spills in an amount of exposure, τ, is given by

$$p(n) = \frac{(n + \nu - 1)! t^n \tau^\nu}{n!(\nu - 1)!(t + \tau)^{n+\nu}}$$

Figures 4.7, 4.8 and 4.9 show the resulting densities on the number of tanker spills over 42,000 gallons in the field life of a "small", "medium", and "large" find respectively if the finds are landed by vessel, where

1. A "small" find is defined to be 500 million barrels of oil in place, 500 billion cubic feet of gas, situated 146 miles offshore. The other reservoir parameters are those shown in Table 3.0.1 in the Offshore Development Model report. Under the assumption used therein, this field produces 122 million barrels of oil, has a field life of 5 years and a peak production rate of 73 million barrels per year. This find then corresponds in all respects to the small find studied in the Offshore Development Model [8].

2. A "medium" find is defined to be 2 billion barrels in place, 1000:1 gas/oil ratio, located in two structures 146 miles offshore. It too corresponds in all respects to the "medium" find studied in the Offshore Development Model report. Under the assumptions used therein, this find produces 567 million barrels in 5 years with a peak production year of 169 million barrels.

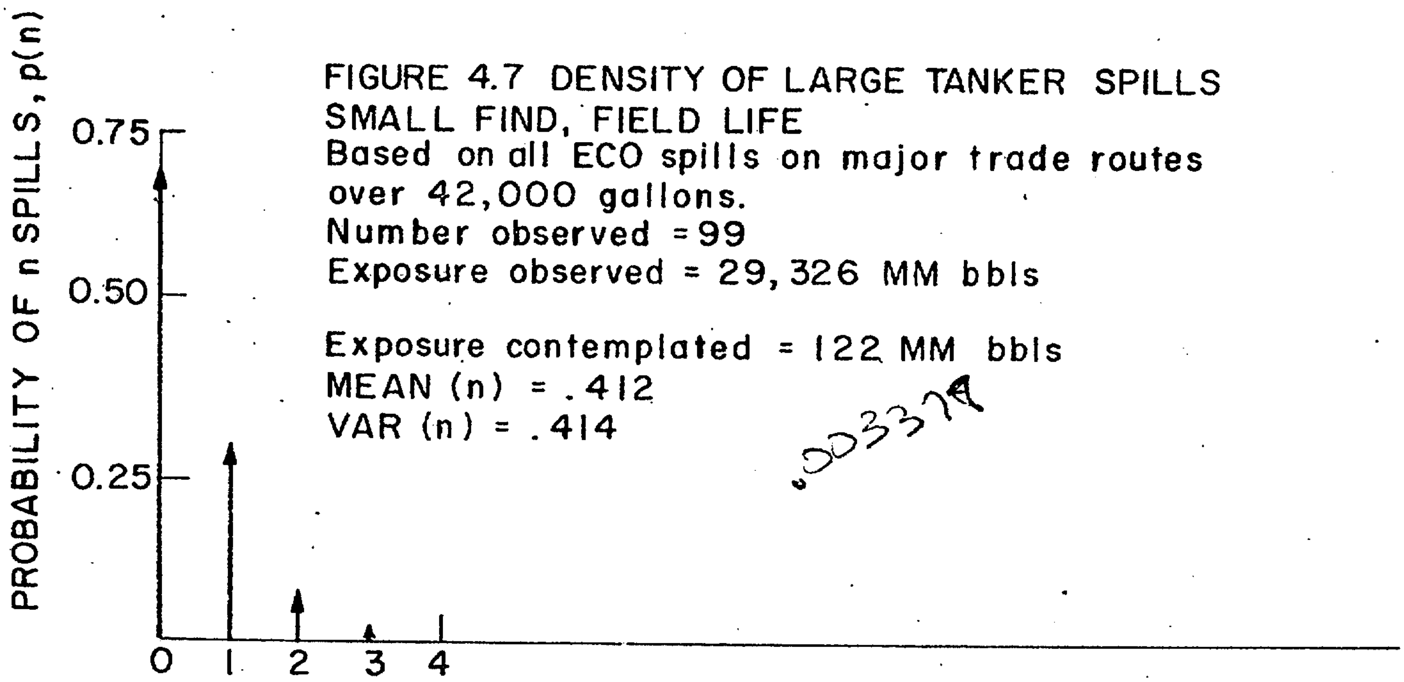

FIGURE 4.7 DENSITY OF LARGE TANKER SPILLS
SMALL FIND, FIELD LIFE
Based on all ECO spills on major trade routes over 42,000 gallons.
Number observed = 99
Exposure observed = 29,326 MM bbls

Exposure contemplated = 122 MM bbls
MEAN (n) = .412
VAR (n) = .414

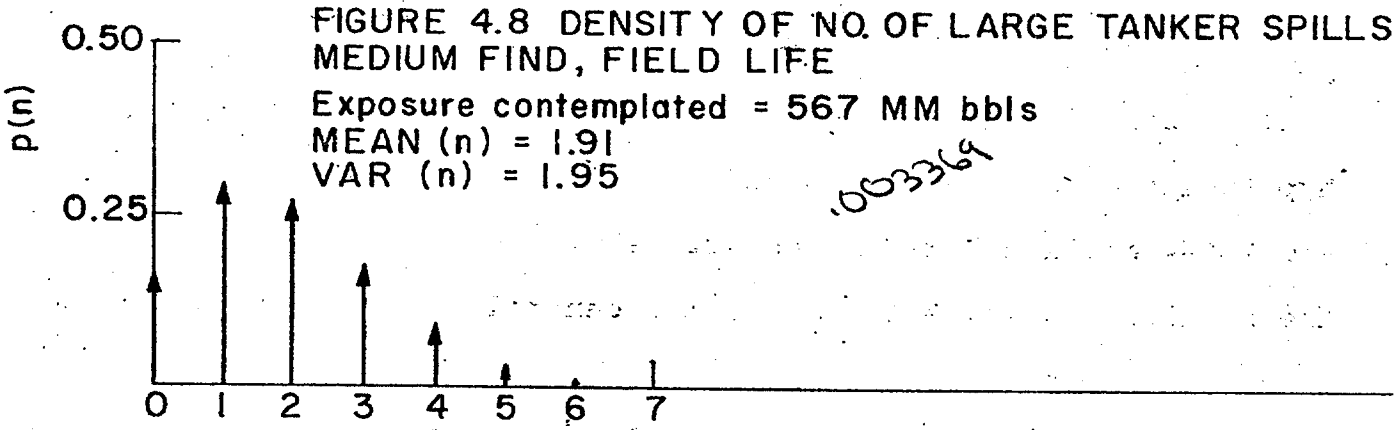

FIGURE 4.8 DENSITY OF NO. OF LARGE TANKER SPILLS
MEDIUM FIND, FIELD LIFE
Exposure contemplated = 567 MM bbls
MEAN (n) = 1.91
VAR (n) = 1.95

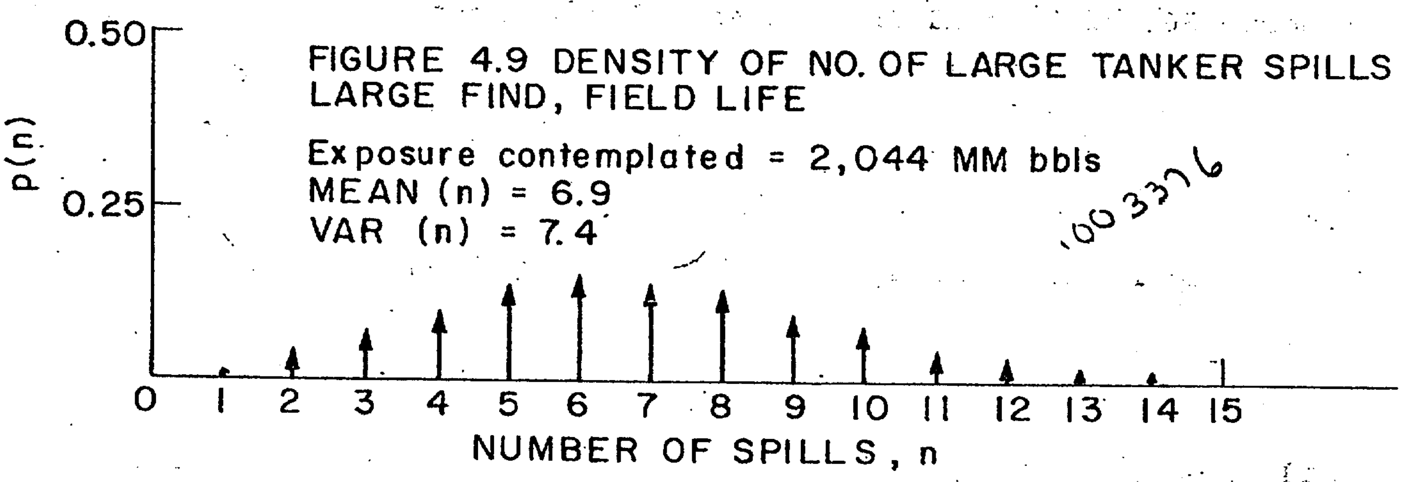

FIGURE 4.9 DENSITY OF NO. OF LARGE TANKER SPILLS
LARGE FIND, FIELD LIFE
Exposure contemplated = 2,044 MM bbls
MEAN (n) = 6.9
VAR (n) = 7.4

3. A "large" find is defined to be 10 billion barrels of oil in 5 structures and it corresponds to the "large" find studied in Section 3 of the Offshore Development Model report. Under the assumptions used therein, this find produces 2,044 million barrels of oil over 12 years with a peak production year of 327 million barrels.

These three figures are based on the fact that ECO has observed 99 spills over 42,000 gallons on our 12 major trade routes in the period 1968 through 1972. During that period, approximately 29 billion barrels of oil were landed on these trade routes, that is, we have observed an exposure of 29 billion barrels. The total exposure contemplated for the hypothesized small, medium, and large finds is 122, 567, and 2,044 million barrels respectively. Notice that, for the small find, while the mean, the central value, of the density is less than 1/2, there is a substantial probability, about .30, of 1 spill and a possibility, about 1 chance in 40, of as many as 2 tanker spills. For the larger fields, both the mean and variance increase as the densities shift to the right and spread out.

Figures 4.10 through 4.12 show the same densities for all spills over 100,000 gallons (approximately the size of the West Falmouth and "Tamano" spills), while Figures 4.13 through 4.15 show the densities for all spills over 1,000,000 gallons

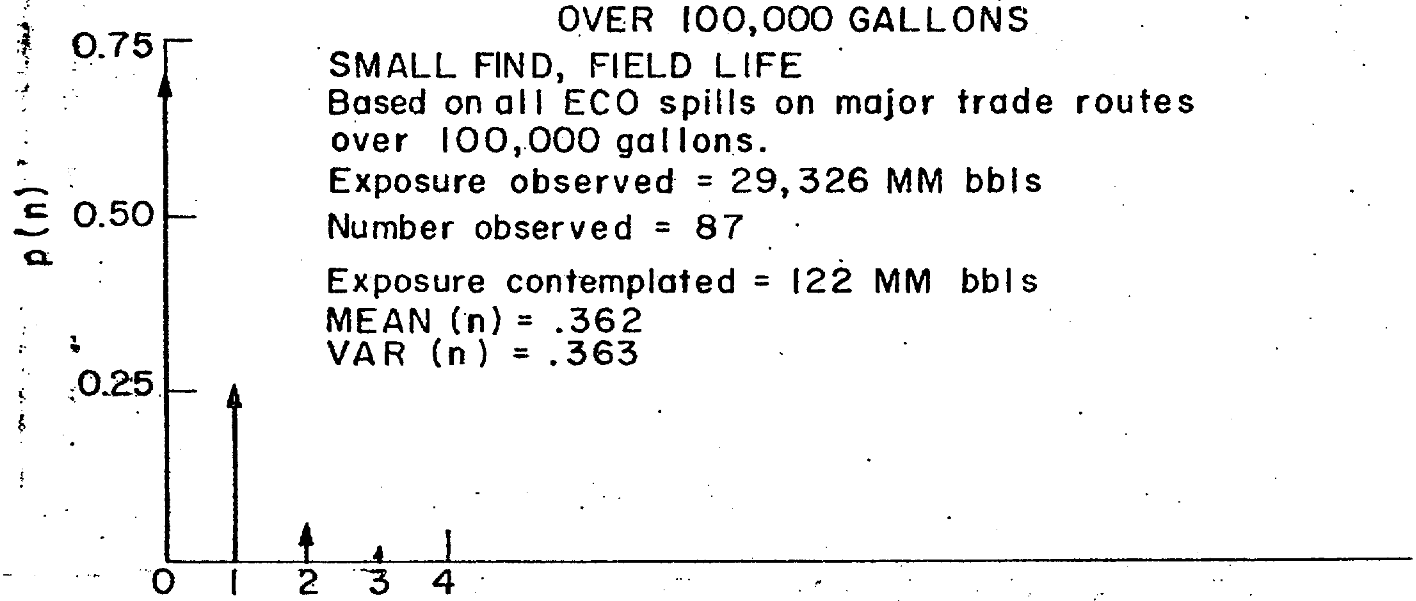

FIGURE 4.10 DENSITY OF NO. OF TANKER SPILLS OVER 100,000 GALLONS

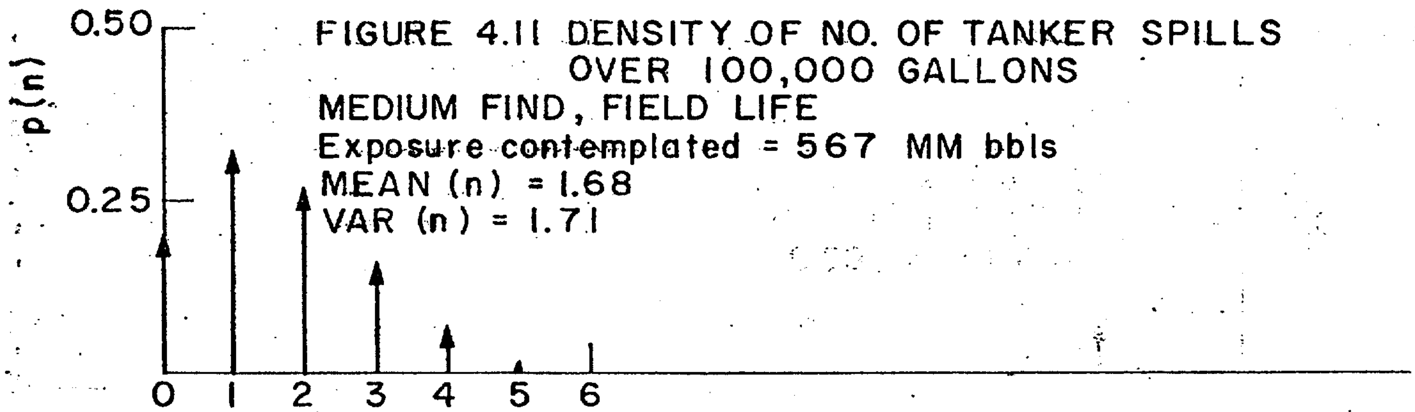

FIGURE 4.11 DENSITY OF NO. OF TANKER SPILLS OVER 100,000 GALLONS

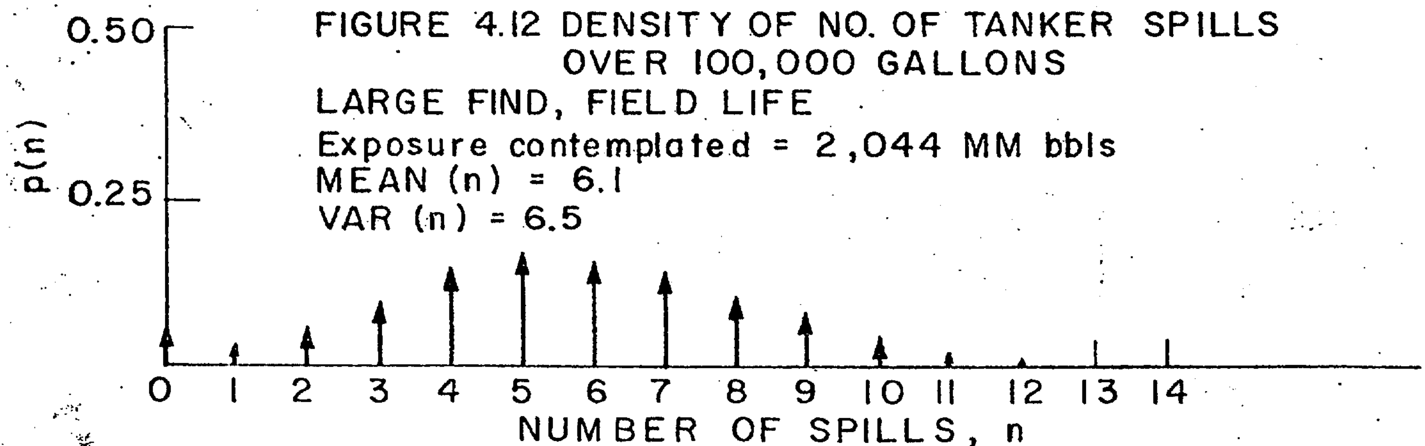

FIGURE 4.12 DENSITY OF NO. OF TANKER SPILLS OVER 100,000 GALLONS

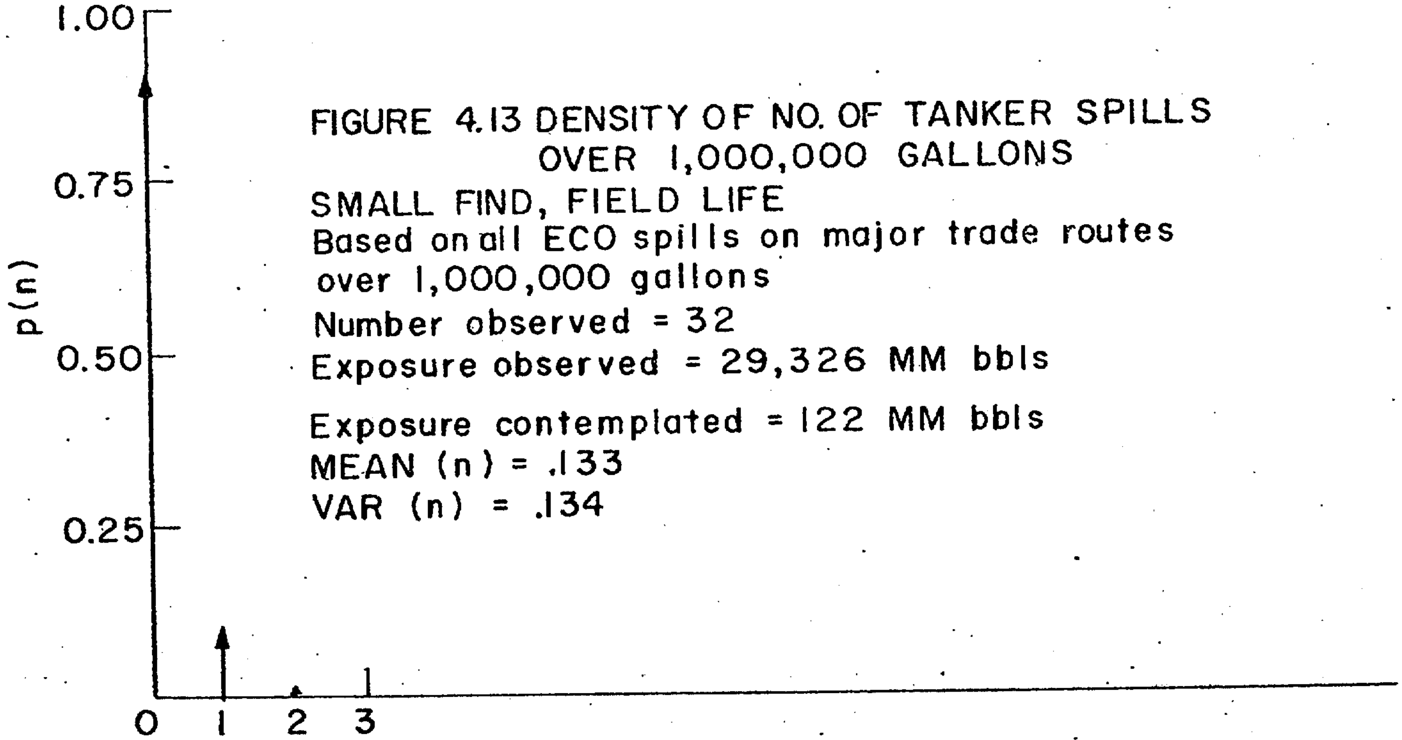

FIGURE 4.13 DENSITY OF NO. OF TANKER SPILLS OVER 1,000,000 GALLONS

SMALL FIND, FIELD LIFE

Based on all ECO spills on major trade routes over 1,000,000 gallons

Number observed = 32

Exposure observed = 29,326 MM bbls

Exposure contemplated = 122 MM bbls

MEAN (n) = .133

VAR (n) = .134

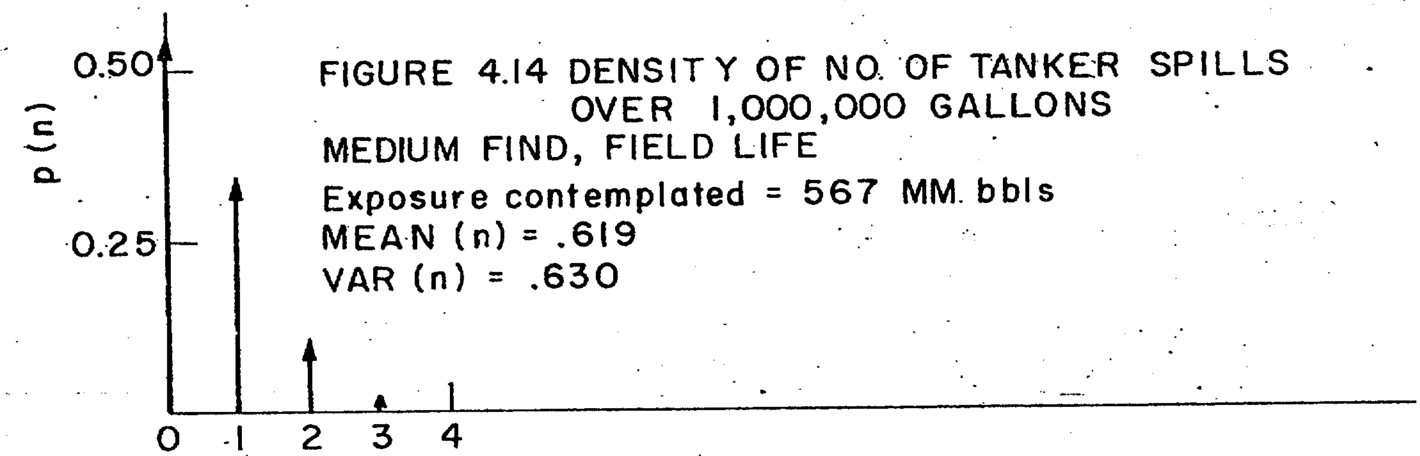

FIGURE 4.14 DENSITY OF NO. OF TANKER SPILLS OVER 1,000,000 GALLONS

MEDIUM FIND, FIELD LIFE

Exposure contemplated = 567 MM bbls

MEAN (n) = .619

VAR (n) = .630

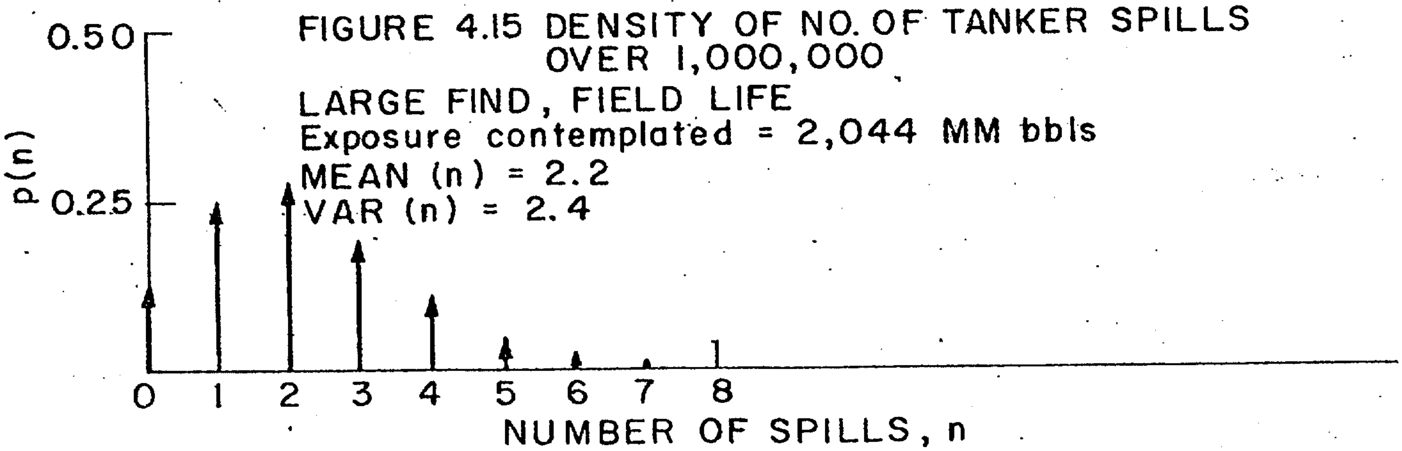

FIGURE 4.15 DENSITY OF NO. OF TANKER SPILLS OVER 1,000,000

LARGE FIND, FIELD LIFE

Exposure contemplated = 2,044 MM bbls

MEAN (n) = 2.2

VAR (n) = 2.4

(approximately one-third the size of the Santa Barbara spill) and Figures 4.16 through 4.18 show the three densities for all spills over 10,000,000 gallons (about one-third "Torrey Canyon"). Notice the increase in the ratio of the variance to the mean as the sample size becomes smaller, reflecting our greater uncertainty about the process generating very large spills.

The rather small change between the density of spills greater than 42,000 gallons and the density of spills greater than 100,000 gallons is perhaps suspicious. There are only 12 spills in the ECO data that are greater than 42,000 gallons but less than 100,000 gallons. Much of our other spill data--much of it admittedly non-tanker--indicates that smaller spills are much more frequent than larger spills. This may not be true for offshore tanker spills, as the ECO data indicates, or the ECO data may not be catching all the spills in this intermediate range. With respect to overall volume spilled, this is certainly not critical. However, the 42,000 gallon spill incidence density must be used with some caution.

The spill incidence analysis can be applied to any specific period during the hypothetical developments operation. For example, one might be interested in the density of the number of large tanker spills which will occur during the peak

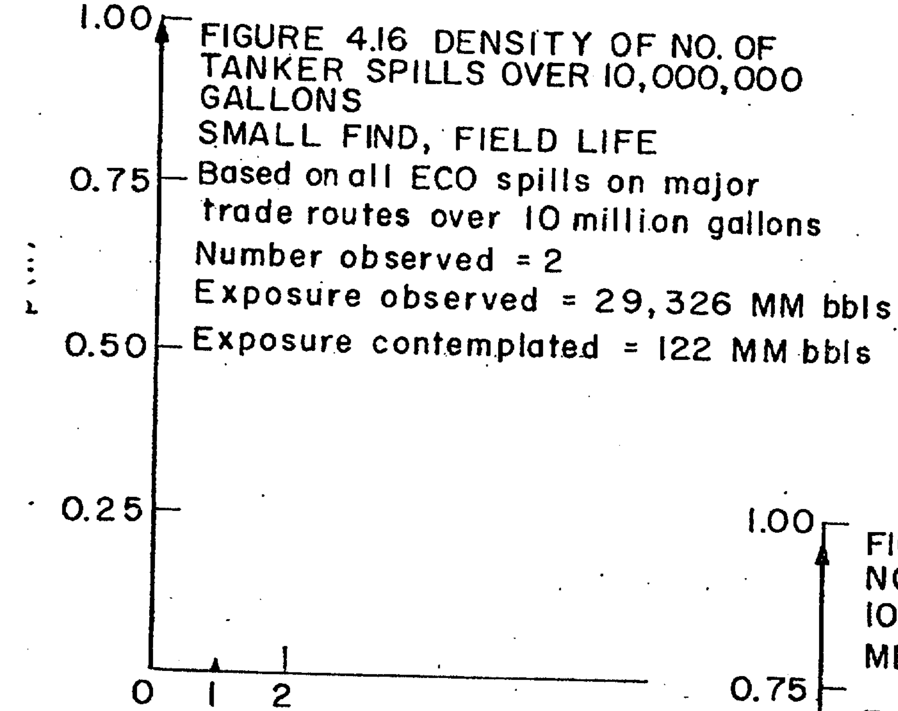

FIGURE 4.16 DENSITY OF NO. OF TANKER SPILLS OVER 10,000,000 GALLONS
SMALL FIND, FIELD LIFE
Based on all ECO spills on major trade routes over 10 million gallons
Number observed = 2
Exposure observed = 29,326 MM bbls
Exposure contemplated = 122 MM bbls

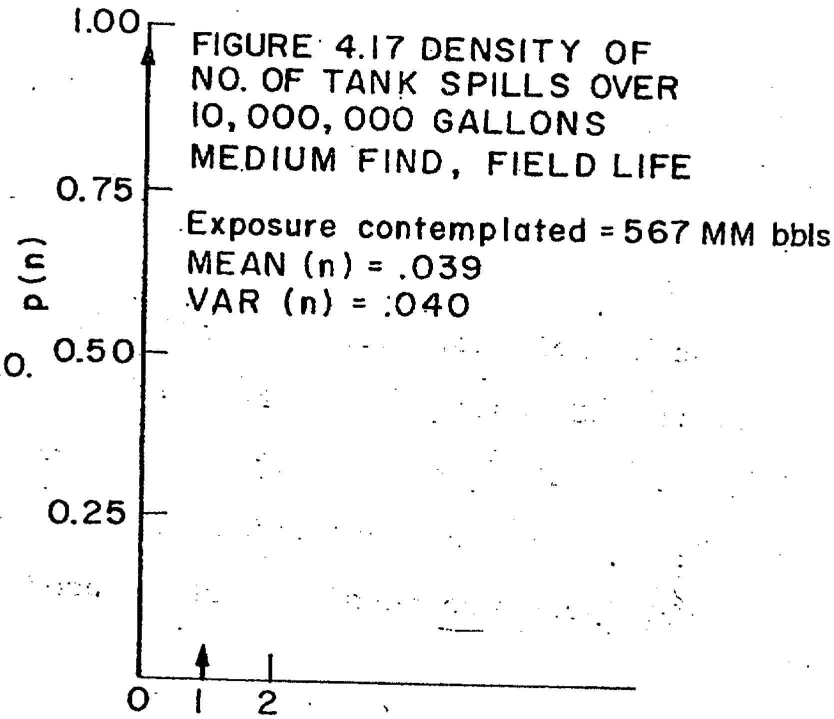

FIGURE 4.17 DENSITY OF NO. OF TANK SPILLS OVER 10,000,000 GALLONS
MEDIUM FIND, FIELD LIFE
Exposure contemplated = 567 MM bbls
MEAN (n) = .039
VAR (n) = .040

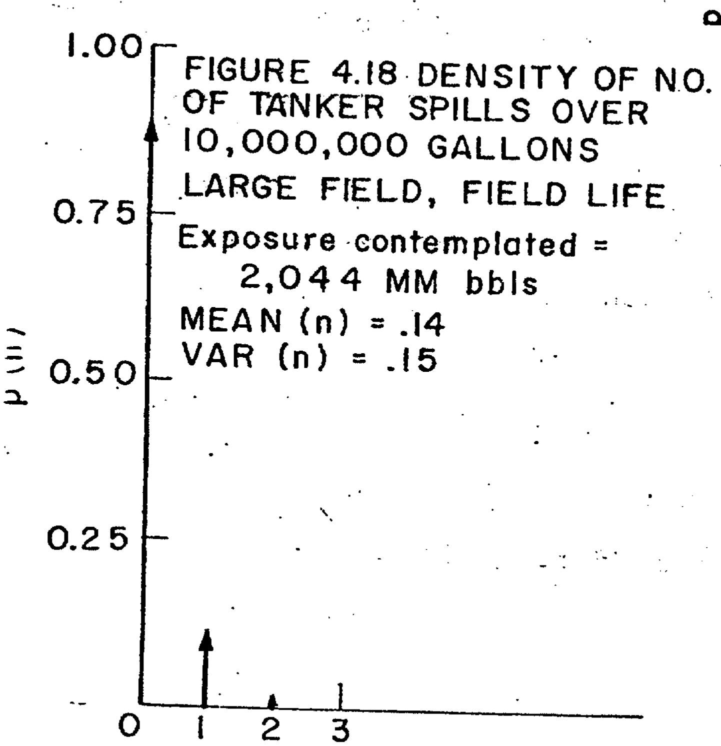

FIGURE 4.18 DENSITY OF NO. OF TANKER SPILLS OVER 10,000,000 GALLONS
LARGE FIELD, FIELD LIFE
Exposure contemplated = 2,044 MM bbls
MEAN (n) = .14
VAR (n) = .15

production year of a given find. This can be obtained by simply using the anticipated peak year production as the exposure contemplated value in the foregoing analysis.

Figures 4.19, 4.20, and 4.21 show the results for our small, medium, and large finds for the year of peak production.

From a biological point of view, the time between large spills may be at least as important as the number of such spills. Figure 4.22 shows the cumulative of the amount of oil handled between tanker spills, v. This density is a straightforward transformation of our earlier negative binomial.* This cumulative can in turn be put in terms of time for any period for which one knows the production rate. Figure 4.22 indicates the equivalent time between spills assuming the small find at peak production and the large find respectively. By reading up from the lower scales for any given time interval, one can find the probability that the time between successive spills will be less than the given interval. For example, assuming a small find at peak production, the probability that the time between successive tanker spills greater than 42,000 gallons will be less than 1 year is .15 while for a large field at peak production this probability

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*The density of the "interarrival time" for a negative binomial process with parameters ν and τ is

$$f(v \mid \nu,\tau) = \nu\tau^{\nu}/(v + \tau)^{\nu+1}$$

The mean of this density is $\tau/(\nu - 1)$ and the variance is $\nu\tau^2/(\nu - 1)^2 \cdot (\nu - 2))$. This density quickly approaches the exponential for large ν.

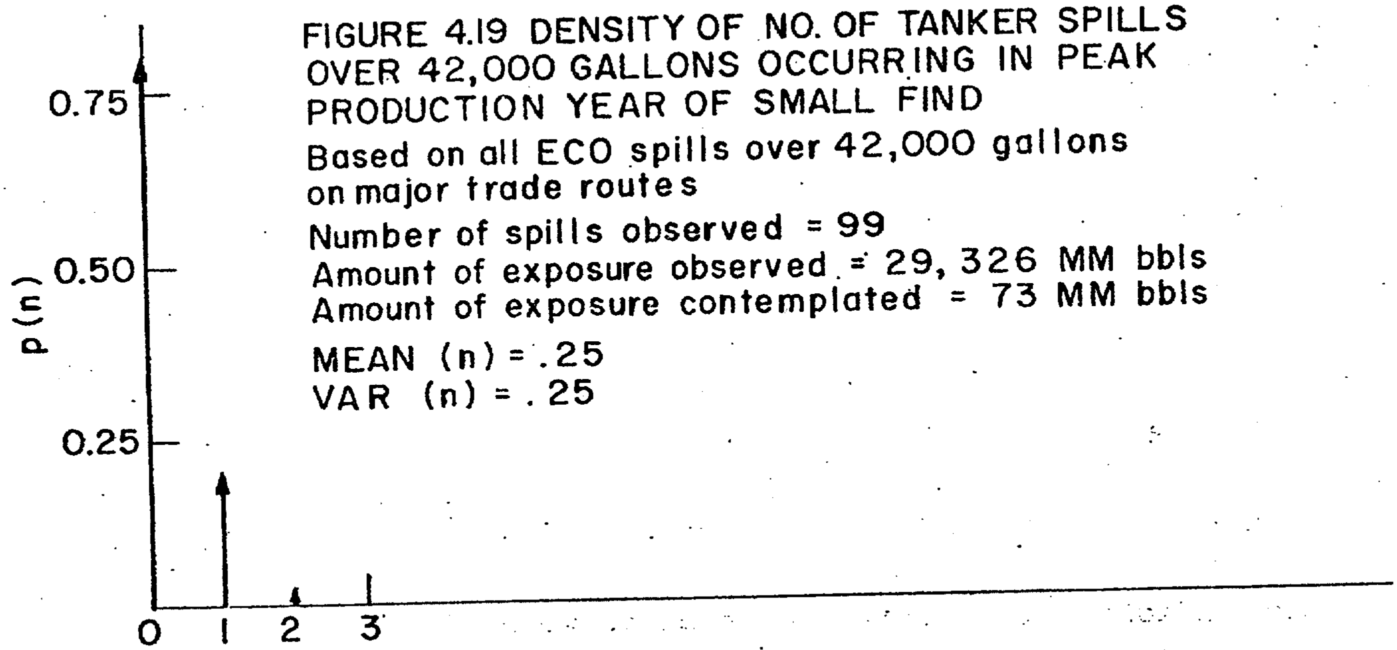

FIGURE 4.19 DENSITY OF NO. OF TANKER SPILLS OVER 42,000 GALLONS OCCURRING IN PEAK PRODUCTION YEAR OF SMALL FIND

Based on all ECO spills over 42,000 gallons on major trade routes

Number of spills observed = 99
Amount of exposure observed = 29,326 MM bbls
Amount of exposure contemplated = 73 MM bbls

MEAN (n) = .25
VAR (n) = .25

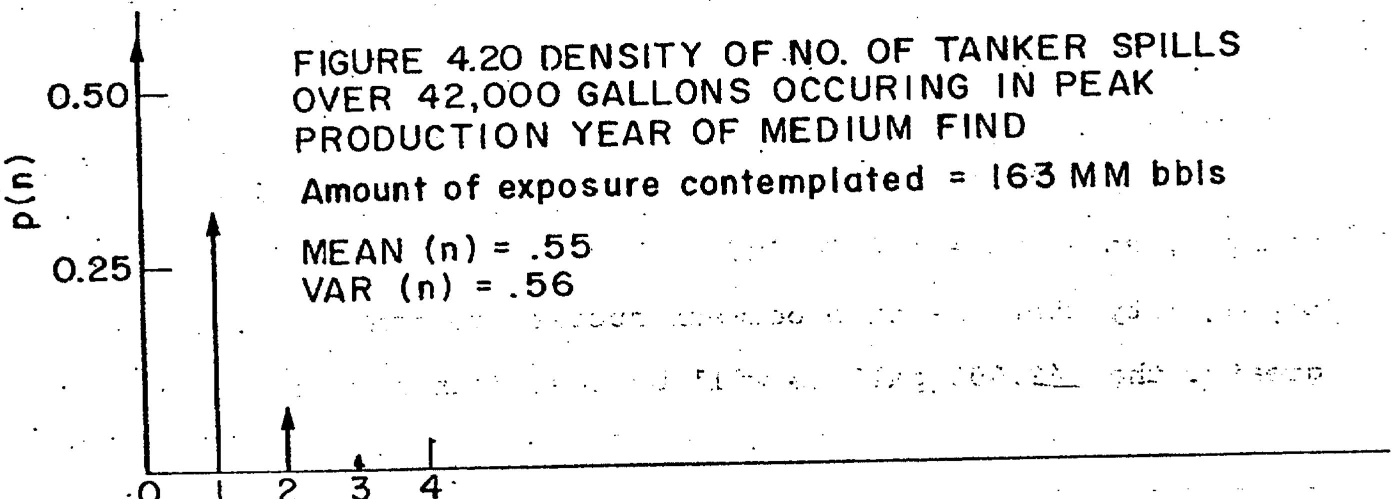

FIGURE 4.20 DENSITY OF NO. OF TANKER SPILLS OVER 42,000 GALLONS OCCURING IN PEAK PRODUCTION YEAR OF MEDIUM FIND

Amount of exposure contemplated = 163 MM bbls

MEAN (n) = .55
VAR (n) = .56

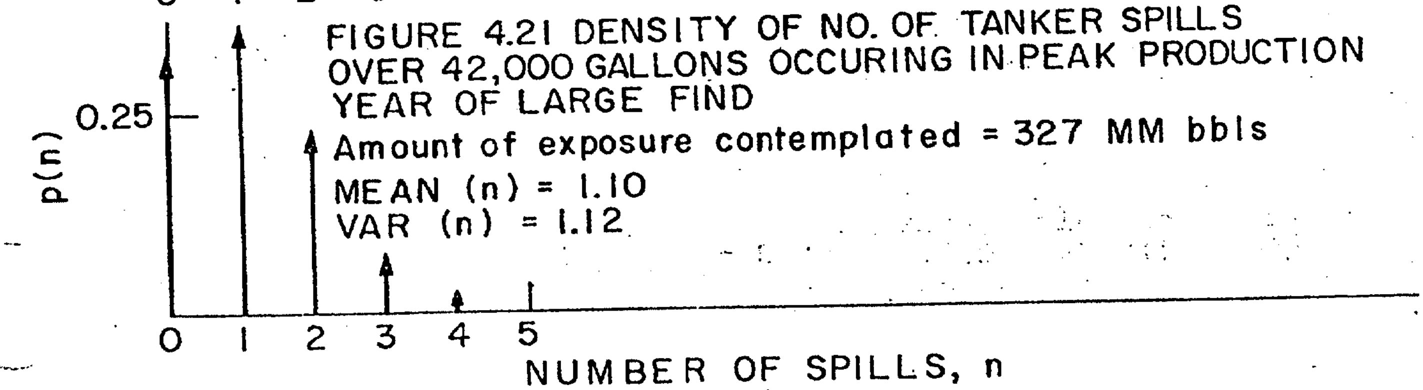

FIGURE 4.21 DENSITY OF NO. OF TANKER SPILLS OVER 42,000 GALLONS OCCURING IN PEAK PRODUCTION YEAR OF LARGE FIND

Amount of exposure contemplated = 327 MM bbls

MEAN (n) = 1.10
VAR (n) = 1.12

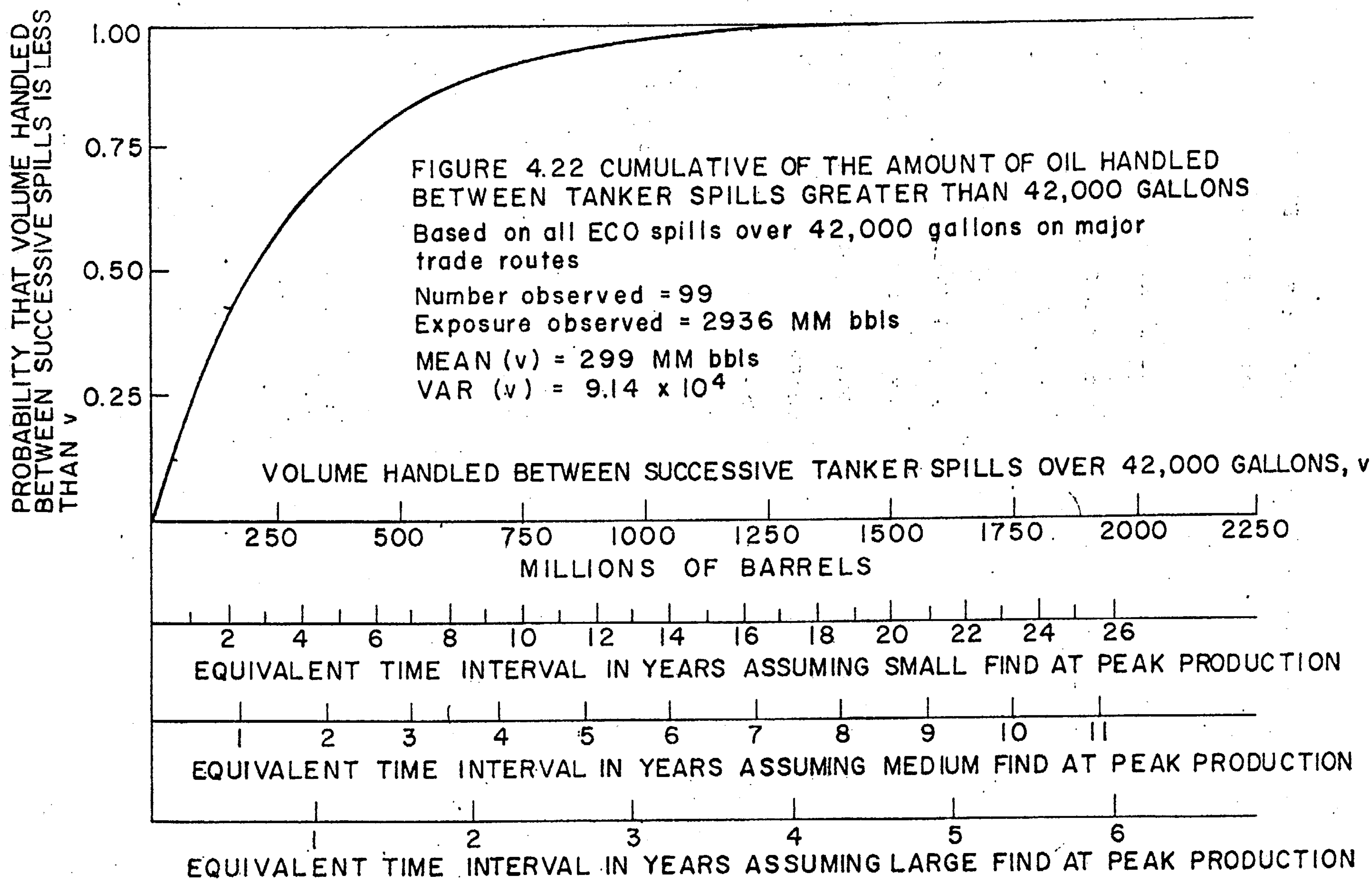

FIGURE 4.22 CUMULATIVE OF THE AMOUNT OF OIL HANDLED BETWEEN TANKER SPILLS GREATER THAN 42,000 GALLONS

Based on all ECO spills over 42,000 gallons on major trade routes

Number observed = 99

Exposure observed = 2936 MM bbls

MEAN (v) = 299 MM bbls

VAR (v) = 9.14×10^4

is .62. In using this graph, it is important to remember that in our hypothetical development, production remains near the peak for only a very few years.

Let us now turn to the problem of obtaining a density on the size of a large tanker spill given that a spill has occurred. As Section 3 argues, our assumptions imply that having observed m spills: $x_1, x_2, \ldots x_i, \ldots x_m$ where x_i is the quantity of the ith spill observed, then the density on size of the net spill, x, is given by

$$f(x) = \int_0^\infty \frac{p^{\rho-1}\Gamma((m+1)\rho)\,d\rho}{(\Gamma(\rho))^{m+1}(s+x)^{(m+1)\rho}S(s,p,m)}$$

where

m = number of spills observed

$s = \Sigma x_i$ = total amount of spillage observed

$p = \Pi x_i$ = product of all the spill quantities observed.

Figure 4.23 shows the cumulative of this density based on all ECO spills over 42,000 gallons. The mean is slightly over 2 million gallons, the mean squared is less than half the variance, indicating a widely dispersed distribution. And as the figure shows, the bulk of the probability is spread over three orders of magnitude ranging from 10,000 to 10 million gallons.

Before turning our attention to other spill categories, there are a few more qualitative insights we can glean from the ECO data.

1. There has been considerable discussion of the effect of vessel size on spillage - some holding that

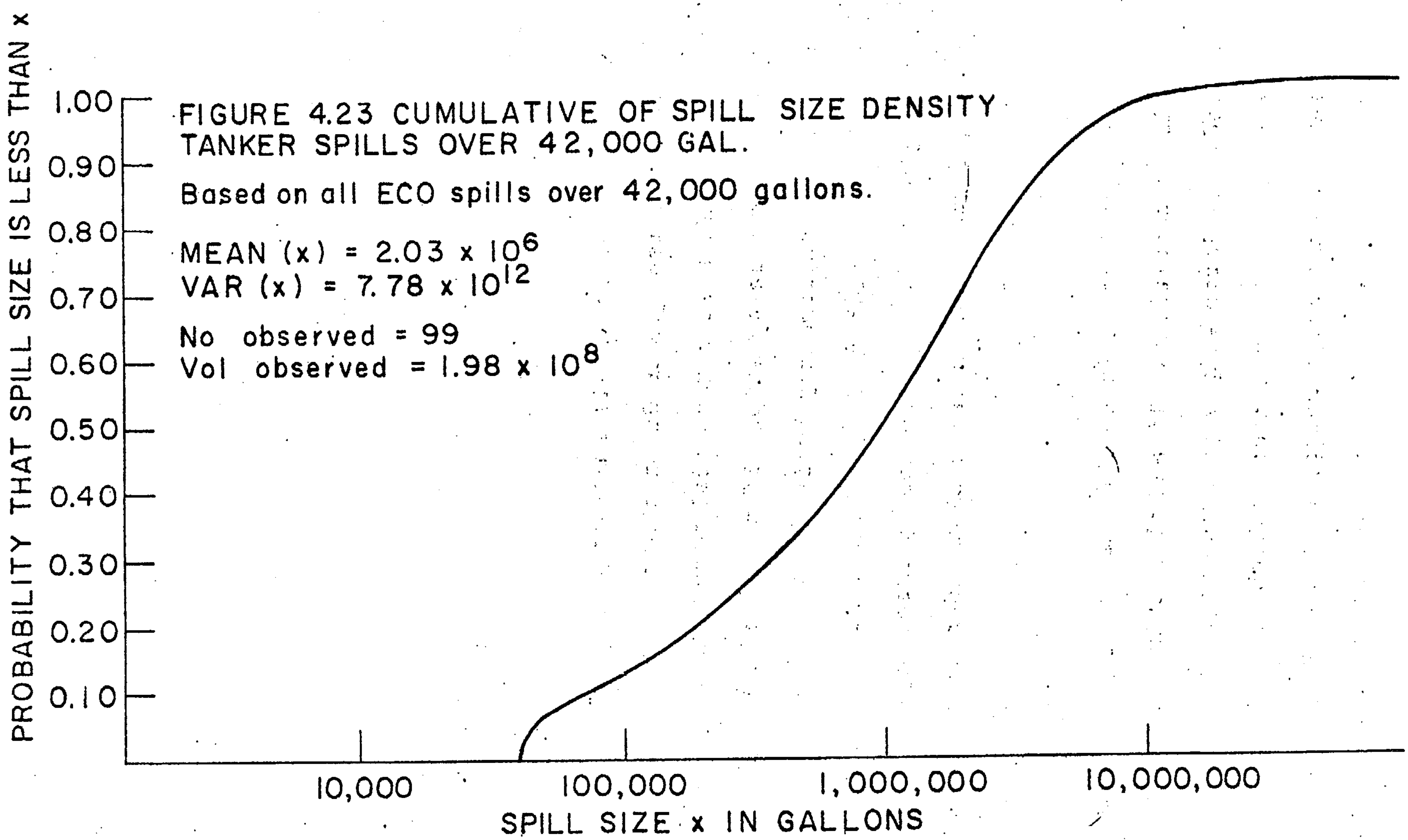

FIGURE 4.23 CUMULATIVE OF SPILL SIZE DENSITY TANKER SPILLS OVER 42,000 GAL.

increased vessel size will decrease spillage due to the smaller number of landfalls and economies of scale with respect to navigational equipment and crew training, others holding that larger vessels will exacerbate the problem due to poorer maneuverability and larger potential spill size. At least with respect to spill number, the ECO data comes down somewhat on the side of the large tankers, as indicated by Figure 4.24.

Number of incidents per vessel-year appears to be only a weak function of size, and this figure is biased against the small ships in one sense, for small ships tend to trade on shorter route lengths and thus will make a good deal more landfalls in a year than a large ship. If number of landfalls is the best explanatory variable, then a comparison of spills per number of landfalls would be more meaningful, in which case the apparent superiority of the large ships in terms of incidents per vessel year in this diagram would undoubtedly disappear. On the other hand, a good portion of the incidents in the very large ship categories are explosion in the light conditions. If and when this problem is solved, the large ship's position would improve considerably. But the factor which tips the scales in favor of the large ships, as far as number of spills is concerned, is that even if the large ship

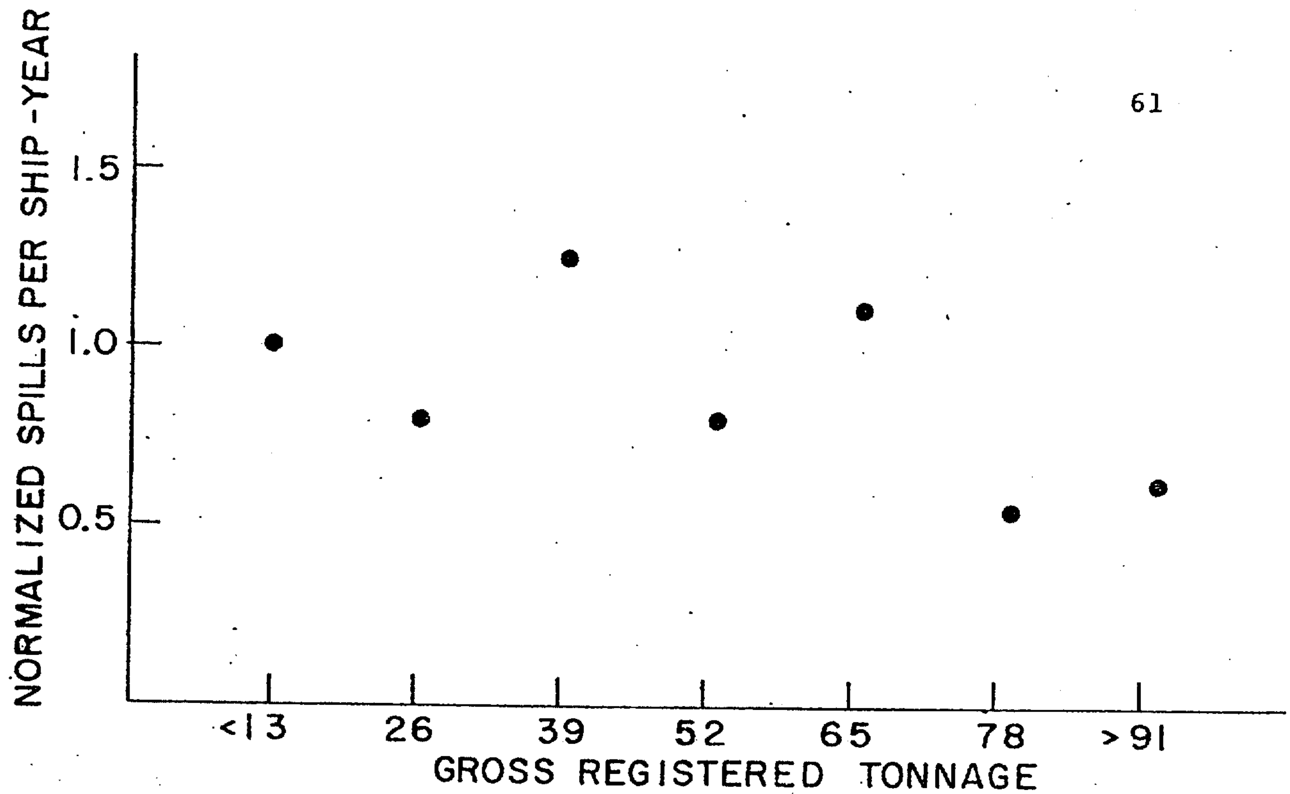

FIGURE 4.24 SPILL INCIDENCE AS A FUNCTION OF SHIP SIZE (NUMBER OF SPILLS PER SHIP-YEAR NORMALIZED RELATIVE TO SMALL TANKER EXPERIENCE)

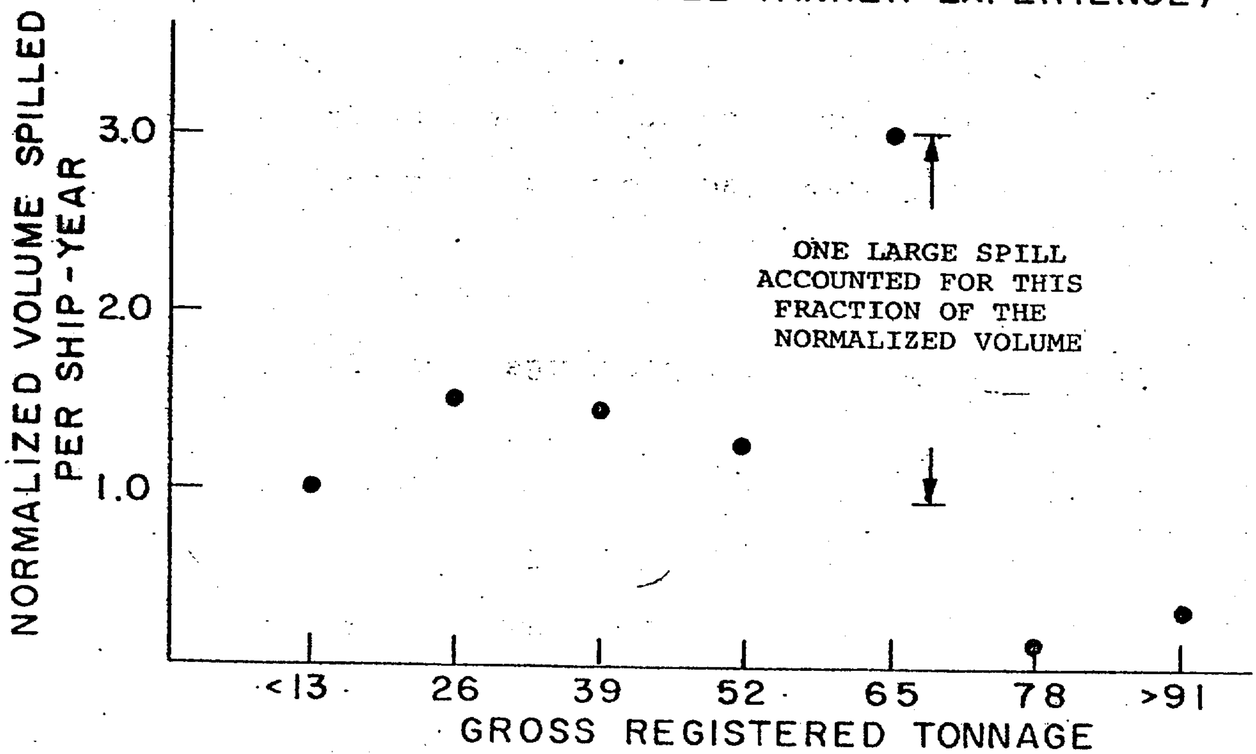

FIGURE 4.25 SPILL VOLUME AS A FUNCTION OF SHIP SIZE (TOTAL VOLUME SPILLED PER SHIP-YEAR BY SIZE CATEGORY NORMALIZED RELATIVE TO SMALL TANKER EXPERIENCE)

has about the same spill incidence in a year as the data indicates, in that year a large ship will be moving more oil than a small ship.

Grimes [13], in examining a sample of 13,379 tanker accidents (not spills) worldwide in the period 1959 through 1968, comes to somewhat similar conclusions. He finds that casualties pervessel remained almost constant over the period. He found that the stranding,collision, and fire rate for the tanker less than 20,000 tons was significantly higher than that of the rest of the population. The stranding rate for tankers over 50,000 tons showed no significant difference, the collision rate was somewhat lower (significant at 5%), and the fire rate was significantly high. The overall accident rate for tankers over 50,000 tons was very slightly lower than that of the rest of the population. Gaines's study did not discriminate between accidents causing spills and non-spill casualties.

2. Interestingly enough, Figure 4.25 together with Figure 4.24 indicate that the average size of the spills emanating from small ships is larger than the average size of spills resulting from big ships. However, factors other than size are probably determinant. As mentioned earlier, a significant portion of the large ship spills are tank explosions in the light condition involving a spill of only bunkers. On the other hand, many of the large small ship spills are structural failures which are almost certainly more a function of

ship age than size. Small ships tend to be considerably older than large ships. In short, we have not been able to identify any significant pattern which appears to be directly related to ship size and, therefore, have not derived densities by ship size.

This is perhaps unfortunate, for if there's one thing one can say with certainty about tanker spills, it is that the largest spill will be no greater than the vessel's displacement. Thus, changing vessel size will change the upper tail of the spill size density. But given the effect of tank explosions and, more importantly, vessel age, it would be misleading to attempt to analyse the change in the upper tail with the available data.*

3. It is of passing interest to examine the effect of time on large tanker spill incidence, Figure 4.26. As expected, there appears to be no strong relationship. This supports our working hypothesis that the process generating the occurrence of spills and spill size has been stable over the recent past. There may be a slight downtrend in

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*Also, slightly different analytical assumptions would be appropriate to analyzing this change. The Gamma process allows the possibility of a spill of infinite size, although it makes the probability of that spill astronomically small. For the purpose of representing the upper bound on spill size generated by vessel capacity, a different process, such as the Beta, where such a bound would appear explicitly, would be a better choice. Unfortunately, the conjugate prior for the Beta sampling process has not been derived as yet.

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incidence, especially as a proportion of total volume landed, but any such trend is overshadowed by the change in the dispersion between 1969-1970 and 1971-1972, for which we have no explanation.

A final comment on the ECO data. Two minor changes would improve the usefulness of this data base. One is that each spill be assigned to a trade route and two is a code which would indicate, for those spills occurring within the 50-mile limit, whether the spill occurred at the loading end of the voyage or the discharge end.

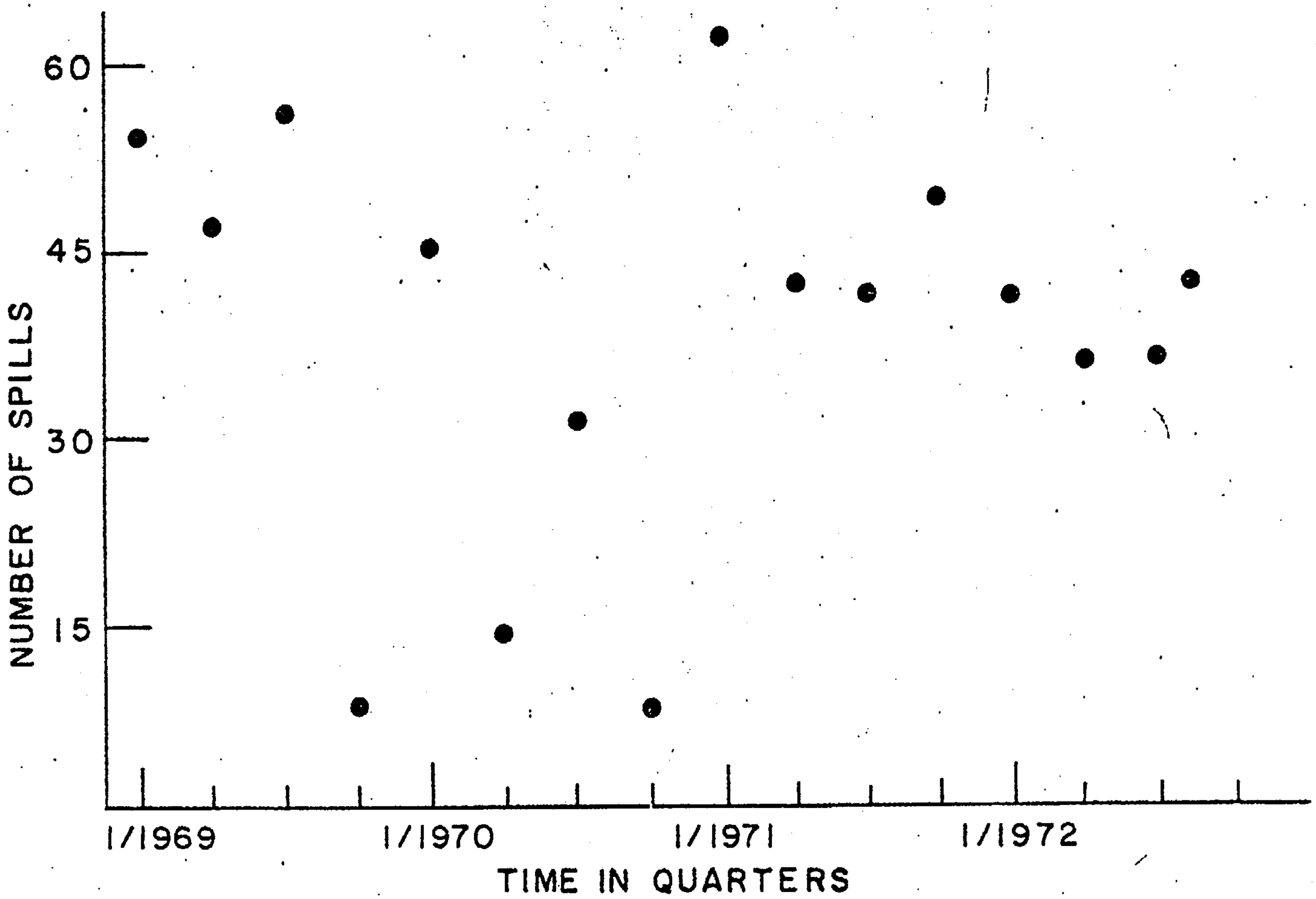

FIGURE 4.26 BREAKDOWN OF ECO SPILLS BY QUARTER OF OCCURRENCE