A number of partial, technical solutions to the problem are now under consideration. The Coast Guard in early 1977 advocated segregated ballasts for tankers over 70,000 DWT. Exxon is experimenting with techniques for cleaning tanks using crude oil washes with water rinses at the terminal prior to the return voyage (Gray et al., 1977). We are unaware of any independent examination of various alternatives, although it seems clear that the Coast Guard's size constraint would except the vast majority of tankers now calling at U.S. ports. More recently, the Magnuson bill reduced this cutoff to 20,000 DWT.

An obvious policy measure that might be considered for OCS developments involving tanker transport is the inclusion of lease clauses that impose either substantial cash penalties for intentional discharge of oil, or requirements for specified control measures. The former would require use of on-board monitoring systems that are not presently available, but which may be available in the near future (Gray et al., 1977). The latter would provide for some degree of uniformity in tanker operations and a decrease in discharges commensurate with the control measures mandated. However, it would also free the operator from responsibility for the discharge and might tend to freeze the technology at the mandated level.

U.S. and foreign tankers

Another issue of considerable interest is the comparison of the spill performance of U.S. and foreign tankers. This comparison is addressed in this section, rather than above, because the spill frequency side of the problem cannot be analyzed directly due to insufficient ship-specific activity information for foreign tankers. At best, the available information allows us to make crude, almost qualitative estimates for the foreign tankers. Thus, inclusion of these results in an impact analysis (comparing, for example, the spillage associated with North Slope crude carried by U.S. tankers versus Indonesian crude in foreign tankers) will require techniques that accommodate the different uncertainties associated with the different analyses. This is particularly difficult because we know of no way of estimating the uncertainties associated with the assumptions underlying the foreign-tanker analysis.

Table 10 shows the percentage by flag of the crude oil and petroleum products carried in the U.S. import and export trade. These figures were obtained from MarAd, and may be considered reliable. Note that U.S.-flag tankers carry only about 6% of all U.S. imports and exports for 1973 through 1975. This is a result of the extra cost of using U.S. tankers compared to the various foreign-flag alternatives.

Table 11 summarizes the tonnage of U.S. import, export, and domestic coastal petroleum traffic for the same three years. The distinction between domestic coastwise commerce and import/export commerce is an important one. By law (the Jones Act), only U.S.-flag tankers may carry petroleum between U.S. ports, so all domestic coastwise trade is in U.S. bottoms. U.S. tankers, therefore, carry the sum of the domestic coastwise category plus about 6% of the import/export trade.

TABLE 10
TANKER CARRIAGE OF U.S. IMPORTS/EXPORTS OF CRUDE AND PETROLEUM PRODUCTS BY COUNTRY OF REGISTRY

	1973 (%)	1974 (%)	1975 (%)
U.S.	6.34	4.44	6.89
Liberia	39.77	43.50	40.22
Greece	10.79	11.16	10.06
Panama	9.82	7.59	10.29
Norway	8.63	5.94	6.69
U.K.	6.84	5.29	5.98
Other	17.81	21.98	19.87

Source: U.S. Maritime Administration, Office of Subsidy Administration.

TABLE 11
SUMMARY OF U.S. PETROLEUM TRAFFIC IN TONS OF 2000 POUNDS

	1973	1974	1975
Foreign imports	3.284×10^8	3.228×10^8	3.295×10^8
Foreign exports	0.049×10^8	0.027×10^8	0.026×10^8
Total	3.333×10^8	3.255×10^8	3.321×10^8
Domestic coastwise	2.099×10^8	1.727×10^8	1.806×10^8

Source: U.S. Army Corps of Engineers, Waterborne Commerce of the United States, 1973, 1974, 1975.

In 1973 the average U.S. tanker, including petroleum and asphalt carriers, was 35,000 DWT; in 1974 the average was 37,000 DWT: and in 1975 it was 39,000 DWT (U. S. Maritime Administration, 1976). This annual trend reflects the increased size of the vessels now being built and brought into service. Equivalent figures for the average size of foreign vessels plying U. S. waters are not available. The average Liberian tanker in 1975 was about 93,000 DWT. However, none of the larger Liberian vessels can trade with continental U.S. ports due to draft limitations. An adequate and generally accepted approximation of the size of foreign vessels trading with U.S. ports, considering the draft limitation, is about 40,000 DWT. Using these figures, the number of trips made by U.S. and foreign vessels is obtained by dividing the DWT (conventionally measured in long tons) into the tonnage carried by these groups. Table 12 shows the results of this calculation. These figures would be correct only if all tankers made an equal number of trips per year. Actually, smaller tankers will be allocated to the shorter routes and so will make more trips than the larger tankers. Thus, the average tanker based on trips will be smaller than the fleet average, so the number of trips in Table 12 is probably underestimated.

Assuming one U.S. port call for vessels in the import/export trade and two U.S. port calls for vessels in the

TABLE 12
ESTIMATED NUMBER OF TRIPS BY TANKERS ENGAGED IN THE CARRIAGE OF CRUDE AND PETROLEUM PRODUCTS

Flag of Registry	1973	1974	1975
U.S.	5,894	4,918	4,658
Foreign	6,968	6,941	6,902
Total	12,862	11,859	11,560

Assumption: Average foreign tanker size = 40,000 DWT

TABLE 13
ESTIMATED PORT CALLS BY U.S. AND FOREIGN-FLAG TANKERS

Flag of Registry	1973	1974	1975
U.S.	11,248	9,085	8,793
Foreign	6,968	6,941	6,902

domestic coastwise trade, we can use Table 12 to estimate the number of port calls, as shown in Table 13. Since tankers usually spend only a day or two discharging or loading, these values may also serve as the basis for estimates of the number of days spent by U.S. and foreign tankers in U.S. ports. Despite the fact that the U.S. tanker fleet is an inconsequential fraction of the total world fleet (8.5% by number and 3.1% by capacity), Table 13 shows that the U.S. flag is by far the most common flag seen in U.S. waters.

The number of port calls shown in Table 13 may strike some as excessively large. They correspond, after all, to a port call by both a U.S. and a foreign-flag tanker about once every hour. The U.S. fleet, however, included some 235 tankers over 1000 GRT (gross registered tons) in 1975. These tankers were generally on trade routes of 1,000-2,000 miles one way. This corresponds to a steaming time at 15 knots of three to six days. Taking the latter figure and adding two days for discharging or loading, we find a one-way trip time of around eight days. Allowing an additional two days per one-way trip for periodic maintenance and hauling, this works out to an average 10-day one-way trip, or a 20-day average round trip. One port call per every 10 days works out to about one port call per hour for the whole U.S. fleet. This agrees with our previous estimates.

On the basis of Tables 10 and 11, we calculate that about 200 U.S. tankers ply routes between U.S. ports. The remaining 30 or 40 U.S. tankers are thus engaged on routes between the U.S. and its trading partners. In this trade, which is largely imports, U.S.-flag tankers are supplemented by 600 or 700 foreign tankers.

Based on the estimated port calls of Table 13 and the corrected Coast Guard PIRS data, spill incidence rates by port call for 1973 through 1975 have been calculated for the six major flags. These are shown in Table 14. We have aggregated both hull rupture and non hull rupture spills for these figures. Over this three year period, the U.S. fleet had a ratio of hull rupture to non hull rupture spills of 1:6. We did not obtain equivalent statistics for each of the foreign flags shown in Table 14, but the ratio of hull rupture to non hull rupture spills for all foreign flag vessels was 1:8. The ratio for Liberian flag vessels was also 1:8. In addition to the assumptions underlying Table 13, these values also rest on the assumption that vessel port calls are distributed among flags in proportion to the tonnage ratios of Table 10.

These numbers seem to tell a rather interesting tale. They show, for example, that U.S. ships have about half as many spills per port call as Liberian tankers, and about one-third to one-fifth as many spills per port call as foreign tankers as a whole. Does this mean that if U.S. tankers replaced all foreign tankers we would have fewer spills? If we hypothesize that spills result from a Bernoulli process in which each port call involves some fixed probability of a spill, then the answer would be yes.

A model based on Bernoulli trials has many attractive features, such as plausibility and analytical tractability. For these reasons, it is widely, albeit implicitly, accepted

TABLE 14
ESTIMATED SPILL INCIDENCE RATES FOR THE SIX MOST COMMON FLAGS IN U.S. WATERS, 1973-1975
(NUMBER OF SPILLS PER PORT CALL)

Year	U.S.	Liberia	Greece	Panama	Norway	United Kingdom
1973	.011	.031	.043	.029	.061	.052
1974	.014	.042	.083	.046	.094	.077
1975	.010	.031	.073	.022	.051	.062

in the literature. Unfortunately, the usual arguments in favor of the port call hypothesis, when this hypothesis is explictly examined, rest on the good linear regressions we get when we plot the number of spills for a region against the corresponding number of port calls. Such regression results may be likened to comparing the number of cancer cases to the number of supermarket visits in several towns. We would expect that larger towns would have larger numbers of both cancer cases and supermarket visits. Thus, such a regression should be a good one. It does not demonstrate, however, that cancer and visits to supermarkets are linked except through an ancillary variable like population. In the same way, good regressions between regional port calls and oil spill number establish neither a causative linkage nor the applicability of the binomial model.

Two observations of the spillage behavior of U.S. tankers tend to refute a binomial model based simply on port calls. First, we saw above that for all U.S. tankers, an acceptable spill incidence model can be based on a Poisson process in which time is the sole exposure variable and in which each ship has the same rate constant in any given year. Since the number of port calls will vary from ship to ship, we would find this observation consistent with a port-call hypothesis only if the number of port calls were Poisson-distributed among the ships in the fleet. But we also saw previously that tankers above and below 6,000 GRT had equivalent spill rates. Since smaller tankers will make more port calls than larger ones, this screening should disrupt any Poisson-like pattern seen in the fleet as a whole. Thus, the observed spill frequencies for individual tankers are not consistent with a port-call model.

The second observation that tends to discredit a binomial model based simply on port calls is that an investigation of spill causes revealed that only 20 of 374 U.S. tanker spill incidents occurred while the vessel was underway or in the process of entering or leaving a dock. Another 50 spills occurred under circumstances that cannot be categorized due to the ambiguous PIRS code, but fully 80% of the spill incidents occurred while the vessel was at anchor or at a dock. This ratio holds even if we look at our spill subclassifications. Forty-six of the fifty-three hull rupture spills, for example, occurred while the vessel was at anchor or at a dock. This undercuts a physical model of the spill generation process in which the act of entering or leaving a port is the crucial event. This, in turn, deprives a simple port-call model of its most compelling explanation. Thus, the values in Table 14 do not form a suitable basis for comparing U.S. and foreign tankers.*

This conclusion, of course, is only valid in terms of the aggregated data, i.e., data like that underlying Table 14. Obviously, subclassifications of the data can be found like vessel collision that will occur only when two vessels are present and one or both are underway. For this kind of event, port calls is a logical exposure parameter. There is far too little data, however, to support any quantitative test of this hypothesis. Table 8, for example, shows only 5 U.S. tanker collisions in the period 1973-1975.

Since we found that a Poisson model based on ship years was suitable for explaining U.S. tanker spill incidence, it is reasonable to assume that a similar model will hold for foreign tankers. Foreign tankers, however, will only spend a fraction of their time in U.S. waters, and the PIRS data will therefore only show a fraction of their spills, assuming the model is correct. One way to think of this is that the failures we observe in the PIRS data for these foreign tankers are those that have accumulated in the time between their last port call (which was in a foreign port) and their U.S. port call. Once the vessel lands at the U.S. port, these failures are discovered as the equipment is brought into operation.

Based on an analysis of the principal regional sources of U.S. petroleum imports, we determined that an average round-trip time was about 32 days for tankers on these routes. This corresponds to an exposure time of about 16 days prior to and including each U.S. port call. This means that if we multiply the observed spillage rates per port call for foreign tankers in Table 14 by (356/16) we will arrive at an annual spill incidence rate in agreement with the tenets of our model. It is this rate that may be compared to the U.S. rate. Table 15 shows the results of this calculation.

Table 15 suggests that foreign tankers may indeed have higher spill incidence rates. However, because of the large number of assumptions we've made, it is best to regard these figures as merely suggestive. It is reasonable to form some

TABLE 15
ESTIMATED SPILL INCIDENCE RATES BASED ON THE ACCUMULATED FAILURE MODEL (NUMBER OF SPILLS PER YEAR)

	1973	1974	1975
U.S.[a]	.627	.587	.417
Liberia	.7	1.0	.7
Greece	1.0	1.9	1.7
Panama	.7	1.1	.5
Norway	1.4	2.2	1.2
United Kingdom	1.2	1.8	1.4

[a]U.S. values reflect actual observations. Other values are based upon a large number of assumptions and do not have the same reliability.

working hypothesis based on these estimates, but it would be foolish to expect complete validation by any subsequent analysis using actual rather than estimated exposure time. The numbers do imply, however, that whatever differences there are, they may well be fairly small. This factor should be considered in formulating any subsequent investigation.

In contrast to the difficulty encountered in comparing spill incidence rates, the volume of oil spilled by U.S. and foreign tankers is readily obtained from the PIRS data. Figure 5 is a cumulative histogram of oil-spill volume. The three curves correspond to the histograms of U.S. tankers, tankers from other western developed countries, and flag-of-convenience tankers. The vertical axis is the fraction of spills less than the volume corresponding to the point on the horizontal axis lying beneath the curve. Thus, 76% of all U.S. tanker spills were less than 100 gallons, while 65% of all flag-of-convenience spills were under 100 gallons. Cumulative histograms of this type are usually shown as a series of steps. For clarity of presentation we have drawn a smooth curve through these steps. In this process we smoothed out a number of peculiar bumps in the curves. The U.S. and flag-of-convenience histograms indicated there was an interpretive round-off in the 10 and 100 gallons regions, while western-developed histograms showed these effects at 4, 42, and 84 gallons, corresponding to convenient multipliers of one barrel (1 BBL = 42 gallons).

The distinction between U.S. and flag-of-convenience spills as shown in these curves is probably significant. That is, if nothing changes with time, as we add more and more samples to the curves they will be unlikely to change positions relative to one another. The difference between the western-developed curve and either the U.S. or the flag-of-convenience curve is not sufficient to rule out the possibility that its position relative to the others is due to random chance, and thus might change with a larger,

FIGURE 5
HISTORICAL ESTIMATE OF THE PROBABILITY THAT A SPILL FROM A TANKER WILL BE LESS THAN V_0 GALLONS BASED ON USCG PIRS DATA 1973 - 1975