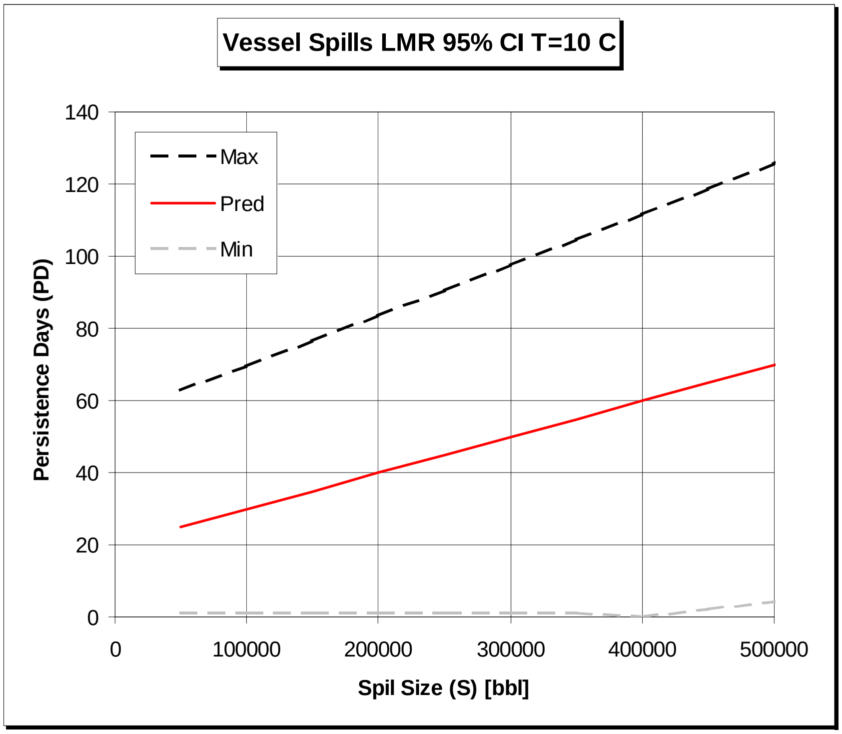


Figure 5: 95% CI Spill Persistence Variation with Spill Size for Water Temperature of 10°C

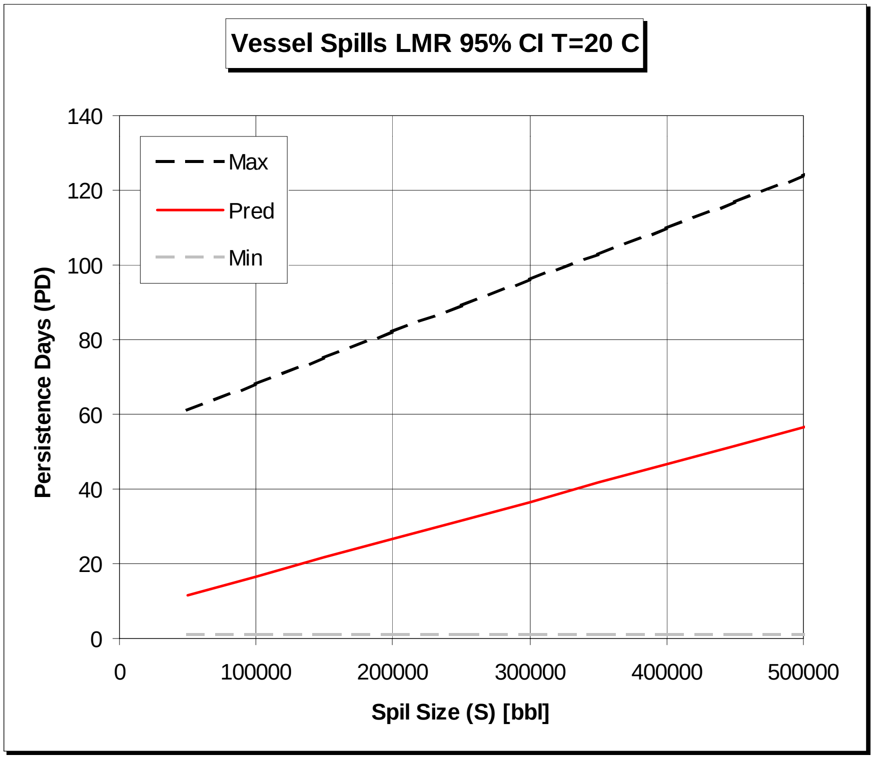


Figure 6: 95% CI Spill Persistence Variation with Spill Size for Water Temperature of 20°C

Experimental Spill Data Regression Analysis

For experimental spills, a similar series of different linear, logarithmic, polynomial, and multiple linear and multiple logarithmic regressions were carried out. Table 7 summarizes the results of these regression analyses.

In this case, the first linear regression analysis between spill size and persistence gives the most favorable indicator of statistical significance of R^2, at a value of 0.34, and a P value of 0.045.

The resultant equation is:

$$\mathbf{PD_E = 0.0034S + 2.02} \qquad \mathbf{(2)}$$

Where,

- PD_E = Spill persistence in days for experimental spills
- S = Spill size in barrels

Table 7: Summary of Different Regression Analysis Results for Experimental Spills
(Lowest value of p highlighted)

No	Independent Variable	Method	R^2	p
1	Size (S)	Linear	0.34	0.045
		Log Linear	0.31	0.626
		Polynomial	0.36	0.133
2	Spec. Gravity (SG)	Linear	0.04	0.539
		Log Linear	0.04	0.512
		Polynomial	0.04	0.832
3	Temperature (T)	Linear	0.01	0.725
		Log Linear	0.07	0.393
		Polynomial	0.45	0.067
4	S, SG, T	Multiple Linear	0.38	0.261
		Log M Linear	0.34	0.311
5	S, SG	Multiple Linear	0.37	0.129
		Log M Linear	0.33	0.169
6	S, T	Multiple Linear	0.35	0.141
		Log M Linear	0.33	0.167
7	SG, T	Multiple Linear	0.06	0.768
		Log M Linear	0.10	0.614

The 95% confidence interval expectations from this linear regression are shown in Figure 7. The experimental spill data provide persistence in a small spill size range (less than 1,000 barrels) for which there was no data on tanker spills.

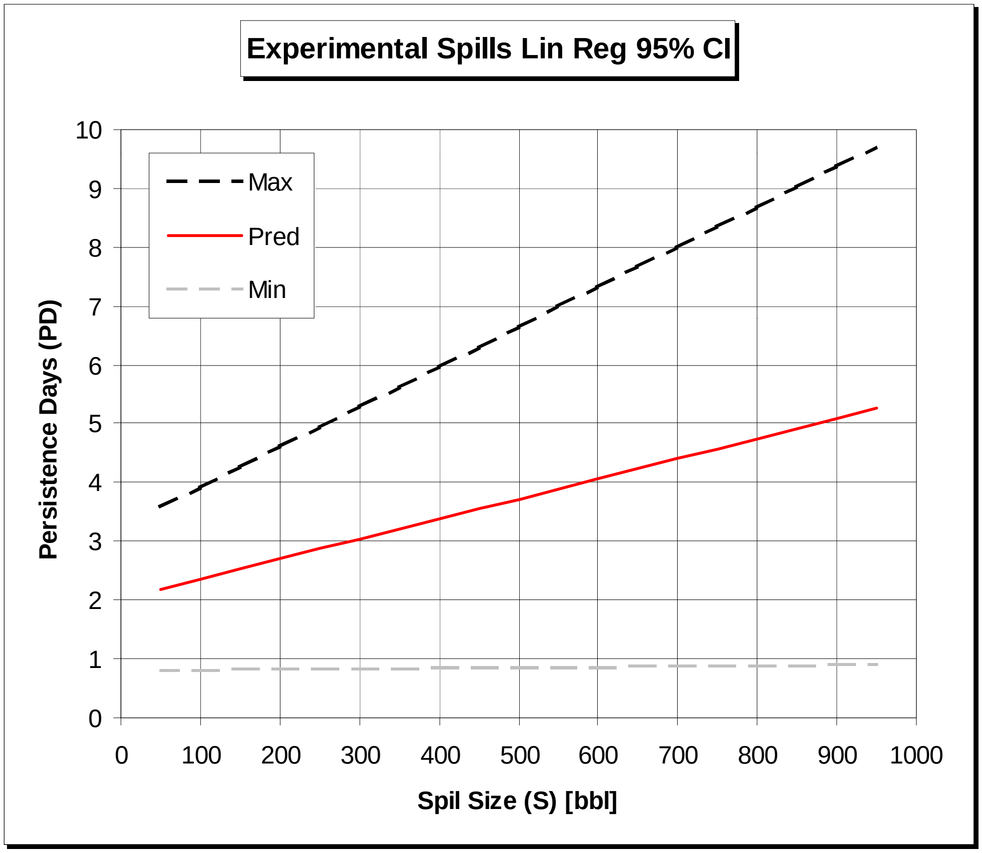


Figure 7: 95% CI Spill Persistence Variation with Spill Size for Experimental Spills

Blowout Spill Data Regression Analysis

Table 8 summarizes the results of various regression analyses for blowout spills. Again, the first combination of dependent and independent variables for the simple linear regression method gives the most favorable levels of statistical significance with R^2 and P values of 0.73 and 0.031, respectively.

The associated equation is:

$$\mathbf{PD_B = 0.0002S + 2.38} \qquad \textbf{(3)}$$

Where,

- PD_B = Spill persistence in days for blowout spills
- S = Spill size in barrels

The spill persistence 95% confidence interval expectation envelope is illustrated for blowout spills in Figure 8.

Table 8: Summary of Different Regression Analysis Results for Blowout Spills (Lowest value of p highlighted)

No	Independent Variable	Method	R^2	p
1	Size (S)	Linear	0.73	0.031
		Log Linear	0.39	0.185
		Polynomial	0.73	0.137
2	Spec. Gravity (SG)	Linear	0.18	0.397
		Log Linear	0.22	0.354
		Polynomial	0.23	0.669
3	Temperature (T)	Linear	0.00	0.979
		Log Linear	0.11	0.512
		Polynomial	0.12	0.832
4	S,SG,T	Multiple Linear	0.74	0.362
		Log M Linear	0.41	0.741
5	S,SG	Multiple Linear	0.74	0.132
		Log M Linear	0.39	0.475
6	S,T	Multiple Linear	0.73	0.141
		Log M Linear	0.41	0.458
7	SG,T	Multiple Linear	0.19	0.724
		Log M Linear	0.23	0.676

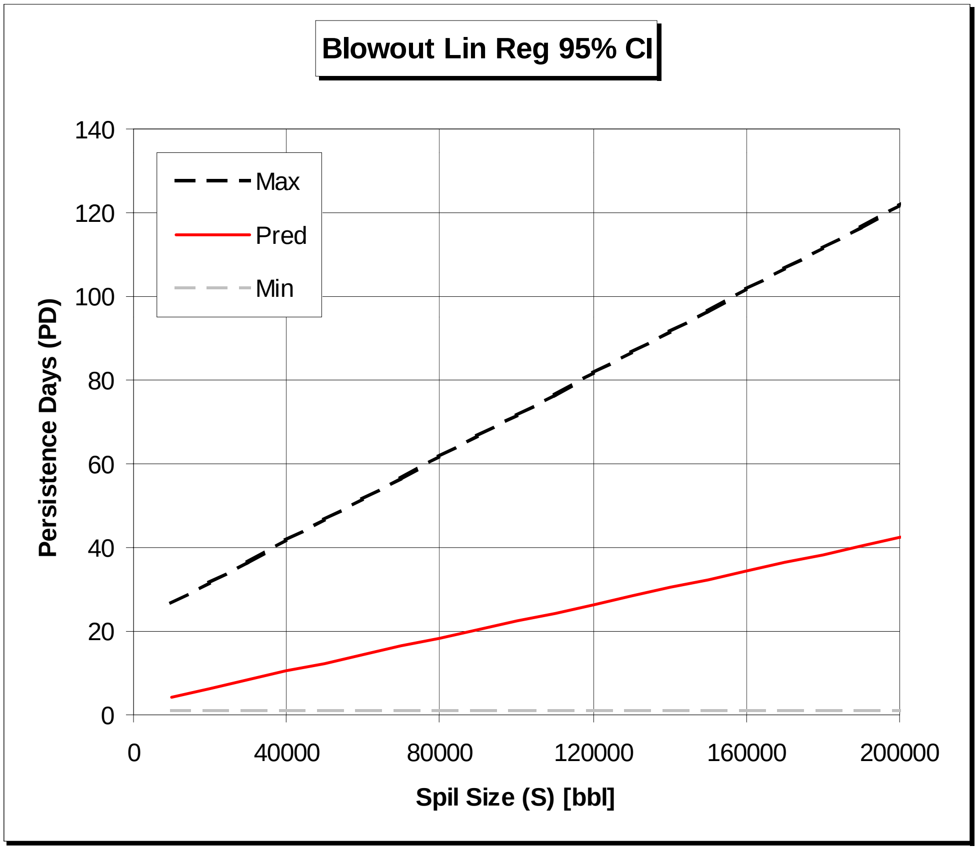


Figure 8: 95% CI Variation in Spill Persistence with Spill Size for Blowout Spills

Effect of Wind Speed on Spill Persistence

The tanker spills data set was subdivided into two data sets, one with the higher set of wind speeds, and the second with the lower set. Essentially, the data points with wind speeds from 8 to 18 m/s were considered to be associated with higher winds, while the balance were considered to be associated with lower winds. The rate of natural dispersion is thought to undergo a step-change at around 4 to 7 m/s wind speed with the onset of cresting waves. A linear multiple regression was then carried out, resulting in the following equation for high wind speed:

$$\mathbf{PD_{Tv,HW} = 0.0001S - 2.74T + 33.38} \qquad \mathbf{(4)}$$

And the following equation for the low wind speed sub-data set:

$$PD_{Tv,LW} = 0.0001S - 0.90T + 22.39 \qquad (5)$$

The plot of these two equations on the same graph, for representative temperatures (in this case, for 10°C), is shown in Figure 9. Although the low wind speed shows slightly higher persistence tendency, as one would intuitively expect, the results have no statistical significance. The 95% confidence interval is so large that it lies outside the axis of the graph, indicating that both plots do not show any difference within the 95% confidence interval.

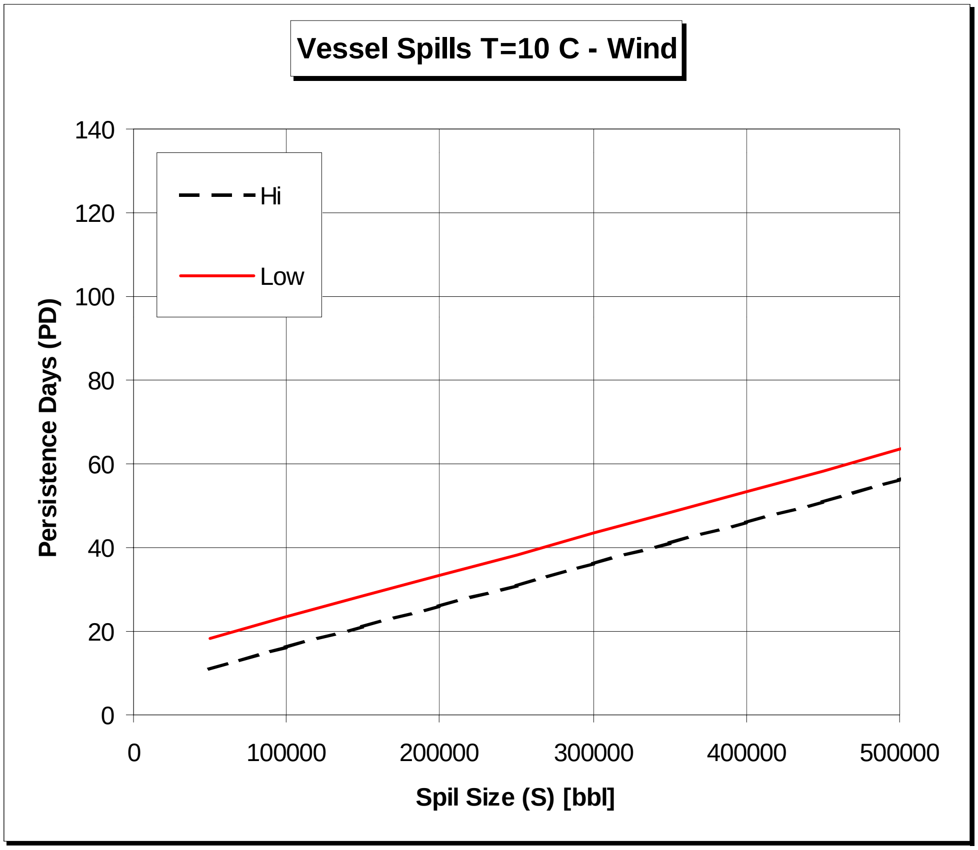


Figure 9: Linear Multiple Regression Plot of Effect of Wind Speed on Spill Persistence

Effect of Countermeasures on Spill Persistence

In the case of countermeasures, the tanker spill data set was subdivided into two subsets; one for spills where countermeasures were present, and one for those in which they were absent. Again a multiple linear regression analysis of the tanker spills was carried out, resulting in the following two equations, with Equation 6 corresponding to the presence of countermeasures, and Equation 7 corresponding to the absence of countermeasures.

$$\mathbf{PD_{Tv,C} = 0.00005S - 1.14T + 31.12} \qquad \mathbf{(6)}$$

$$\mathbf{PD_{Tv,\,NC} = 0.00006S - 1.46T + 34.82} \qquad \mathbf{(7)}$$

Again, the results were plotted for a representative temperature of 10°C, yielding the graph shown in Figure 10. The difference shown in this graph is again statistically insignificant, with the confidence interval lying well outside the scale of the graph. Again, the two lines intuitively show a similar physically plausible trend, with the 'no countermeasures' line showing slightly higher persistence than the line at the bottom with countermeasures. For both of these analyses, alternative representative temperatures of 0°C and 20°C were also investigated, with no improvement in statistical significance.

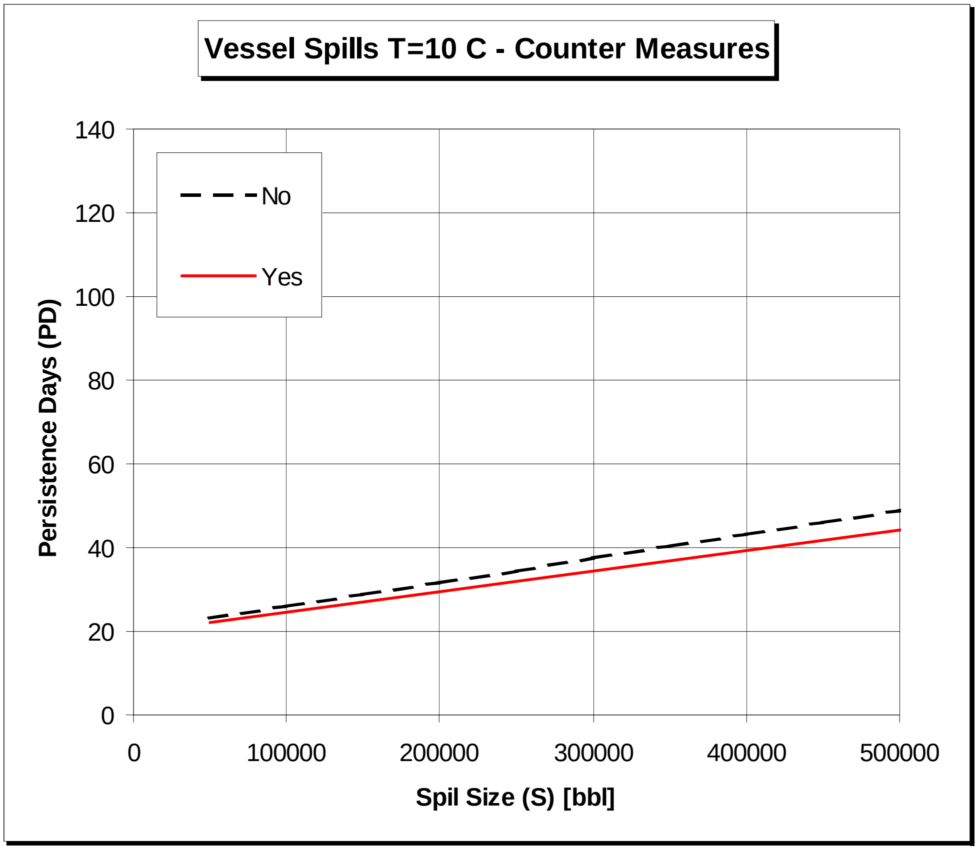


Figure 10: Linear Multiple Regression Plot of Effect of Countermeasures on Spill Persistence

4.4 Monte Carlo Approach to Spill Persistence Analysis

The Monte Carlo method was used to generate probability densities that were then transformed into cumulative distribution functions (CDFs), or probabilities of exceedence, for oil spill persistence. Numerical distributions for each of the regression coefficients were generated from statistical confidence limit data and probability distributions of the spill persistence associated with the most statistically significant regression equations for each of the three data sets (Equations 1, 2, and 3).

Tanker Spill Monte Carlo Analysis

Figure 11 shows a graphical form of the cumulative distribution functions generated for each of three spill size ranges: 10,000 (10K); 100,000 (100K); and, 1,000,000 (1000K) barrels. Each of the graphs in Figure 11 show three lines, one each for 0°C, 10°C, and 20°C water temperatures. These cumulative distribution functions can be used to assist in the prediction of the likelihood of the persistence of spills of various sizes. For instance, consider the case of the 100,000-barrel (100K) spill illustrated in the second graph in Figure 11. Consider the middle line, corresponding to a temperature of 10°C. First, we can see at the 0.5 probability level, one could expect the longest that such spills would persist is approximately 32 days. However, there is a 10% (0.1) chance that such spills would persist no more than 10 days and a 90% chance that the spills will persist no more than 55 days. Similar conclusions can be drawn for the low temperature and the high temperature spills, and the other representative sizes.

Experimental Spill Monte Carlo Analysis

Figure 12 shows similar cumulative distribution functions (CDF) for the experimental spills, for sizes ranging from 100 to 2,000 barrels. This CDF is useful because it covers a range of spill sizes (< 1,000 bbl) for which data were inadequate from the tanker spills.

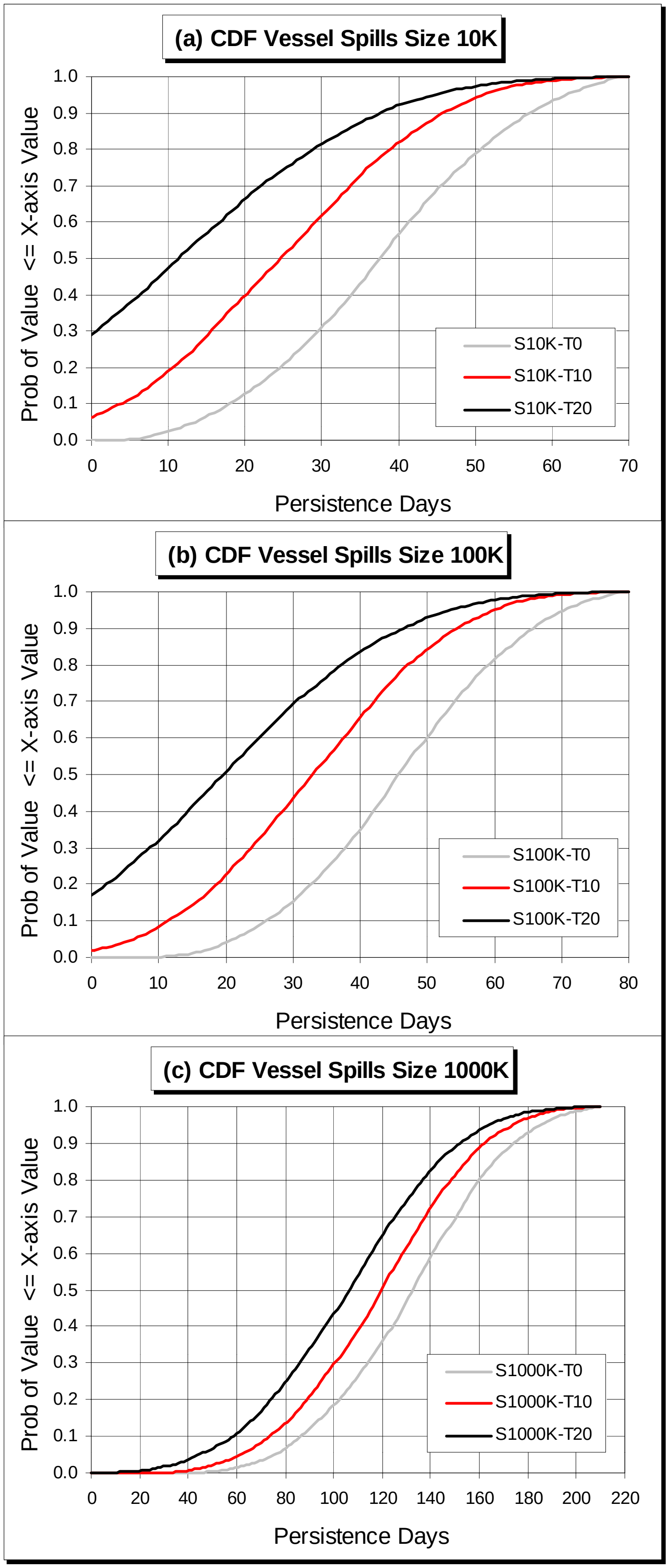


Figure 11: Probability Distributions of Spill Persistence for Different Sizes of Tanker Spills

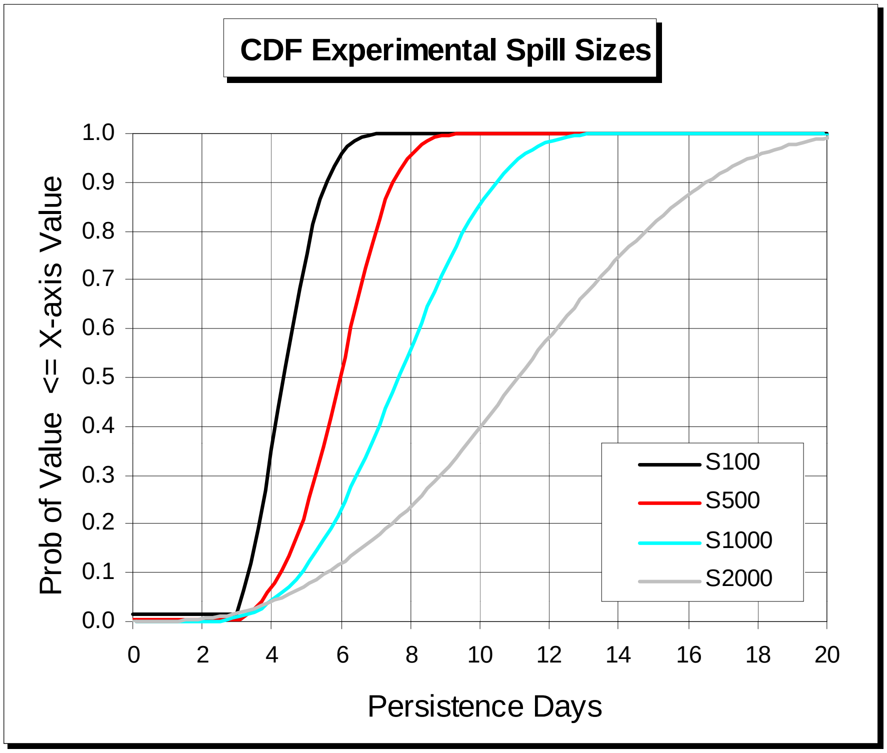


Figure 12: Probability Distributions of Persistence for Different Sizes of Experimental Spills

Blowout Spill Monte Carlo Analysis

Figure 13 shows the spill persistence CDF for blowout spills from 10,000 to 300,000 bbl size. Although the blowout spills are associated with a different spill mechanism than the tanker spills (a continuous release over days for blowouts, as opposed to the near-instantaneous release, or series of releases, expected from tankers), there appears to be a similarity between the comparable spill sizes for both tankers and blowouts.

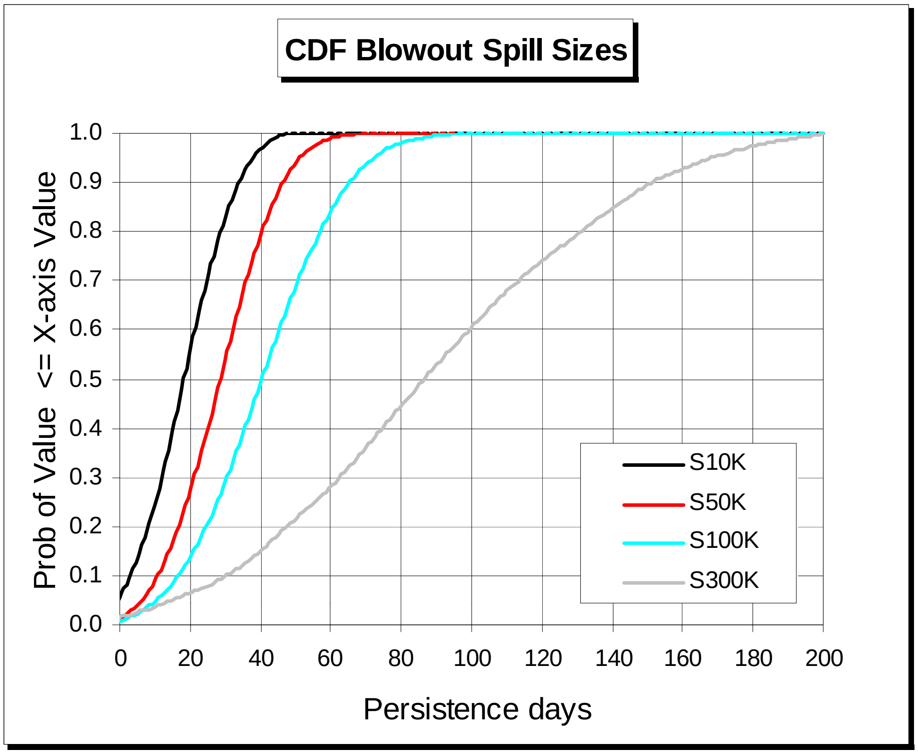


Figure 13: Probability Distributions of Spill Persistence for Different Sizes of Blowout Spills

5. REFINEMENT OF EMPIRICAL PREDICTORS FOR SPILL SIZE CATEGORIES USED BY MMS

The linear and multiple linear regressions that predict the relationship between spill persistence, spill size and temperature, for the three spill types, provide the best basis for assigning persistence values to the size ranges of interest to MMS.

5.1 Use of Equations for Smaller (< 1000 bbl) Spills

The equations (1 and 2) predicting spill persistence for tanker and experimental spill data sets have been plotted on a single graph for comparison. Figure 14 shows the best-fit regressions and their 95% confidence interval (dashed lines) for these data sets. The average temperature of the experimental spills (13.3°C) was used in equation 1 for predicting the tanker spill persistence. It is obvious that there is a discontinuity between the two “batch” spill predictions (experimental and tanker). The tanker spill equation predicts significantly higher spill persistence for spills smaller than about 3000 barrels, than does the experimental spill predictions. This difference in persistence can possibly be explained as follows. The edges of slicks are subjected to more energy and more rapid breakup of coherent oil slicks into smaller and smaller particles than are the interior portions of the slick. Another way to think of this is that breaking waves, which cause natural dispersion, affect only the edges of a slick – their propensity to break is attenuated as they propagate into the middle of a slick. Large slicks have smaller edge to area/volume ratios than small slicks and so their breakup and dispersion is slower. Conversely, smaller slicks will dissipate relatively more quickly.

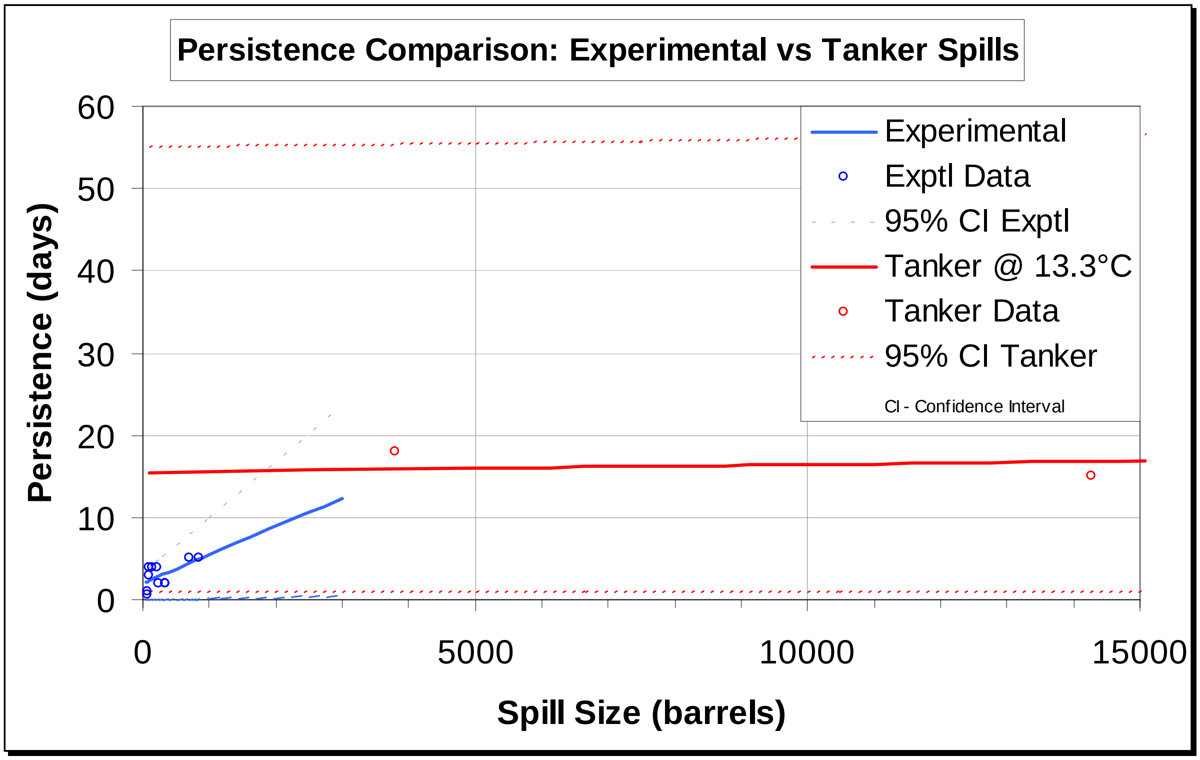


Figure 14: Persistence Correlation Comparison

It is recommended that the persistence predictions from the experimental spill results be used for batch spills less than 1000 barrels. The tanker spill correlation should be used for all batch spills greater than or equal to 1000 barrels.

5.2 Blowouts vs. Tanker Spills

Figure 15 compares the predictions for tanker spill persistence and blowout spill persistence.

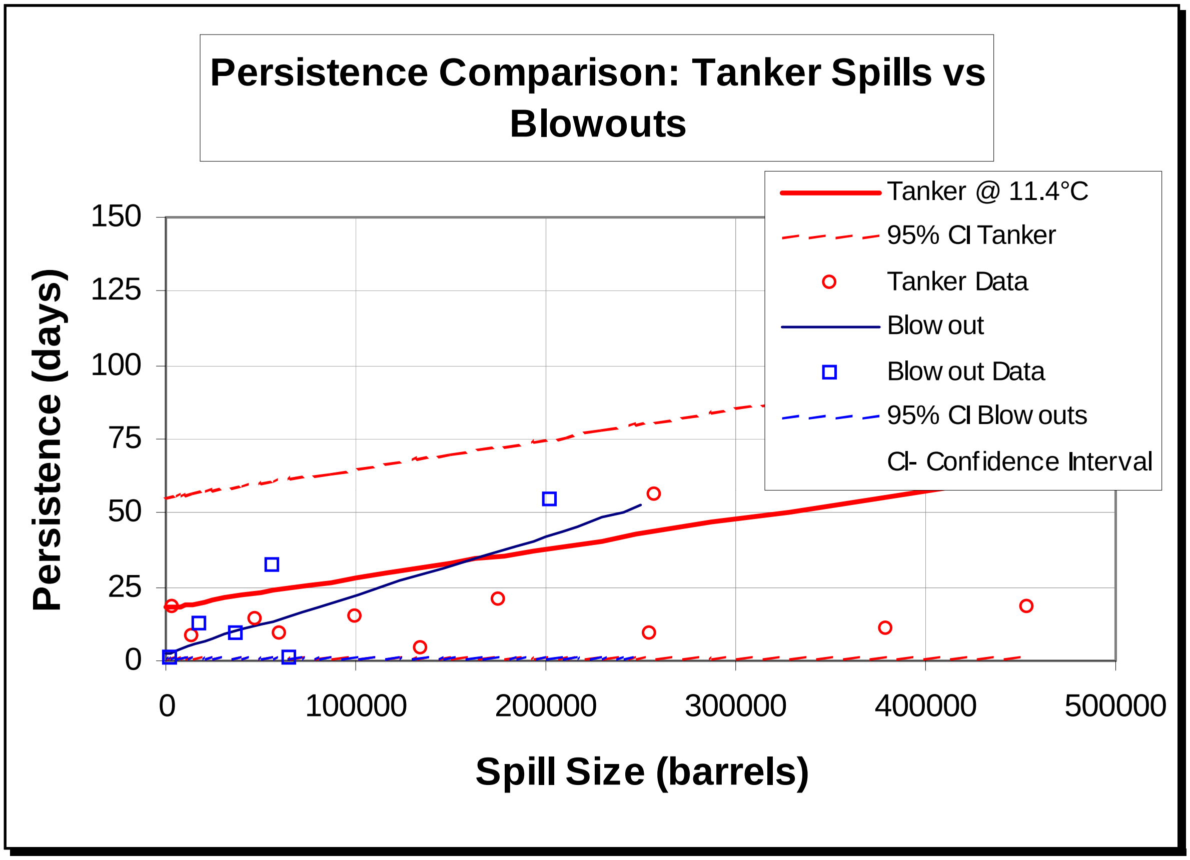


Figure 15: Comparison of Predictions for Tanker Spills and Blowouts

The graph shows the data, best-fit regressions and their 95% confidence interval (dashed lines) for these data sets. The average temperature of the blowout spills (11.4°C) was used in equation 1 for predicting the tanker spill persistence. Although the prediction appears to be that blowout spills less than 150,000 bbl dissipate faster than tanker spills of the same size, the small data sets and large scatter mean that there is no statistically significant difference. It is recommended that the tanker spill prediction be used for spill persistence predictions because it is based on a larger data set. In hindsight, the blowout and tanker data could perhaps have been combined in the statistical assessments. They were separated for the statistical analysis because it was thought that the very different release conditions and subsequent different initial slick characteristics from these two types of spills would generate significantly different slick persistence characteristics.

5.3 Additional Considerations: Use of Oil Properties in Prediction of Spill Persistence

None of the historical spill data sets gave the lowest P value for correlations of spill persistence with oil properties (specifically oil density or gravity). Due to the limited size of the data sets (N=12 was the largest) it is not possible to conclude whether or not the lack of a correlation was due to the small number of data points or the true absence of a correlation. However, it seems reasonable that there must be some effect of oil properties on spill persistence, at least in the extremes (light condensates will not persist; heavy asphaltic crude oils will persist for very long times). Justification for the use of oil property information to establish spill persistence limits for very light crude oils, based on the understanding of basic spill behavior processes and the efforts by other researchers in the classification of oils follows.

5.4 Effect of Spilled Oil Properties on Spill Persistence

The major processes that lead to the disappearance, dissipation or lack of persistence of a coherent slick on the sea surface include evaporation, natural dispersion and slick fragmentation. Brief descriptions of these processes and the oil property most affecting the rate of each follows.

Evaporation

Evaporation of the more volatile oil components will remove oil volume from the sea surface by transferring it as hydrocarbon vapors into the atmosphere. The rate of this process will depend on ambient environmental conditions and slick characteristics, and the extent will depend on the proportion of oil that is volatile under the prevailing conditions.

Oil property most affecting evaporation. Oil components that have boiling points below 200ºC, including all n-alkanes with less than 12 carbon atoms (this includes gasoline, naphtha and most kerosene), will evaporate quite rapidly under most conditions. The proportion of crude oil that consists of these components will also rapidly evaporate, leaving behind a non-volatile residue on the sea surface. If the oil contains a very high proportion of volatile components very little residue will be left behind and it will be left behind as a thin layer.

Natural Dispersion

Natural dispersion is the conversion of the surface slick into small oil droplets by the prevailing breaking wave action. The small droplets will remain indefinitely suspended (or dispersed) in the water column under the existing conditions of turbulence generated by wave action and currents. The oil in the slick is removed from the sea surface and transferred into the water column. The size of the oil droplets that will be indefinitely suspended is around 100 microns diameter or less (somewhat smaller for calmer seas, larger for rougher seas).

Oil property most affecting natural dispersion. The disruption of the oil slick into small oil droplets by breaking wave action is resisted by the increasing viscosity of the oil residue that remains after evaporation or by the soaring viscosity of the emulsified oil. Although no accurate data apparently exists, it is possible that natural dispersion effectively ceases (that is, no significant volume of the spilled oil is converted into very small droplets) when the slick viscosity exceeds some limiting value around 1,000 to 5,000 cP. This is not exactly the same as the limit for chemical dispersion because that involves the drastic (but temporary) reduction of interfacial tension to promote small droplet formation.

A breaking wave passing through a thin layer of low viscosity oil will create a droplet size distribution that includes a high proportion of very small, permanently dispersible, oil droplets. As the slick viscosity increases, the proportion of these small oil droplets decreases. At some point, the proportion of droplets small enough to stay in suspension becomes negligible, and natural dispersion effectively ceases for the given breaking wave energy applied to the slick. Above some limiting viscosity, even repeated, large breaking waves will cause no significant natural dispersion; the slick merely fragments into smaller patches, mats or particles.

Slick Fragmentation

Slick fragmentation is the conversion of a coherent slick into progressively smaller pieces without significant natural dispersion. The oil volume on the sea surface remains the same but is distributed in smaller and smaller pieces over an increasing area of sea surface.

Slick fragmentation is a particularly relevant process for the thicker layers of oil (several millimeters to several centimeters) formed by high viscosity oils (e.g. heavy fuel oils or stable emulsions). Heavy fuel oils probably do not naturally disperse to any significant extent, yet these slicks eventually dissipate in fragments that ultimately yield tar balls. This also occurs with high viscosity (and highly stable) emulsions formed by high asphaltene content crude oils. Lower viscosity and lower stability ('weaker') emulsions formed from crude oils containing less asphaltenes break up more easily than highly stable emulsions.

Slick fragmentation appears to happen mainly at the edges of slicks. Thick layers of high viscosity oil dampen out breaking waves except at the edges of a slick or a patch. Large coherent slicks are broken up into smaller (but still relatively large) pieces by the shearing action of wind and currents. Slicks with high Pour Points that have gelled at ambient temperatures can be “fractured” into many small pieces by wave action. Both processes slowly yield more slick edge to be broken up into tiny, non-detectable fragments, or tar balls.

Oil property most affecting fragmentation. The main oil property controlling slick fragmentation is likely oil viscosity, or more accurately, some rheological property such as yield stress or the elastic component, that will allow the slick to resist shear and/or reform after near-disruption by a breaking wave. Slick thickness is also involved. Since high viscosity oils (and emulsions) tend to form much thicker layers, the two are connected. Waxes content (roughly estimated by Pour Point) also plays a role in determining at what point some oils will gell, or solidify, at ambient temperatures.

5.5 Existing Computer Models for Predicting Oil Weathering

Most oil 'weathering' computer models normally consider the main processes affecting oil slick persistence to be:

1. Evaporative loss. This is the volume decrease of the surface oil as some components are transferred to the atmosphere. The consequential increase in oil residue viscosity, compared to the viscosity of the original oil, is calculated.
2. Water-in-oil emulsification. The oil residue that remains on the sea surface incorporates water as droplets that may be stabilized by precipitated asphaltenes. This process is normally considered in terms of the consequent volume and viscosity increase.
3. Natural dispersion. The spilled oil is removed from the sea surface by transfer into the water column as very small droplets. This proceeds most rapidly in the thin layers of sheen that cannot emulsify because they are too thin for emulsification to occur. Sheen formation is therefore probably an important intermediary step in natural dispersion.

Evaporation can be modeled with a high degree of accuracy. Emulsification requires specific lab studies. The theoretical basis of algorithms for natural dispersion - which normally relate droplet size produced by energy dissipation (related to wind speed and calculated wave energy) to oil viscosity is known to be weak. Viscosity (especially emulsion viscosity) is very likely to be an inadequate description of the oil's rheological parameters that control droplet formation.

Provided that the spilled oil is not transferred in other compartments (evaporated to the atmosphere or dispersed into the water column) it is modeled to remain on the sea surface until it reaches shore. Different models have been calibrated, or 'validated', against results from specific sea-trials, but all models have inherent weaknesses in that they involve extrapolations into sea and weather conditions where they have not, and cannot, be tested.

In particular, few, if any, existing models model the horizontal distribution of the oil on the sea surface in a realistic way; slick fragmentation by wind and current shear is not included. In particular, slick persistence (according to this study's definition) is not modeled.

5.6 Oil Spill Persistence Classification Schemes

There have been many attempts to classify oils (crude oils and refined products) into groups based on common characteristics in attempts to indicate the probable behavior and persistence of the oils if spilled at sea. The main oil properties used in these classification schemes are:

1. Distillation characteristics. Can be used to estimate the proportion of oil that will evaporate.
2. Viscosity. Indicates spreading behavior and is indirectly indicative of other behaviors.
3. Pour Point. Oils at temperatures well below their pour point will be solid.
4. Asphaltene content. High asphaltene content oils form more stable, more viscous emulsions more readily than low asphaltene content oils.

It is not always possible to obtain all of this information about an individual crude oil or refined product. The most readily available oil property is density (Specific Gravity or ºAPI). Attempts have therefore been made to relate probable spilled oil persistence to density.

International Oil Pollution Compensation Funds Classification

The persistence of spilled oil is relevant to the compensation schemes administered by the International Oil Pollution Compensation (IOPC) Funds because these schemes only apply to 'persistent' crude oils and fuel oils from tankers. The term 'persistent oil' is not precisely defined in any of the Conventions, but the IOPC Funds use a guideline that states: "An oil is considered non-persistent if - at the time of shipment - at least 50% of the hydrocarbon fractions (by volume) distill at 340ºC and at least 95% distill at 370ºC". Oils that are normally classified as 'persistent' include: crude oils, fuels oils, heavy diesel and lubricating oils. 'Non-persistent' oils include gasoline, light diesel oil and kerosene.

International Tanker Owners Pollution Federation Limited

The International Tanker Owners Pollution Federation Limited (ITOPF) have classified a number of oils and refined oil products according to their Specific Gravity into four groups as shown in Table 9. Additional oil properties also given for each group include viscosity at 15ºC, % boiling below 200ºC and % boiling above 370ºC.

Table 9: ITOPF Oil Classification System

Oil Group	Oil Descriptions	Specific Gravity & (°API)	Viscosity Range or Average @ 15 °C (mm^2/s=cSt)	% Boiling below 200°C	% Boiling above 370°C
1	Gasoline, naphtha and kerosene	<0.8 (>45)	0.5 to 2.0	50 to 100	0
2	47 crude oils plus Gas Oil. 26 oils with PP > +5°C, 4 oils solid @ 15 °C	0.8 - 0.85 (35 - 45)	8	19 to 48	12 to 50
3	43 crude oils plus Medium Fuel Oil, 8 oils with PP > +5°C, 8 oils solid @ 15 °C	0.85 - 0.95 (17.5 - 35)	275	14 to 34	28 to 50
4	21 crude oils plus Heavy Fuel Oil	> 0.95 (<17.5)	1500 to solid	3 to 24	33 to 92

ITOPF have related the grouping of the oils to persistence by means of computer models and practical experience and represent this as in Figure 16. The volume of oil and oil-in-water emulsion remaining on the sea surface over time is shown as a percentage of the volume spilled. Note that greater than 100% is shown on the graph for some oil groups due to slick volume increases as a result of the formation of water-in-oil emulsions.

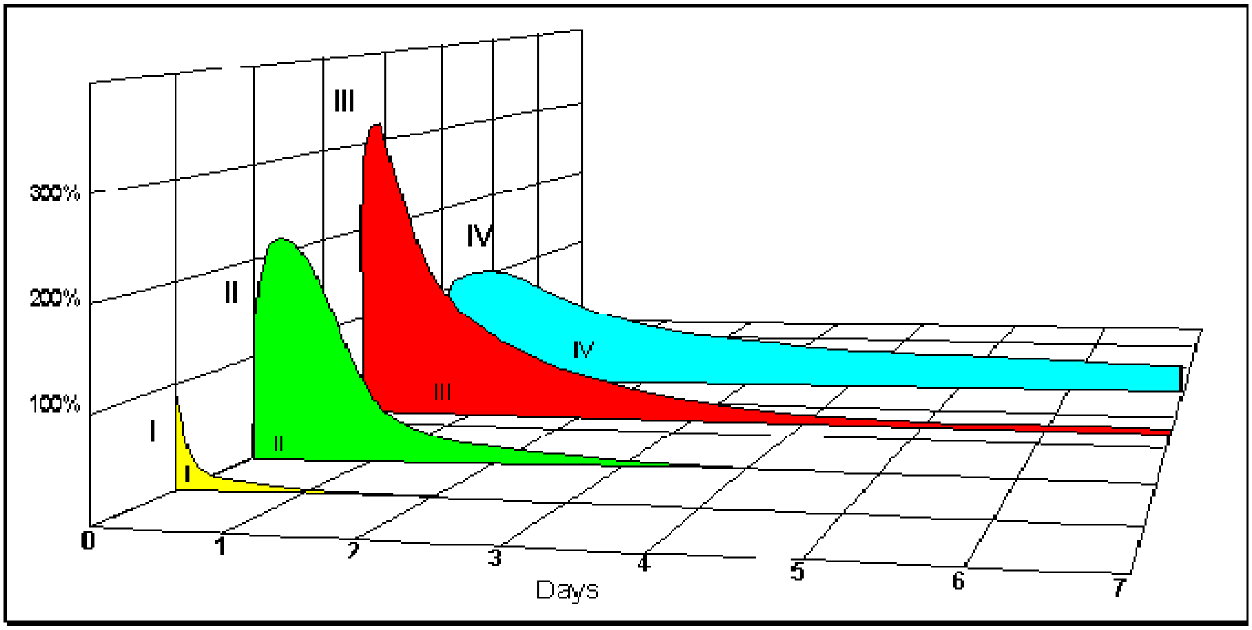


Figure 16: ITOPF Oil Persistence Model

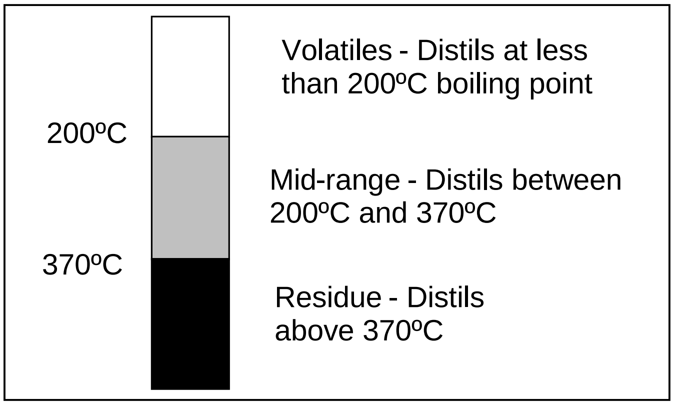
United States Coast Guard Oil Classification System

The United States Coast Guard's (USCG) system for classifying oils, shown in Table 10, is very similar to the ITOPF system. The difference in the schemes is that non-persistent oils (Group I) are classified explicitly by volatility/boiling range (using the IOPC Funds criteria) rather than density. The other groups are defined by density.

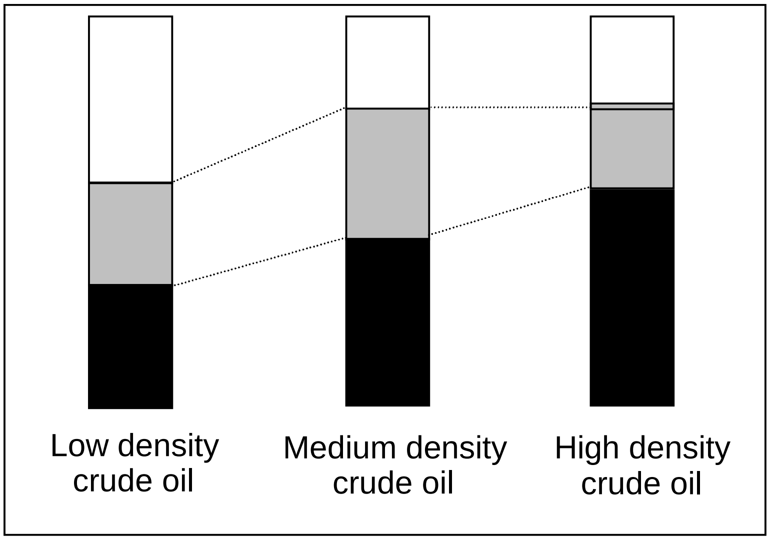
Table 10: Oil Groupings Used in USCG Vessel Response Plan Regulations

Oil Group	Specific Gravity
Group I	i) at least 50% (volume) distill at 340°C; and ii) at least 95% (volume) distill at 370°C
Group II	SG < 0.85
Group III	0.85 ≤ SG ≥ 0.95
Group IV	0.95 ≤ SG ≥ 1.0
Group V	SG > 1.0

The density of a crude oil is a broad indicator of other oil properties. Higher density (low ºAPI) crude oils contain a higher proportion of 'heavier' (higher molecular weight) hydrocarbons than lower density (higher ºAPI) crude oils. For comparison purposes, crude oil composition can be greatly simplified to a 3-component blend based on distillation range:



Higher density crude oils will contain a greater proportion of mid-range and residue components than lower density crude oils. The relative proportions of mid-range and residue may also vary, giving rise to a very wide range of densities as the residue is of higher density than the mid-range.



The proportion of volatiles indicates the proportion of crude oil that will easily evaporate when the oil is spilled at sea. The properties of the oil residue that will remain on the sea surface can be inferred from the relative proportions of mid-range and residue components. Remaining oil residues with a higher proportion of mid-range components will be of lower viscosity than those with a higher proportion of residue components. Higher residue contents are broadly indicative of higher asphaltene contents. The ITOPF and USCG groupings therefore have a broad correlation with more specific oil 'weathering' properties.

5.7 Correlation of Oil Properties in Environment Canada's Catalogue with Persistence

In order to determine whether or not it is possible to defensibly define a certain category of crude oils as non-persistent (since there is only one actual non-persistent spill data point – the Uniacke blowout) the Environment Canada oil properties database (http://www.etcentre.org:8080/cgi-win/OilPropspill_e.exe?Path=\Website\river\) was used to construct a spreadsheet with key persistence-related properties of the 222 crude oils listed (see Appendix A, or use the following hyperlink to access the original spreadsheet file EC and ITOPF Crudes.xls). Of these, it was determined that 10 fell into the ITOPF Group 1 category (API > 45°). It is worthy of note that none of them would fall into the USCG Group I category (>95% boiled off at 370°C). Of the 11 with API > 45°, only one contained any asphaltenes, which are a strong indicator of emulsification tendency. Of the 222 crude oils investigated, only 2 had no asphaltenes and formed emulsions in standard laboratory tests. Both of these (Issungnak and Nektoralik) had Pour Points (at the degree of evaporation and temperature at which they formed emulsions) higher than the ambient temperature. Thus, in order to be reasonably certain that a crude oil will not persist, it would be necessary to state that it's API Gravity must exceed 45.5° and its Pour Point must be less than ambient temperature. Nine of the crude oils in the list would meet this criteria at 25°C and seven at 0°C.

5.8 Crude Oils in Present Study

The crude oils involved in the spills considered in the current study have a broad range of density (ºAPI Gravity) and other properties as seen in Table 11. The Uniacke condensate, having a very low density, consists almost entirely of volatile components and would (and did) almost totally evaporate and be non-persistent on the sea surface.

The crude oils classified as ITOPF Group 2 would be expected to form emulsions, but these would be relatively weak and would not be very persistent.

The crude oils classified as ITOPF Group 3 are of a type that would be expected to be very persistent, having relatively high asphaltene contents that would stabilize the emulsions as they are formed. These oils would be expected to be more persistent than the other crude oils. This is particularly the case for the Maya crude oil that has a very high viscosity.

The conundrum is that the statistical analysis of the spill persistence data for these oils does not detect the expected trends described above. The available data set is too small and incomplete for these trends to be evident. The best that can be concluded with the available data is that crude oils with API > 45.5° and Pour Points below ambient temperature will not persist because they will evaporate rapidly and their residue will not form emulsions that could persist.

Table 11: Properties of Crude Oils from Historic Spills Used in this Study

Spill No.[1]	**Oil Type**	**°API Gravity**	**Viscosity (cSt)**	**Emulsion Formation**	**Pour Point (°F)**
ITOPF Group 1					
1	Uniacke Condensate	45.0		No	
ITOPF Group 2					
105, 107, 108	Forties Blend	41.0	10	Yes	-10
104	Statfjord crude	41.0	4.5	Yes	-29
9	Murban Light crude	40.5	7 @15°C		-31°
15	Nigerian Blend Crude	39.3		Yes	
22	Palanca Crude Oil	38.6		Yes	10
110, 111	Forties	38.0	8	Yes	-10
24, 102, 103	Ekofisk Crude Oil	35.7	5 @ 15°C	Yes	-12
28	Claymore Tartan blend	35.0		Yes	
106	Oseberg crude	35.0	12	Yes	-9
ITOPF Group 3					
2, 5, 101	Light Iranian Crude	34.7	6.6	Yes	
8	Arabian Light Crude	33.4			
7	Kuwait Crude Oil	31.4	22 @15°C	Yes	-18
13	Iranian Heavy	31.0	9.4	Yes	-20
109	Troll	27.0	27	Yes	-18
10, 19, 16, 112	North Slope Crude	26.8	23 @ 15°C	Yes	-8
12	Mexican Maya crude	22.0	280 @ 15°C	Yes	-15
11	Iranian Heavy	?20.0?	250 @15°C	Yes	-26

[1] Spill identifier as in original Microsoft Access database (Spill Database.mdb)

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

- The following definition of oil slick persistence was developed for this study:

  > "An oil slick is considered to be persisting on the sea surface when it can be observed to be a coherent slick, or perceptible segments of a coherent slick, by normal methods of slick detection, such as aerial surveillance."

- An MS Access database of 154 historic spill incidents was developed for the study after an extensive worldwide search of data sources, from which a total of only 20 offshore oil spill incidents that contained adequate persistence and other information were uncovered. Of these, 13 were crude oil tanker spills and 7 were oil well blowouts.
- In addition to the 20 spill incidents, a database of 12 crude oil experimental spills was compiled, for which good persistence data existed. These spills all involved much smaller oil volumes than the tanker releases, and were thus kept in a separate database.
- An inspection of the data revealed that the main quantitative variables relating to spill persistence were:
  - Spill size
  - Oil specific (or API) gravity
  - Water temperature
- Correlation analyses were carried out on the data sets and, although they by no means gave definitive results because of the small size of the sets, they did indicate the relative importance of different variables and their dependencies for each of the three data sets.
  a. For tanker spills, correlation between persistence and spill size and water temperature seemed promising;
  b. For experimental spills, the only promising correlation was that between spill persistence and spill size;
  c. For blowout spills, the most promising correlation was also between spill persistence and spill size.

- Regression analysis with the three data sets showed that:
    a. A multiple linear regression of persistence, spill size and water temperature manifested the highest statistical significance ($R^2 = 0.52$, and a P value of 0.036) for the tanker spills and yielded:

    $$\mathbf{PD_{Tv} = 0.0001S - 1.32T + 33.1}$$

    Similar equations to predict the 95% confidence limits for the tanker spills were also derived.

    b. In the case of the experimental spill data, a simple linear regression analysis between spill size and persistence gave the most favorable indicator of statistical significance, with R^2 at a value of 0.34, and a P value of 0.045.

    $$\mathbf{PD_E = 0.0034S + 2.02}$$

    Similar equations to predict the 95% confidence limits for experimental spills were also derived.

    c. For the blowout spills, the simple linear regression method gave the most favorable levels of statistical significance with R^2 and P values of 0.73 and 0.031, respectively.

    $$\mathbf{PD_B = 0.0002S + 2.38}$$

    Similar equations to predict the 95% confidence limits for blowout spills were also derived.

    d. Wind speed did not have a statistically significant effect on persistence

    e. Countermeasures effort did not have a statistically significant effect on persistence.
- Cumulative distribution function plots were prepared for several different discrete spill sizes using the three data sets.
- There was a discontinuity between the persistence predictions from the experimental spill data set and the tanker spill data set. The experimental spill data set prediction best represents batch spills less than 1000 barrels. The tanker spill correlation should be used for all batch spills greater than 1000 barrels.
- Comparison of the blowout and tanker spill predictions appears to indicate that blowout spills less than 150,000 bbl dissipate faster than tanker spills of the same size; however,

the small size of the two data sets and large scatter mean that there is no statistically demonstrable difference.

- A review of worldwide oil persistence classification schemes, and an analysis of crude oil property databases concluded that, in order to be reasonably certain that a crude oil will not persist, it would be necessary to specify that it's API Gravity must exceed 45.5° and its Pour Point must be less than ambient temperature.

6.2 Recommendations

The following equations should be used by MMS to estimate the mean persistence of slicks on open water for modeling purposes:

For spills greater than or equal to 1000 barrels in size:

$$\mathbf{PD_{\geq 1000bbl} = 0.0001S - 1.32T + 33.1}$$

Where,

- PD = Spill persistence in days
- S = Spill size in barrels
- T = Water temperature in degrees Celsius

For spills less than 1000 barrels in size:

$$\mathbf{PD_{<1000bbl} = 0.0034S + 2.02}$$

Spills of crude oils (or more specifically, condensates) whose API Gravity exceeds 45.5° and whose Pour Points are less than ambient temperature will not persist as slicks on the open ocean and are likely to dissipate in less than one or two days.

To improve the data set for future statistical studies of oil persistence it is recommended that spill responders be encouraged to conduct frequent over-flights of large slicks and monitor weather and sea state conditions in the vicinity of the slicks until they dissipate offshore. These observations should be published in the open oil spill literature, such as the International Oil Spill Conference proceedings.

As well, consideration should be given to studies of the basic mechanisms of slick dissipation at sea. It is possible that there are as yet unknown, oil-property driven constraints on the processes involved in natural dispersion that limit it to moderately viscous slicks. The processes that eventually render persistent slicks undetectable may be the continuous fragmentation of the oil down to small particle sizes combined with horizontal dispersion of the “slick” over the sea surface, rather than conventional natural dispersion of small droplets into the water column. Until the mechanisms that control dissipation of a slick are understood, computer modeling cannot reasonably be expected to predict slick persistence or impacts.

7. REFERENCES

Citations in text of main report

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Yoshioka, G., E. Wong, B. Grossman, W. Drake, B. Urban and T. Hudon. 1999. Past In-situ Burning Possibilities. USCG R&D Center Report CG-D-17-99. Groton, CT. 347 pgs.

Citations in Microsoft Access database

The references cited in the database of spills developed for this project are available as a ProCite compatible database, reproduced as Appendix B.

Data sources in main report

ITOPF Handbook 2003 / 2004, International Tanker Owners Pollution Federation Limited, London UK.
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United States Coast Guard, Regulations on Vessel Response Plans, Oil Group Definitions, 33 CFR Part 155
http://www.uscg.mil/vrp/reg/33cfr155d.shtml

National Response Center Database- http://www.nrc.uscg.mil/foia.html

MSRC Report – Kucklick, J., and D. Aurand., 1995. An Analysis of Historical Opportunities for Dispersants and In-Situ Burning Use in the Coastal Waters of the United States, except Alaska Marine Spill Response Corporation Technical Report Series 95-005, Herndon, VA

USGC Marine Casualty and Pollution Database -
http://transtats.bts.gov/Tables.asp?DB_ID=610&DB_Name=Marine%20Casualty%20And%20Pollution%20Database&DB_Short_Name=Marine%20Casualty/Pollution

NOAA Marine Environmental Buoy Database - http://www.nodc.noaa.gov/BUOY/buoy.html

Comprehensive Ocean-Atmosphere Data Set - http://www.cdc.noaa.gov/coads/products.html

Other oil spill data sources consulted in the search included; NOAA's Historical Incident Database (http://www.incidentnews.gov/incidents/history.htm), which provides details on oil and chemical spills around the world of over 100,000 barrels internationally and 10,000 barrels in US water. NOAA's Oil Spill Case Histories (http://response.restoration.noaa.gov/oilaids/spilldb.pdf) gives information on significant U.S. and international spills between 1967 and 1991. NOAA's Oil and Hazardous Materials Response reports detail oil and chemical incidents in the US coastal zones (http://response.restoration.noaa.gov/oilaids/spillreps/spillreps.html) to which NOAA provided technical or operational assistance. The MMS Spill Incident Database (http://www.mms.gov/incidents/pollution.htm) has information on spills from 1974 through 2003. Environmental Canada's Oil Spill Database (http://www.etcentre.org:8080/cgi-win/TankerSpill_e.exe?Path=\Website\river\) provides details on international tanker oil spills of over 1,000 barrels.

APPENDIX A – OIL PROPERTY DATABASE

Crude oil	Viscosity at 15ºC	API Density	Pour Point (ºC)	Asphaltenes	% below 200C	% mid-range	% above 370C
ITOPF Group 1 - Specific Gravity <0.8 (ºAPI >45)							
Griffin	(1 @20º)	55.0	-48		66	27	7
Margham Light	(1 @20º)	50.3	-8	0.0	52	34	14
Arabian Super Light	3	49.3	-29	0.0	36	22	39
Bekok	(2 @38º)	49.1	-3		45	33	22
Thevenard Island	1	48.6	-70	0.0	49	41	10
Bass Straight	15	47.0	15		40	40	20
Gippsland Mix	Solid (3 @20º)	47.0	15	0.0	40	40	20
Nkossa		46.5	-4	0.0	27	29	44
Sahara Blend	4	45.5	-18	0.0	48	25	27
Belida	(8 @21º)	45.1	16	1.1	40	35	25
ITOPF Group 2 - Specific Gravity 0.8 - 0.85 (ºAPI 35 - 45)							
Tapis	(3 @21º)	44.3	4	0.0	37	45	18
Anoa	Solid	44.0	19				
Bu Attifil	Solid	43.6	39		19	34	47
Ekofisk	4	43.4	-12	1.0	46	29	25
Kerapu		43.3	26	1.4			
Liverpool Bay	(7 @20º)	43.3	-18	0.0	33	31	36
Sirtica	7	43.3	-3		44	29	27
Zarzaitine	(7 @10º)	43.0	-12		40	28	32
Kutubu Light		42.7	5	0.0	43	38	19
Kimkol	(7 @30º)	42.5	10		31	25	44
Pulai	(2 @21º)	42.5	-5	0.0	45	47	8
Attaka	2	42.3	-23		48	39	13
Skua	(3 @20º)	41.9	12		34	59	7
Qatar Land (Dukhan)	9	41.7	-9	0.0	36	31	33
Tartan	(12 @4º)	41.7	-9		40	28	32
Badak	(6 @38º)	41.3	-26				
Bent Horn	24	41.3	-18	0.0	19	28	53
Zuetina	9	41.3	9		35	35	30
Brass River	4	40.9	2		38	45	17
West Texas Intermediate	7	40.8	-29	1.0	28	37	35
Lower Zakum		40.6	-9	0.0	34	31	35
Forties	8	40.5	-12	0.0	32	32	36
Murban	7	40.5	4	0.0	32	34	34
Brega	9	40.4	-1		30	38	32
Marib Light (Alif)		40.3	-4	0.0	40	40	20
Montrose	7	40.1	-9		36	33	31
Bekapi	(2 @38º)	40.0	-21	0.0	36	50	14
Olmeca	(4 @20º)	39.8	-32	0.0	32	36	32
Lucina	Solid (16 @20º)	39.5	16	0.9	26	33	41
Bombay High	Solid	39.4	30		29	37	34
Fulmar	(3 @40º)	39.3	-12		51	16	33

Magnus	(5 @21º)	39.3	-3		30	31	39
Dulang	Solid	39.0	29		35	40	25
East Zeit Mix	7	39.0	-1		36	26	38
Federated	4	39.0	-15	1.0	34	36	30
Maureen		38.8	7		40	20	40
Beatrice	32	38.7	12		25	40	35
Bach Ho	Solid	38.6	35	0.0	21	32	47
Draugen		38.6	-3				
Norman Wells	5	38.4	-85		27	28	45
Brent Blend	6	38.3	-42		30	32	38
Sarir	Solid (5 @50º)	38.3	24		24	37	39
Argyll	11	38.0	9		29	32	39
Khalda	Solid	38.0	29	1.0			
Murchison	7	38.0	7		36	44	20
Pitas Point	2	38.0	-60		54	43	3
Salawati	(4 @38º)	38.0	-26		30	39	31
Siberian Light	(7 @20º)	37.8	-6	0.3	24	24	52
Statfjord	6	37.8	-3	2.0	30	35	35
Soyo	Solid	37.6	17	0.4	20	30	50
Hydra	(5 @38º)	37.5	10		29	41	30
Nanhai		37.5	32	0.8			
Abu Dhabi	7	37.4			36	33	31
Tembungo	(2 @38º)	37.4	-4		38	48	14
Auk	9	37.2	9		33	32	35
Berri (Saudi Arabian Light)	9	37.2	-29		35	30	35
Nemba		37.2	3	0.0			
Lalang	Solid	37.1	33	0.4	19	32	49
Kittiwake	8	37.0	-24		30	34	36
Mubarek	(3 @38º)	37.0	-12		35	34	31
Thistle	9	37.0	9		35	27	38
Dai Hung	Solid	36.9	25	0.0	30	37	33
Alberta	6	36.8	-24	1.0			
Barrow Island	7	36.8	-30	0.0	37	48	15
Bonny Light	25	36.7	12		30	40	30
Es Sider	11	36.7	6		28	30	42
Palanca		36.6	4	0.0	30	35	35
Pennington		36.6	6		34	39	27
Beryl	9	36.5			45	21	34
Miri Light	(4 @21º)	36.3	-6	0.0	25	50	25
Oman		36.3	-23	3.0	23	32	45
Escravos	9	36.2	10		35	50	15
Escravos		36.2	10		30	38	32
Seria	Solid	36.2	18		37	48	15
Amna	Solid	36.1	18		25	45	30
Arabian Extra Light		36.1	-26	0.0	26	35	39
Rincon de Los Sources	16	36.1	-4		30	40	30
Statfjord C		36.1	1	0.0			
Avalon	11	36.0	12	3.0	15	39	46
Rostam	(3 @50º)	35.9	-23		30	24	46
Umm Shaif		35.9	-9	0.3	29	32	39

Qua Iboe	7	35.8	15	0.5	29	39	32
Ninian Blend	8	35.6	2		23	37	40
Qatar Marine	53	35.3	-12	0.6	29	32	39
Ardjuna	Solid	35.2	27		37	48	15
ASMB		35.1	-8	2.0	33	22	45
Kirkuk	(13 @10º)	35.1	-22		35	29	36
Medanito	16	35.1	-1		25	35	40
Isthmus							
ITOPF Group 3 - Specific Gravity 0.85 - 0.95 (ºAPI 17.5 - 35)							
Forms emulsions at 0°C but not 15°C despite 0% asphaltenes							
Hibernia	49	35.0	2	3.0	26	21	50
Issungnak		35.0	11	0.0	20	55	25
Statfjord B		35.0	4	0.0			
Cormorant	13	34.9	12		32	30	38
Dunlin	11	34.9	6		29	35	36
Kole Marine	(11 @10º)	34.9	-6		34	31	35
Flotta	11	34.7	-21		34	40	26
Danish North Sea	(9 @20º)	34.5	-30	0.0	33	28	39
Minas (Sumatran Light)		34.5	37	2.0	14	29	57
Loreto		34.0	-18	7.7	17	33	50
Rabi	Solid	34.0	30	2.3			
Gorm	(5 @40º)	33.9	-37		32	38	30
Salmon (Sassan)	(52 @25º)	33.9	-21		31	17	52
Empire	11	33.8	-41	1.0	19	35	46
Iranian Light		33.8	-9	0.7	26	31	43
Basrah Light	(15 @10º)	33.7	-15		26	29	45
Buchan	14	33.7	6		31	30	39
Oseberg	10	33.7	-4	0.5	28	33	39
Rangely	33	33.7	17	4.0	17	36	47
Soyo Blend	Solid (10 @38º)	33.7	15		21	31	48
Brae	14	33.6	-6	0.0	40	21	39
Dorrood	(6 @38º)	33.6	-20		35	20	45
Arabian Light (Berri)	14	33.4	-53	3.0	24	31	45
Cinta	Solid	33.4	43		10	36	54
Lucula	43	33.4	18	4.0	18	17	65
Lavan		33.3	-7	0.8			
Labuan	(4 @21º)	33.2	11	0.0	33	45	22
Daquing (Taching)	Solid	33.0	36		12	22	66
Taching	Solid	33.0	35		12	39	49
Handil	Solid (4 @38º)	32.8	35		23	44	33
Hout	15	32.8	-18	4.6	24	28	48
Trinidad (Galeota Mix)	Solid	32.8	14		23	49	28
Isthmus	13	32.7	-15	0.9	28	30	42
Upper Zakum		32.7	-24	2.5	26	30	44
Takula	110	32.2	15	2.0	17	28	55
Tia Juana Light	2,500	32.1	-43		24	31	45
Arimbi	Solid	31.8	38				
Gamba	Solid	31.8	23		11	35	54
Miri		31.8	-1	0.0	25	50	25

Bunyu	Solid, (3 @38º)	31.7	18		29	59	12
Cabinda	Solid	31.7	17		18	26	56
Zaire	Solid (362)	31.7	15		18	27	55
Abu Al Bu Khoosh		31.6	-12		27	32	41
Lagomedio	41	31.5	-26		15	35	50
Espoir		31.4	-15		26	31	43
Kuwait Export	30	31.4	-15	2.5	23	25	52
Widuri	Solid	31.4	46	2.6	7	23	70
Foroozan	(15 @20º)	31.3	-37		24	27	49
Basrah Medium	(41 @10º)	31.1	-30		24	48	28
Iranian Heavy	25	31.0	-18	2.5	24	28	48
Malongo	Solid	31.0	21	4.0	15	25	60
Mars Blend	33	31.0	-36		32	33	45
Sirri	(20 @10º)	30.9	-9		35	19	46
Arabian Medium (Khursaniyah)	25	30.8	-15	6.0	22	27	51
Cano Limon	46	30.8	16	8.0	23	37	40
Masila Blend		30.8	8	1.2			
Alaskan North Slope	23	30.6	-55	5.0	26	27	47
Mandji	70	30.5	9		21	26	53
Dan	(9 @40º)	30.4	-43		27	9	64
Point Arguello Light	22	30.3	-22	7.0	22	33	45
West Texas Sour	13	30.2	-27		26	34	40
Dubai	(13 @20º)	29.9	-7	2.0	24	31	45
Forcados	12	29.7	-20		17	46	37
Al Shaheen		29.6	-7				
Suez Mix	30	29.6	10	1.4	24	27	49
Sockeye Sweet	20	29.4	-20	4.0	23	47	40
Gullfaks	13	29.3	-32		21	39	40
Oriente	85	29.2	-4		20	32	48
Ashtart	(24 @20º)	29.0	9	2.0	16	32	52
Jatibarang	Solid	29.0	43		14	21	65
Heidrun	18	28.6	-48	1.0	19	36	45
Khafji	80	28.5	-30	4.1	21	24	55
Troll		27.9	-39	0.3			
Belayim	Solid	27.5	15		22	23	55
Arabian Heavy (Safaniya)	55	27.4	-28	4.0	20	24	56
Lago	Solid	27.3	21		12	24	64
Bahrgansar / Norwuz	(20 @38º)	27.1	-33		19	22	59
Aboozar	(37 @20º)	26.9	-34		25	21	54
Djeno	(220 @10º)	26.9	6		16	22	61
Bintulu Neat	Solid	26.5	17		24	42	34
Canadon Seco	(279 @20º)	26.3	-3	2.0	16	26	58
Sockeye	45	26.2	-12	8.0	21	31	48
Odudu		26.1	-39	0.2			
Sanga Sanga	(151 @38º)	25.7	-15		19	48	33
Dos Cuadros	51	25.6	-30	6.0	19	31	50
La Rosa	180	25.3	-46	6.0	17	28	55
Bonny Medium	(12 @38º)	25.2	-27		14	47	39
Souedie	(88 @10º)	24.9	-30		20	23	57

Prudhoe Bay	68	24.8	0	2.0	16	31	53
Basrah Heavy	(86 @10º)	24.7	-30		19	39	42
Forms emulsions at 0°C but not 15°C despite 0% asphaltenes							
Nektoralik	(21@10°)	24.5	3	0.0	7	58	35
Shengli	Solid	24.2	21		9	21	70
Escalante	2120	24.1	-1		12	21	67
Leona	(31 @38º)	24.0	-36	1.7	14	30	56
Champion Export	18	23.9			15	47	28
BCF 24	125	23.5	-51	7.0	13	17	70
Burgan		23.3	-21		13	24	63
Syrian Blend		23.3	0		25	32	43
Endicott	84	23.0	-2	4.0	11	24	65
Kuparuk		23.0	-48		19	25	56
Lago Treco	272	22.6	-20		16	29	55
Maya	500	22.2	-27	5.8	17	22	61
Santa Clara	304	22.1	-3	13.0	15	21	64
Emerald	170	22.0	-29		7	37	56
Point Arguello Comingled	533	21.4	-12		14	21	65
Duri	Solid	21.1	14		5	21	74
Duri (Sumatran Heavy)	Solid (13300)	21.1	18		5	20	75
Hondo Blend	511	20.8	-21		20	30	50
Alba	(259 @20º)	20.0	-30		4	35	61
Hondo	735	19.6	-15	12.0	14	22	64
Sockeye Sour	821	18.8	-22	13.0	15	22	63
Wafra Eocene	3000	18.6	-29		11	26	63
Point Arguello Heavy	3250	18.2	-4	19.0	11	20	69
Cyrus (Soroosh)	10000	18.1	-12		12	22	66
Soroosh	(1381 @20º)	18.1	-12		15	15	70
ITOPF Group 4 - Specific Gravity > 0.95 (ºAPI < 17.5)							
Bachequero	5000	16.8	-20		10	30	60
Port Hueneme	4131	14.8	-9	12.0	5	23	72
Merey	7000	14.7	-18	5.4	7	23	70
Belridge Heavy	12610	13.6	2	3.0	2	26	72
Tia Juana Heavy	(2983 @50º)	12.1	-1		3	15	82
Tia Juana Pesado	Solid	12.1	-1		3	19	78
California	34000	10.3	0		7	18	75
Boscan	Solid	10.1	15	18.0	4	16	80

APPENDIX B –DATABASE OF REFERENCES CITED IN MICROSOFT ACCESS DATABASE OF SPILLS

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   Notes: API Publication No. 4452; Spill not selected

2. Allers, Jan (NOSCA - Norwegian Oil Spill Control Association). Oil Recovery and Oil-On-Water Exercises in High Seas, Offshore Norway. Oil Spill Symposeum 1997; Tokyo, Japan. Petroleum Association of Japan; 199725 pages.
   Notes: Selected spill: Piper/Claymore/Flotta

3. Audunson, Tore. The Fate and Weathering of Surface Oil From The Bravo Blowout. Marine Environmental Research. 1980; 3:35-61.
   Notes: Selected spill: Ekofisk Bravo;

4. ---. Fate of Oil Spills on the Norwegian Continental Shelf. In: Ludwigson, John O., Editor. Prevention, Behavior, Control, Cleanup; Los Angeles, California. Washington, D.C.: American Petroleum Institute; 1979; c1979: 675. 755 Pages. 1979 Oil Spill Conference Proceedings. v. 6). ISBN: LCCN 75-4161.
   Notes: API Publication No. 4308; Selected spill: Ekofisk Bravo; The text of the article was not printed in the proceedings but was said to be "distribted at the conference by the author"

5. Barber, Mary C.; Merther, Susan M.; Ireland, George F., and Breslau, Lloyd. An Analysis of Historical Oil Spills and Current Cleanup Requirements to Aid in Selecting New Technologies for Spill Cleanup Operations. Washington, D.C.: Marine Spill Response Corporation; 1992; 92-001. 57(MSRC Technical Report Series). Marine Spill Response Corporation; Research & Development; 1350 I Street N.W., Suite 300; Washington, D.C. 20005.
   Notes: Selected spill: Glacier Bay

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   Notes: Spill not selected

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   Notes: API Publication No. 4580; Selected spill: Kirki

8. Carter, J.; MacGregor, C.; Tidmarsh, W. G.; Chandler, P. C. P.; Parsons, J., and Bonke, C. Monitoring programs associated with the Uniacke G-72 gas/condensate blowout on the Scotian shelf. In. Proceedings of the Eighth Annual Arctic Marine Oilspill Program Technical Seminar; Edmonton, Alberta. Ottawa, Ontario: Environmental Protection Service; 1985; c1985: 403-422. 442 Pages. Proceedings of the Eighth Annual Arctic Marine Oilspill Program Technical Seminar. v. 8).
   Notes: Selected spill: Uniake

9. Cormack, D. and Nichols, J. A. (Warren Spring Laboratory). Investigation of Factors Affecting the Fate of North Sea Oils Discharged at Sea. Part 2: The Ekofisk Blow-out April/May 1977. Stevenage, Hertfordshire: Warren Spring Laboratory; 1978Warren Spring Laboratory, Dept. of Industry, Gunnels Wood Road, Stevenage, Hertfordshire SG1 2BX.
Notes: Selected spill: Ekofisk blow-out

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11. Daniel, Pierre. Numerical Simulation of The Aegean Sea Oil Spill. In: Ludwigson, John O., Proceedings Editor. Achieving and Maintaining Preparedness; Long Beach, California. Washington, D.C.: American Petroleum Institute; 1995; c1995: 894. 1085 Pages. 1995 International Oil Spill Conference Proceedings. v. 14). ISBN: LCCN 75-4161.
Notes: API Publication No. 4620; Spill not selected

12. Finley, J. Heather; Hanifen, James G.; Roscigno, Pasquale F.; Debusschere, Karolien; Newell, Maura J., and Julius, Brian E. A Cooperative Damage Assessment: Lessons From The Greenhill Spill. In: Ludwigson, John O., Proceedings Editor. Achieving and Maintaining Preparedness; Long Beach, California. Washington, D.C.: American Petroleum Institute; 1995; c1995: 355. 1085 Pages. 1995 International Oil Spill Conference Proceedings. v. 14). ISBN: LCCN 75-4161.
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Notes: API Publication No. 4385; Selected spill: Uniake Blowout

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19. Horn, Stuart A. and Neal, Captain Phillip. The Atlantic Empress Sinking - A Large Spill Without Environmental Disaster. In: Parrotte, Rita B., Editor. Prevention, Behavior, Control, Cleanup; Atlanta, Georgia. Washington, D.C.: American Petroleum Institute; 1981; c1981: 429. 759 Pages. 1981 Oil Spill Conference Proceedings. v. 7). ISBN: LCCN 75-4161.
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