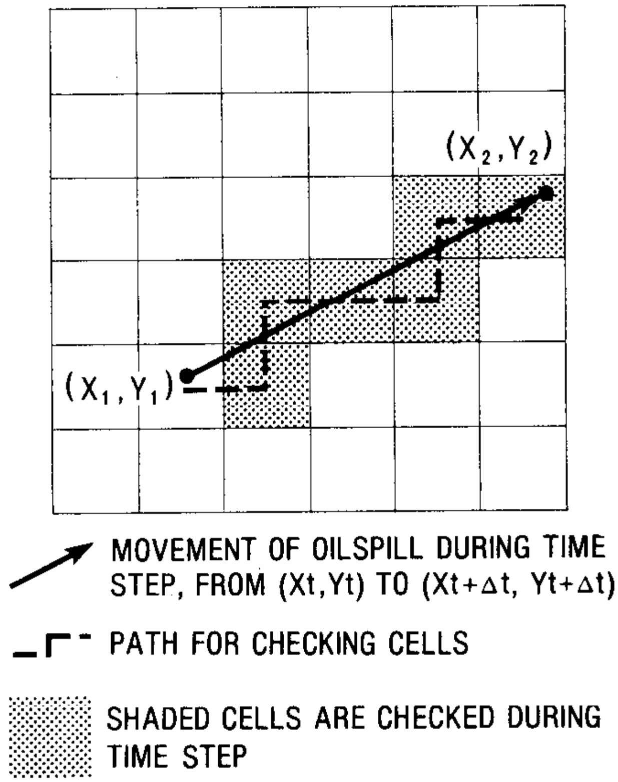

FIGURE 9.—Movement of a hypothetical oilspill through the model's grid system during one time step.

CONDITIONAL PROBABILITIES OF CONTACTING LAND SEGMENTS: PROGRAM LANDSEG

Program LANDSEG calculates the probability that, if an oilspill occurs at a given launch point, it will, within a specified period of time, contact a particular segment of coastline. As in HITPROB, conditional probabilities are calculated for each launch point for oilspills with maximum ages of 3, 10, 30, and 60 days. Each of the two sets of land segments is processed independently, using two slightly different versions of LANDSEG, called LANDSEG 1 and LANDSEG 2. Typical output from LANDSEG is shown in table 4; the same type of information is stored on a disk for use by program NU, which calculates overall risks.

Identification of land segments does not explicity account for spreading of the oil. Although a large oilspill, in reality, could affect several land segments, a "hit" is scored on only one; the user must examine neighboring segments, as well as oilspill travel times, and separately calculate the possible extent of spreading.

TRAVEL TIMES FOR OILSPILLS CONTACTING TARGETS: PROGRAM FIRSTPAS

Program FIRSTPAS calculates the average, minimum and maximum times-of-travel for oilspills occurring at a given launch point to make first contact with a target. This tabulation, an example of which is shown in table 5, is presented by season as well as for the entire year. Spills which do not contact a target are not included in the statistics for that target.

Program FIRSTPAS was, in earlier versions of the model, the only means of accounting for oilspill age. When HITPROB was revised to present its results for spills of different travel times, FIRSTPAS became partially obsolete. However, it has still proven to be a useful program for checking the behavior of the model and for helping to understand oilspill transport.

SPILL OCCURRENCE

This section describes how spill occurrence probabilities are estimated.

To construct the estimated probability distribution on spill occurrence for a fixed class of spills, certain simplifying assumptions must be used which may be unsatisfactory in particular instances. The forecasting method used in the model is sufficiently flexible for incorporation of new and specific assumptions, however.

The following were considered some desirable features of a spill occurrence-forecasting method:

1. The method should include an estimate of the uncertainty in the forecast by providing a probability distribution rather than a predicted number of spills.
2. The method should be consistent with past observations and intuitively reasonable.
3. The dependence on past occurrence rates should be clear and explicit.
4. The method should be flexible; that is, changes in the assumptions concerning use of past occurrence rates should be easily accommodated. and the method should be easy to update as new data are accumulated.

SOME BASIC FEATURES OF SPILL OCCURRENCE FORECASTING

Forecasts of oilspill occurrence are made via a predicted probability distribution on the number of spills which might occur during the production life of a lease area. The predicted distributions are constructed using Bayesian methods to incorporate the uncertainty due to limited historic spill-incidence data. The appendix describes this method in detail.

Simple summary statistics to describe the frequency of spills expected to occur during the production life of a lease area must be chosen to reflect, as best as possible, the shape of the probability distribution. Considerable uncertainty in forecasting for a new offshore lease area is reflected in a predicted probability distri-

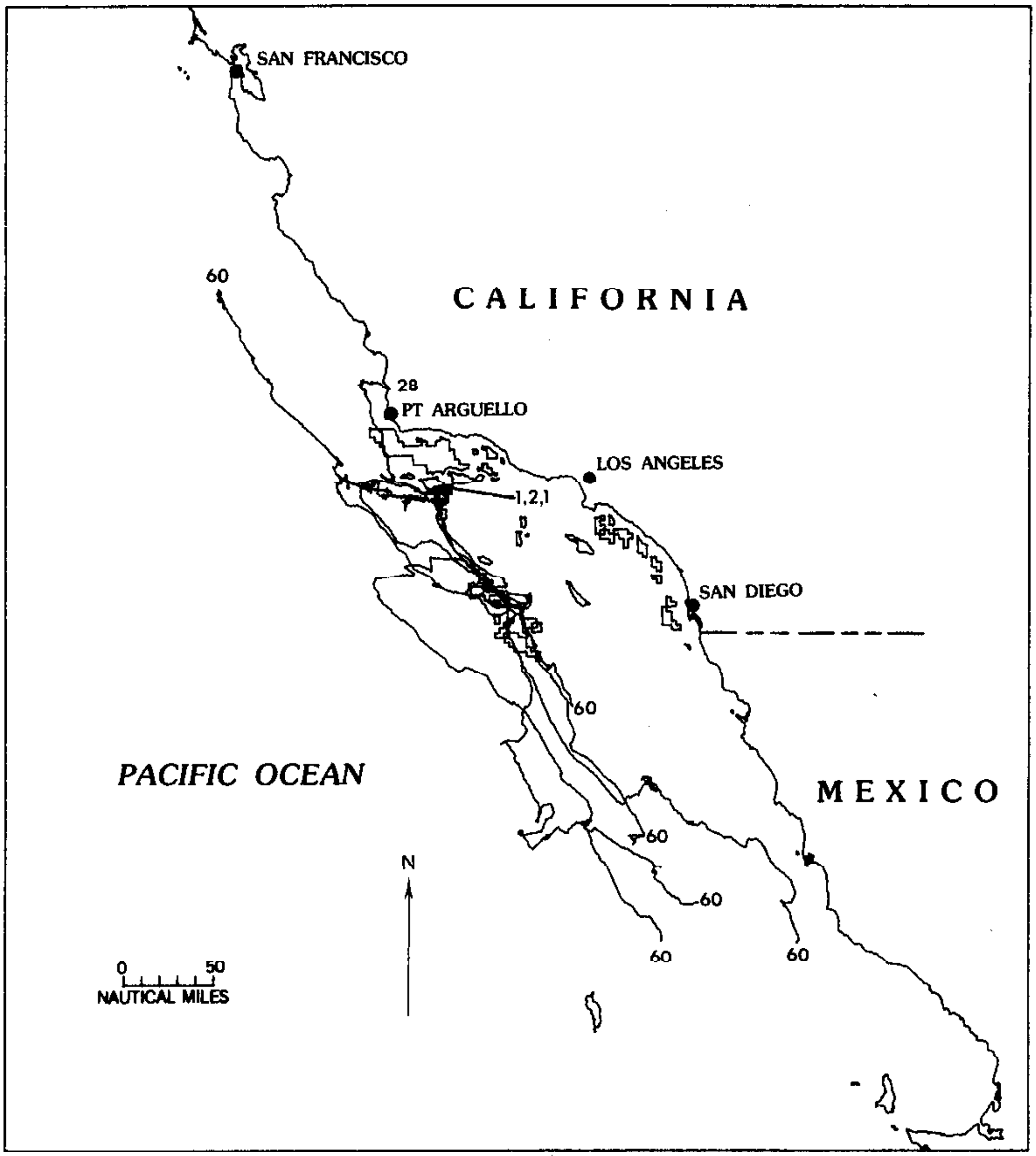

FIGURE 10.—Example oilspill trajectories for a spill site near southern California (OCS Lease Sale 48). Rectangles are proposed lease tracts. Number on trajectory is the time to the end point in days (Slack, Wyant, and Lanfear, 1978).

bution with high variance, implying that one cannot forecast a single number of future spills with much confidence. Presenting the "expected number" of spill can be misleading, as a wide range of possible spill totals may be as likely to occur over the life of the lease area as the "expected number," which is the hypothetical average over many lease area lifetimes. Thus, model forecasts are presented in terms of the most likely number of spills based on the predicted probability distribution (in statistical terms, the mode rather than the mean) as well as the predicted probability that one or more spills of a given size will occur in the lifetime of a lease area.

Spill occurrence forecasts are made separately for different spill-size categories. Oilspills of different magnitudes have different damage potentials, and may be expected to exhibit different statistical properties in their occurrence. The largest spills occur relatively rarely, but account for a large proportion of the total volume spilled. For example, the Argo Merchant

TABLE 3.—*Example of typical output from program HITPROB, showing probabilities (expressed in percent chance) that an oilspill starting at a particular location will reach a certain target in 30 days*

[n, less than 0.5 percent chance; *, greater than 99.5 percent chance]

	Hypothetical spill location (launch point)												
Target	P1	P2 -E2	P3 -E3	P4 -E4	P5	P6	T1	T2	T3	T4	T5	T6	T7
Land	3	2	n	1	1	1	4	11	39	5	17	2	11
1	1	1	n	n	n	n	2	3	6	3	6	1	8
2	n	1	n	1	1	n	2	5	15	5	19	2	6
3	2	1	n	1	1	n	1	4	11	4	12	1	5
4	n	n	n	n	n	n	n	n	n	2	3	n	1
5	n	1	n	n	n	n	2	4	4	n	n	n	2
6	n	1	n	1	n	n	1	2	2	2	6	1	3
7	n	n	n	n	n	n	n	n	n	2	4	n	1
8	n	n	n	n	n	n	n	n	n	n	n	n	n
9	1	1	n	n	n	n	1	1	5	2	5	1	5
10	n	n	n	n	n	n	n	1	1	n	n	n	n
11	n	n	n	n	n	n	1	3	4	n	n	n	n
12	n	n	n	n	n	n	n	n	n	1	4	n	1
13	n	n	n	n	n	n	n	n	n	n	n	n	n
14	n	n	n	n	n	n	n	n	n	n	n	n	n
15	3	2	n	1	1	1	4	12	44	6	19	3	11
16	n	1	n	n	n	n	1	3	9	1	3	1	4
17	n	1	n	n	n	n	n	1	5	2	5	1	1
18	n	n	n	n	n	n	1	3	11	1	5	n	1
19	1	1	n	n	n	n	2	4	4	2	4	1	3
20	n	n	n	n	n	n	n	n	n	n	n	n	2
21	3	n	n	n	n	n	1	n	n	n	n	n	n
22	n	n	n	n	n	n	n	n	n	1	3	n	1
23	n	n	n	n	n	n	n	n	n	n	n	n	n
24	n	n	n	n	n	n	n	n	n	n	n	n	n
25	n	n	n	n	n	n	n	n	n	n	1	n	n
26	n	n	n	n	n	n	n	n	n	n	n	n	n
27	n	n	n	n	n	n	n	n	1	n	n	n	n
28	n	n	n	n	n	n	n	3	*	n	n	n	n

n - less than 0.5 percent chance
* - greater than 99.5 percent chance

spilled 7.7 million gallons when it broke up off Nantucket in December 1976 (Grose and Mattson, eds., 1977, p. 1); by comparison, the total volume spilled in 1975 by U.S. tankers was 7.8 million gallons in 587 incidents (Stewart, 1976, p. 60). The largest spills have the most damage potential, and generally occur under different circumstances from smaller spills. Major blowouts of wells or complete ship breakups, for instance, are somewhat distinct from minor collisions or equipment malfunctions.

Spill occurrence forecasts are made separately for different types of spill sources—tankers, pipelines, and platforms. It is reasonable to expect that spill occurrence rates will differ for the various modes of production and transport, and past data support this contention (see table 6). A principal use of the risk analysis model has been to help compare transportation mechanisms for given lease areas.

Continued accumulation of data may enable greater refinement of spill-source categorization in the future. For example, tankers might be considered separately by age class (Stewart and Kennedy, 1978, p. 25), or deep-water production rigs with single-buoy moorings might be considered separately from rigid, near-shore structures. The exact approach taken for a given risk analysis should depend on available data, the precise concerns of the analysis, and how the model results are to be interpreted; the model can be straightforwardly applied, using the same methodology, programs, and reporting structures as for the present pipeline-tanker breakdown.

Spill occurrence forecasts, as well as any assessment of risk from a given development program, depend fundamentally on the estimated amount of oil to be produced in a lease area. First described by Devanney and Stewart (1974), the Bayesian methodology used to construct the probability distributions on spill occurrence utilizes past production and oilspill occurrence data and future production estimates in a straight-forward way. The following sections provide further details.

TABLE 4.—*Example of typical output from program LANDSEG, showing probabilities (expressed in percent chance) that an oilspill starting at a particular location will reach a certain land segment in 30 days*

[n, less than 0.5 percent chance]

Land Segment	Hypothetical spill location												
	P1	P2 -E2	P3 -E3	P4 -E4	P5	P6	T1	T2	T3	T4	T5	T6	T7
A1	n	n	n	n	n	n	n	n	n	n	n	n	n
A2	n	n	n	n	n	n	n	n	n	n	n	n	n
A3	n	n	n	n	n	n	n	n	n	1	2	n	1
A4	n	n	n	n	n	n	n	n	n	n	1	n	n
A5	n	n	n	n	n	n	n	n	n	n	n	n	n
A6	n	n	n	n	n	n	n	n	n	n	n	n	n
A7	n	n	n	n	n	n	n	n	n	1	1	n	n
A8	n	n	n	n	n	n	n	n	n	1	2	n	1
A9	n	n	n	n	n	n	n	n	n	1	5	n	1
A10	n	n	n	n	n	n	n	n	n	n	5	n	1
A11	n	n	n	n	n	n	n	n	n	n	1	n	n
A12	n	n	n	n	n	n	n	n	n	n	n	n	3
A13	n	n	n	n	n	n	1	1	1	n	n	1	3
A14	n	n	n	n	n	n	2	6	8	n	n	n	1
A15	n	n	n	n	n	n	n	2	18	n	n	n	n
A16	n	n	n	n	n	n	n	n	1	n	n	n	n
A17	n	n	n	n	n	n	n	n	3	n	n	n	n
A18	n	n	n	n	n	n	n	2	8	n	n	n	n
A19	n	n	n	n	n	n	n	n	n	n	n	n	n
A20	n	n	n	n	n	n	n	n	n	n	n	n	n
A21	n	n	n	n	n	n	n	n	n	n	n	n	n
A22	n	n	n	n	n	n	n	n	n	n	n	n	n
A23	n	n	n	n	n	n	n	n	n	n	n	n	n
A24	n	n	n	n	n	n	n	n	n	n	n	n	n
A25	n	n	n	n	n	n	n	n	n	n	n	n	n
A26	n	n	n	n	n	n	n	n	n	n	n	n	n
A27	n	n	n	n	n	n	n	n	n	n	n	n	n
A28	1	n	n	n	n	n	n	n	n	n	n	n	n
A29	1	n	n	n	n	n	n	n	n	n	n	n	n
A30	n	n	n	n	n	n	n	n	n	n	n	n	n

n - less than 0.5 percent chance

PREDICTED PROBABILITY DISTRIBUTION FOR A FIXED CLASS OF SPILLS

This subsection describes the predicted probability distribution for spill occurrence within a fixed class of spills. A fixed class of spills consists of spills in a single size range (say, spills larger than a thousand barrels) originating from a single spill source (say, tankers).

A basic assumption of the method is that spills occur as a Poisson process, with volume of oil produced or handled as the exposure variable. (Other exposure variables can also be considered, as discussed in the next subsection.) That is, the probability P, of observing n spills in the course of handling t barrels of oil is

$$P(n) = \frac{(\lambda t)^n e^{-\lambda t}}{n!} . \quad (3)$$

where λ is the spill occurrence rate per unit exposure, (spills per million barrels of oil).

The Poisson assumption requires that spills occur independently of each other. One could clearly question this assumption — if, for example, safety and inspection standards were improved as a result of a particular spill, several potentially subsequent spills might be averted. Nonetheless, there is evidence that a Poisson model for spill occurrence provides a reasonable approximation (see Stewart and Kennedy, 1978, p. 36).

The spill occurrence rate, λ, is unknown. A Bayesian methodology, described in detail in appendix A, provides one way to weight the different possible values of λ, given the past frequency of spill occurrence for a fixed class of spills by taking a weighted average of the distributions (equation 3) over different values of λ. If ν is the number of past spills in the fixed spill class in the

TABLE 5.—*Example of output from program FIRSTPAS. Average minimum, maximum, and mean time-of-travel for oilspills occurring at site P1 to contact targets. Winter season and all seasons.*

LAUNCH POINT: P1
500 SPILLS PER SEASON

		WINTER				ALL			
TARGET		NO.	MIN	MAX	MEAN	NO.	MIN	MAX	MEAN
1	TANNER AND CORTEZ BANKS	64	11	59	33.3	350	6	59	25.5
2	RANGER BANK	3	53	56	54.6	13	35	56	46.9
3	MAJOR MARKETFISH	296	0	60	14.4	1626	0	60	7.0
4	MAJOR COM PELAGIC FISH	97	10	60	32.9	441	5	60	26.5
5	SALMON	0	0	0	0.0	11	7	20	12.7
6	ALBACORE	0	0	0	0.0	372	3	60	27.5
7	BONITO	0	0	0	0.0	11	5	56	35.2
8	TUNA	0	0	0	0.0	78	15	60	41.3
9	SWORDFISH	0	0	0	0.0	18	34	58	45.2
10	COMMERCIAL SHELLFISH	192	1	60	21.8	1189	1	60	11.2
11	SEABIRDS (APRIL-JUNE)	0	0	0	0.0	400	1	19	2.6
12	SEABIRDS (JULY-SEP)	0	0	0	0.0	42	0	58	16.2
13	SEABIRDS (OCT-DEC)	0	0	0	0.0	1	19	19	18.6
14	SEABIRDS (JAN-MAR)	129	5	60	27.1	141	4	60	26.0

course of handling τ barrels of oil, the estimated predicted probability that there will be n spills in the next t barrels handled is

$$P(n) = \frac{(n+\nu-1)!\, t^{n} \tau^{\nu}}{n!(\nu-1)!(t+\tau)^{n+\nu}} \tag{4}$$

This is the negative binomial distribution with expectation

$$E = \nu t/\tau \tag{5}$$

and variance

$$V = \frac{\nu t}{\tau}\left(1+\frac{t}{\tau}\right) \tag{6}$$

The probability of one or more spills is

$$P(n \geq 1) = 1 - \left(\frac{1}{1+t/\tau}\right)^{\nu} \tag{7}$$

Thus, the predicted probability distribution equation on spill occurrence for a fixed class of spills (a single spill-size range, a single spill-source category) incorporates the predicted volume to be handled, t, the past occurrence rate, (ν/τ), and the uncertainty which stems from the fact that $(\nu t/\tau)$ is not likely to equal the true occurrence rate, λ, exactly.

CHOOSING AN EXPOSURE VARIABLE

Fundamental to the spill occurrence forecasting method is the notion of an exposure variable. An exposure variable is some quantity related to oil production or transportation which has a precise statistical relationship to spill occurrence. In the past, the exposure variable used in the model has been volume of oil handled. Predicted probability distributions have been constructed by utilizing past rates of spills per volume of oil handled and the projected volume of oil to be handled.

Other exposure variables could be used. In the case of tankers, for example, number of port calls and numbers of tanker years have been contemplated (Stewart, 1976, p. 53, and Stewart and Kennedy, 1978, p. 23). The model described here permits the use of any exposure variable without major alteration of programs or other parts of the analysis.

An exposure variable should measure some aspect of oil production or oil transport such that for an amount of exposure t the probability of n spills occurring is given by the Poisson distribution:

$$P(n) = \frac{(\lambda t)^{n} e^{-\lambda t}}{n!}, \tag{3}$$

where λ is the average rate of spill occurrence per unit exposure and t is the exposure. This implies the following technical assumptions:

- The mean and variance of spills for a given amount of exposure should be λt.
- Spills must occur independently.

In practice, this relationship holds only approximately for any specific exposure variable, and it may be impossible to reject any of several alternative exposure variables simply on the basis of analysis of past data. Further criteria for choosing exposure variables are:

TABLE 6.—*Historic spill occurrence rates used in the Oilspill Risk Analysis Model*

Spill source	Number of spills	Volume handled (millions of bbls)	Data source	Area covered	Time period covered	Model runs used in
			Spills over 1,000 barrels			
Platforms	9	3,927	Devanney and Stewart (1974, p. 89).	U.S.	1964-72	Before May 1977.
Do	10	5,338	Stewart (1975, p. 32) and personal commun. May 1977.	U.S.	1964-75	After May 1977.
Pipelines	8	3,169	Devanney and Stewart (1974, p. 94).	U.S.	1964-72	Before May 1977.
Do	11	4,780	Stewart (1975, p. 33) and personal commun. May 1977.	U.S.	1964-75	After May 1977.
Tankers	99	29,326	Devanney and Stewart (1974, p. 49).	World	1969-72	Before May 1977.
Do	178	45,941	Stewart (1976, p. 66)	World	1969-73	After May 1977.
			Spills under 1,000 barrels			
Platforms and pipelines.	1,230	4,396	Devanney and Stewart (1974, p. 102).	U.S.	1971-72	All.
Tankers	624	1,412	Devanney and Stewart	U.S.	1971-72	All.

- The exposure should be simple.
- It should not intuitively violate the preceding technical assumptions to any significant extent.
- It should be a quantity which is predictable in the future.

The last criterion is particularly important in forecasting applications. If the analyst has an estimate of future production from a large area, but no specific information on how the area is to be developed, in terms of number of platforms, etc., then volume produced might be preferable as an exposure variable over platform-years, even if platform-years appear to be a better exposure variable based on past data.

How can a contemplated exposure variable be checked using past data? One way is by testing the assumption that the mean and the variance are both equal to λt. The linear relationship between the expected number of spills and the exposure variable suggests the use of least-squares regression techniques; weighted least squares should be used because the variance of the number of spills is not constant, and is also linearly related to exposure (see Draper and Smith, 1966, p. 77). Thus, if $(\tau_1, \tau_2, \ldots, \tau_k)$ are the exposures in regions $(r_1, r_2, \ldots, r_n)$ during some year, and $(\nu_1, \nu_2, \ldots, \nu_k)$ are the respective numbers of spills observed, then a regression of $\nu_i\sqrt{\tau_i}$vs. $\sqrt{\tau_i}$ checks the first technical assumption. This gives $\Sigma\nu_i/\Sigma\tau_i$ as the true rate of spill occurrence per unit of exposure. The usual tests of a regression fit can be used to evaluate the appropriateness of this assumption. Mean and variance equal to λt is a necessary but not sufficient condition for the Poisson model. (Stewart and Kennedy, 1978, p. 60, present this point quite forcefully). Devanney and Stewart (1974, p. 45) give some examples of regression investigations where volume of oil handled is used as an exposure variable.

Occasionally it will be possible to test directly the Poisson assumption in its entirety. If there are numerous observations, each with the same exposure, then the associated numbers of spills represent independent observations from a single Poisson distribution, and the standard statistical tests for goodness-of-fit can be employed. A possible base is tanker spills, where a contemplated exposure variable is tanker-years. Every tanker which has been in service for the same time period will have the same exposure. Stewart and Kennedy (1978, p. 24) performed goodness-of-fit tests in this situation and felt the Poisson model to be acceptable.

In practice, however, these statistical testing procedures rarely demonstrate unequivocally that a given exposure variable is "correct." They provide one way to rank contemplated exposure variables based on past experience. The ultimate choice of an exposure variable will rest largely on the judgment of the analyst.

The regression work of Devanney and Stewart (1974, p. 26) indicated that volume of oil handled is at least a reasonable exposure variable. The variable is simple, bears a good intuitive connection to the number of spills, and is relatively easy to predict in advance within known error limits. Recently, though, Stewart and Kennedy (1978) have investigated the use of other exposure variables.

SPILL OCCURRENCE RATES AND EXPOSURE VARIABLES

The sources for the spill occurrence rates used in the model are Devanney and Stewart (1974), and Stewart (1975 and 1976). Those authors obtained data primarily from three sources: the Conservation Division of the U.S. Geological Survey, the U.S. Coast Guard, and a survey of world-wide major tanker spills in 1969-1972 (Devanney and Stewart, 1974, p. 1). In the past, there have been many problems in screening and reconciling the information in these data sources; Stewart and Devanney have done much in this area and describe it in the above-cited reports. Table 6 gives the spill occurrence information used to date in runs of the model. The occurrence rates were used to construct predicted probability distributions on spill occurrence as described in the earlier subsection, "Predicted Probability Distribution for a Fixed Class of Spills." For small spills, pipelines and platform occurrences are lumped together due to the data base ambiguity concerning the precise division point between a platform and a pipeline spill.

TRANSPORTATION SCENARIOS

The previous section presented a method for constructing a probability distribution on spill occurrence. The next logical step is to show how site-specific details are applied to calculations of spill occurrence.

CONSTRUCTION OF TRANSPORTATION SCENARIOS: PROGRAM SCENARIO

The risks of oilspills resulting from OCS development do not arise solely from platform operations. Transporting oil to shore entails additional risks which can exceed the risks of extracting the oil. Therefore, each group of leasing tracts must be considered as part of an integrated production and transportation system; program SCENARIO provides a means of describing this system so that spill occurrence probability distributions can be calculated.

For each production site, a transportation route must be defined by linking together any of the launch points analyzed by program SPILL with destination points (see figure 11). The method of transport (that is, pipeline or tanker) must be specified for each transportation route segment. It is not necessary for the route to be strictly continuous, since this description is only an approximation of an actual route. The modeler must use judgment in striking a balance between a precise route description and a reasonable computational effort, and should be watchful against specifying a transportation route more detailed than justified by the resolution of the model. Figure 11 shows how oil produced from lease tract group P14 would be brought to land in tankers following a route starting at P14 and continuing through T21 and T20. At least one transportation route must be defined for every lease tract group contained in an analysis, and the complete set of transportation routes is called the transportation scenario. The coding of program SCENARIO allows the inclusion of sources of oilspill risk other than OCS leasing in a transportation scenario.

In the preceding subsection, "Spill Occurrence Rates and Exposure Variables," it was explained that the exposure variable for transporting oil is the volume of oil handled. That is, a given volume of oil, t, moved from A to B can be expected to result in lt spills, regardless of the distance between A and B. The route from A to B can be described as a series of launch points with the oilspill risks distributed among the route segments according to their length. (In figure 11, for example, typical weights may be 20 percent for P14, 40 percent for T19, and 40 percent for T20, demonstrating a rough proportioning of risk to length.) Use of other exposure variables would require a similar weighting of transportation route segments. To accomplish this, program SCENARIO is designed with a highly flexible weighting process that allows the user to assign an arbitrary weight to each segment of a transportation route. This flexibility allows the user to specify a complicated transportation route that involves multiple movements of oil (e.g. "pipeline to port A, then tanker from port A to port B"), or to divide the oil from a lease tract among several different transportation routes (that is, "half to port A, half to port B"). If deemed justifiable, "high risk" transportation segments can even be assigned higher weights.

ESTIMATED VOLUMES OF OIL RESERVES

For calculating actual oilspill risks, it is necessary to include the volume of oil that is expected to be produced from each lease tract group as input to program SCENARIO. This information is compiled by the Conservation Division of the U.S. Geological Survey and is considered proprietary information.

PROBABILITY THAT AN OILSPILL WILL OCCUR AND CONTACT A TARGET

The model produces as an end result an estimated probability distribution for the number of spills con-