APPENDIX 13

A PREDICTIVE MODEL FOR OIL SPILL FROM SHIP COLLISIONS ON PUGET SOUND

A. Introduction

Previous studies on the probability of a ship collision in Puget Sound have analyzed the Sound as a one body of water, yielding a single probability collision value.[1] This type of analysis certainly is of some value when attempting to predict future collision frequencies in the face of growth in waterborne commerce. However, when trying to identify portions of the Sound that are more hazardous than others, in terms of the number of potential collisions and resultant oil spills, it becomes necessary to view the region as a system comprised of a number of waterways on which vessels travel. By applying a ship collision model to each individual waterway (channel), an estimate of the collision probability for that channel and probability of a resultant oil spill can be obtained. Examination of all channels will give an indication of which areas are most hazardous.

B. Model Description

The model used in this study is based on one developed by Sperry Piedmont Company[2] for predicting the probable number of vessel collisions in a channel of a given configuration. The discussion presented in this appendix will not duplicate the model development, but will depict its final form. The interested reader is referred to the original study for a detailed derivation.

The model is based on two assumptions:

1. The decision making behavior of the watch officer onboard ship is essentially the same in all seas, and
2. The behavior of collision victims (vessels) is not radically different from that of non-collision vessels.

The model, as developed by Sperry, is comprised of four separate parts:

1. The encounter rate of vessels (E_T):

$$E_T = 1/2 \frac{LN^2}{KV_T}$$

where

L = average length of channel

N = total number of vessels passing through the channel in one year

K = 8,760, the number of hours in one year, a constant

V_T = velocity of encountered ship

2. The number of collisions per encounter, defined as the probability of a vessel collision P(C):

$$P(C) = \frac{\bar{C}}{E_T}$$

where

$\bar{C}$ = the number of collisions per year.

3. The probability of a collision situation in a given channel $(P(C_o))$:

$$P(C_o) = b/w$$

where

b = breadth of a ship

w = width of a channel

4. The probability of a ship collision given a collision situation $(P(C|C_o))$:

$$P(C|C_o) = \frac{P\ (C)}{P(C_o)}$$

since a collision cannot happen unless there exists a collision situation.

For the purposes of analyzing Puget Sound, only equations (1) and (2) have direct impact on the results. The goal of this analysis was to determine relative rankings, rather than attempt an exact numerical evaluation. Equations (3) and (4), when utilized with appropriate input data, will enhance the achievement of the latter objective.

The model was programmed on a CDC 6400 computer, using 1970 as a base year for input data. The relevant independent variables which were varied includes vessel speed (V_T), and the number of vessels in a given channel (N). Data was computed in each channel for five year periods between 1970 and 1990. These results are the basis from which the probable number of vessel collisions per time period, per channel, were calculated. The ultimate goal of the model is to predict future oil spills resulting from vessel collisions.

Evaluation of the range of vessel speeds led to the selection of 15 knots as the speed used in the following discussion. The number of collisions per encounter, P(C), is dependent on the channel in which the collision takes place. That is, owing to the physical dimension and the number of vessels in the various channels, there will result a unique value for number of collisions per encounter in a channel.

C. Analysis of Data Base

The initial efforts in analyzing this problem was to divide the Puget Sound Region into a number of channels. Basis for the sectioning were traffic patterns and geographic characteristics. Table 13-1 describes the five selected channels and their dimensions, and these are shown in Figure 13-1. Examination of the diagram shows two areas, one just inland of Channel 1; and the other, the Strait of Georgia, have been omitted. The behavior of vessels in these areas does not fit the Sperry model and they are analyzed separately.

Any future projections of ship collision in these waters requires an established data base on today's vessel behavior. Specifically, two parameters need to be identified, the number of collisions per year, $\bar{C}$, and the number of ship encounters per year, E_T. After extensive searching, it was concluded that accurate collision records were not readily available in the Puget Sound area.

These estimates are critical to the final results as the $\bar{C}$ values directly determine the probability of a collision in any particular channel. What is required is historical data on the number of collisions between all vessels regardless of size in each channel. At present the only known source of information that approximates these requirements is the casualty files at Coast Guard Headquarters in Washingotn, D.C. These files, however, include data pertinent only to registered vessels and only reported accidents. It would not include those vessels engaged in commerce that are not registered, the numbers of which are unknown. It is also

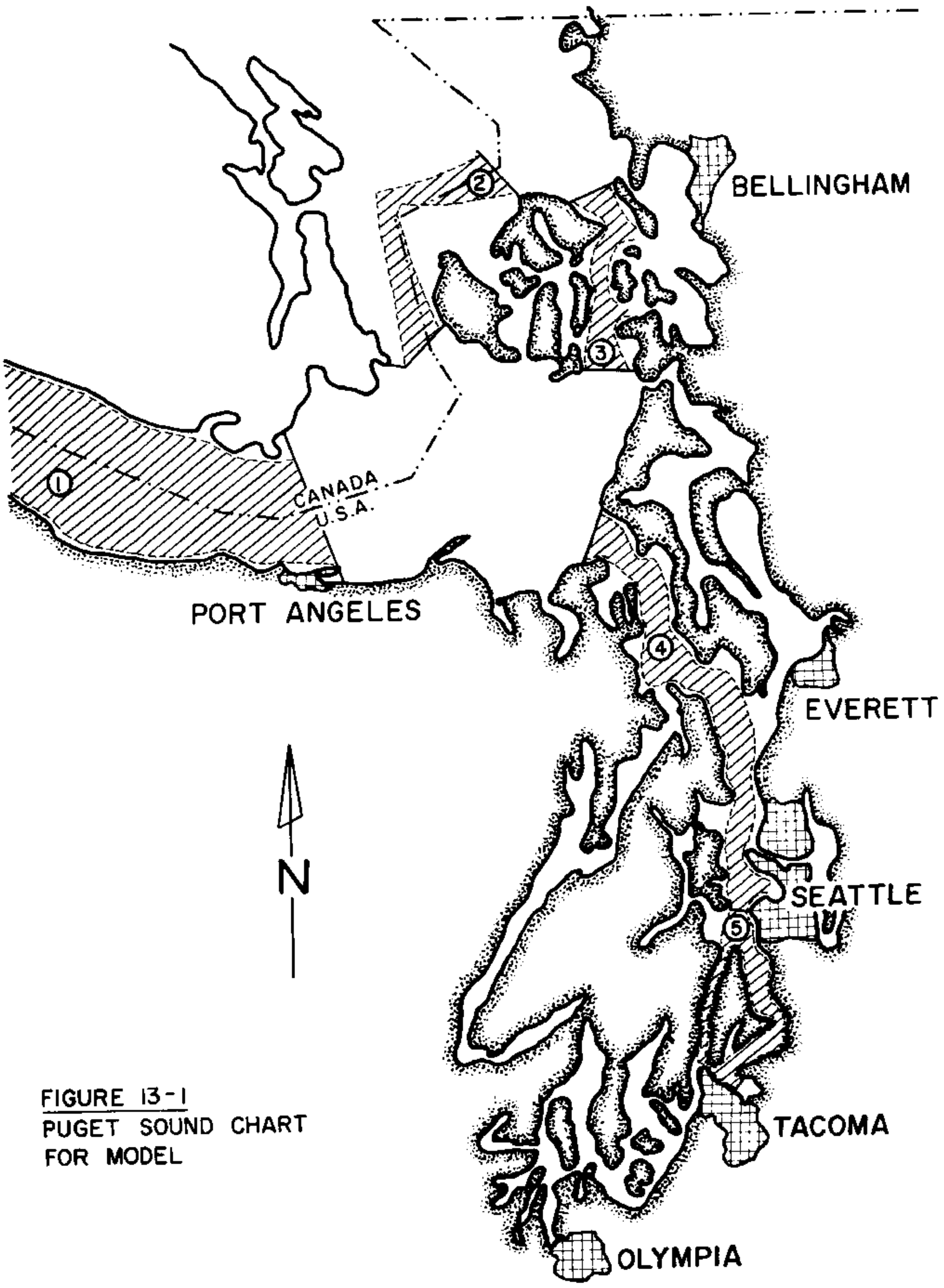

FIGURE 13-1
PUGET SOUND CHART
FOR MODEL

TABLE 13-1: CHANNEL DEFINITION FOR SHIP COLLISION MODEL

	Approximate Average Width (miles)	Approximate Average Length (miles)
Channel 1:		
Cape Flattery-Bannilla Pt. to Dungeness Spit - Trail Islands	12.2	65.0
Channel 2:		
Discovery Island - Cattle Pt. to East Pt. - Alden Pt.	4.2	28.9
Channel 3:		
Pt. Colville - West Pt. to Lawrence Pt. - Village Pt.	3.19	18.0
Channel 4:		
Pt. Wilson - Admiralty Head to Elliott Bay	3.45	39.0
Channel 5:		
Restoration Pt. - Alki Pt. to Commencement Bay (Two Passages) -		
Colvos Passage	1.01	17.3
East Passage	2.53	23.5

necessary to consider those collisions between vessels that went unreported for one reason or another. Again no specific numbers can be placed on these occurrences, only estimates.

Because of time and logistics problems the Coast Guard data could not be utilized. It has therefore been necessary to estimate the $\bar{C}$ values based on the number of major collisions in the Puget Sound region over the past five years.[3] For each channel, three figures were computed, the historical value, a high value, as well as a low value to produce a band of possible collisions rather than a specific number. These are shown in Table 13-2 below. The historical value was considered the median value and the upper bound is twice the median value, while the lower bound was one-half of the median.

TABLE 13-2: NUMBER OF COLLISIONS PER YEAR ($\bar{C}$)

Channel	Low	(Historical) median	High
1	.2	.4	.8
2	.1	.2	.4
3	.1	0	.4
4	.4	.8	1.6
5	.1	.2	.4

Where the data indicated no collision had taken place during the five year period in a particular channel a low value of .1 was assumed, a high value of .4.

In Part B, it was shown that E_T was a function of the length of the channel, number of vessel movements and the velocity, which has been assumed to be 15 knots for the purpose of presenting a set of results. Channel dimensions are shown in Table 13-1. There remains the task of defining the number of vessel movements.

The historical data for the volume of vessel traffic is derived from 1967 data accumulated by the Corps of Engineers.[4] Analysis of the vessel movement trend between 1965-1970 reveals little change in the year-to-year volume. The following assumptions were made for the analysis.

1. The number of ship movements in each channel is a fucntion of the number of ships arriving or departing each port along the channel, plus those ships that must traverse the channel to arrive or depart ports beyond the channel.
2. The total number of ship movements in each channel can be arrived at by analyzing separately the external and internal waterborne commerce which moves within the channel.

The total number of vessel movements in each channel was determined as a percentage of the total vessel movements in the Puget Sound region. The referenced data indicates 308,860 movements in 1967. This number represents all vessels entering or leaving a port in the Sound, and includes non-self-propelled as well as self-propelled vessels, cargo vessels as well as tank vessels. The following are the per channel vessel movement calculations:

Channel 1:

Of the total waterborne commerce of 49 million short tons, 57% was commerce internal to Puget Sound, while 43% was external. Since all external traffic must assume to traverse the Strait of Juan de Fuca,

.43 (308,860) = 132,000 external vessel movements are allocated to this channel. In addition, the internal traffic allocated to the ports of this channel were:

Neah Bay	5.2%
Port Angeles	1.4%

totaling 6.6%. Thus, the total vessel movement in this channel is 132,000 + (.066)(308,860) = 152,300 vessels.

Channel 2:

This channel includes Canadian ports only, since external commerce from those ports must traverse U.S. waters; in particular, this channel.

Vancouver	2.9%
New Westminister	0.5%
Other B.C. Ports	0.6%
TOTAL	4.0%

This leads to a total of 12,300 vessel movements.

Channel 3:

Anacortes	5.8%
Bellingham	6.2%
TOTAL	12.0%

This yields 37,000 ship movements.

Channel 4:

Port Townsend	3.8%
Everett	7.6%
Seattle	40.0%
Lake Washington Ship Canal	7.2%
Waterway	2.0%
Traffic from Channel 5	15.1%
TOTAL	75.7%

The total vessel movements for this channel is 233,500. It is assumed that all traffic in Channel 5 must traverse Channel 4 in arriving or leaving a port. This assumption may lead to slightly larger values for Channel 4, but based on the above values, the effect is negligible.

Channel 5:

Tacoma	13.2%
Olympia	1.9%
TOTAL	15.1%

This yields 46,600 vessel movements.

The summing of vessel activity per channel from the 1967 data, and is utilized in this model as the 1970 base:

Channel	Vessel Movements
1	152,300
2	12,300
3	37,000
4	233,500
5	46,600

```
PROBABILITY OF A SHIP COLLISION IN PUGET SOUND


                    CHANNEL NUMBER

     C        1          2          3          4          5
    .10   .00000002  .00000691  .00000123  .00000001  .00000059
    .20   .00000004  .00001382  .00000245  .00000003  .00000118
    .30   .00000006  .00002074  .00000368  .00000004  .00000178
    .40   .00000008  .00002765  .00000491  .00000006  .00000237
    .50   .00000010  .00003456  .00000613  .00000007  .00000296
    .60   .00000012  .00004147  .00000736  .00000009  .00000355
    .70   .00000014  .00004839  .00000859  .00000010  .00000415
    .80   .00000016  .00005530  .00000981  .00000011  .00000474
    .90   .00000018  .00006221  .00001104  .00000013  .00000533
   1.00   .00000020  .00006912  .00001226  .00000014  .00000592


PROBABILITY OF A COLLISION SITUATION IN PUGET SOUND


                    CHANNEL NUMBER

              1          2          3          4          5
          .0011639   .0033649   .0044514   .0041159   .0056126


PROBABILITY OF A SHIP COLLISION ON PUGET SOUND GIVEN A COLLISION SITUATION


                    CHANNEL NUMBER

     C        1          2          3          4          5
    .10    .0000172   .0020542   .0002755   .0000035   .0001055
    .20    .0000344   .0041084   .0005510   .0000069   .0002110
    .30    .0000517   .0061626   .0008266   .0000104   .0003165
    .40    .0000689   .0082167   .0011021   .0000138   .0004221
    .50    .0000861   .0102709   .0013776   .0000173   .0005276
    .60    .0001033   .0123251   .0016531   .0000207   .0006331
    .70    .0001206   .0143793   .0019286   .0000242   .0007386
    .80    .0001378   .0164335   .0022041   .0000276   .0008441
    .90    .0001550   .0184877   .0024797   .0000311   .0009496
   1.00    .0001722   .0205418   .0027552   .0000345   .0010552


VELOCITY OF VESSELS IN THE CHANNELS IS 15 KNOTS


THE ENCOUNTER RATE OF VESSELS IN CHANNEL 1 IS      4988730
THE ENCOUNTER RATE OF VESSELS IN CHANNEL 2 IS        14467
THE ENCOUNTER RATE OF VESSELS IN CHANNEL 3 IS        81537
THE ENCOUNTER RATE OF VESSELS IN CHANNEL 4 IS      7035927
THE ENCOUNTER RATE OF VESSELS IN CHANNEL 5 IS       168950
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FIGURE 13-2

COMPUTER PRINTOUT, 1970,

15 KNOTS

At a velocity of 15 knots, the resultant E_T per channel is as follows for 1970:

Channel	E_T(Vessel Encounters)
1	4,990,000
2	14,800
3	81,800
4	7,036,000
5	168,900

For a given channel, this encounter rate varies inversely with the ship velocity. In a given body of water, the faster a vessel traverses that body, the lower the number of vessels he will encounter, given that all other vessels maintain their original performance.

Having computed $\bar{C}$ and E_T, the model can now generate the probability of collision, P(C). Figure 13-2 shows the computed output for 1970, with V_T = 15 knots. For each channel the probabilities corresponding to the upper and lower bound of the $\bar{C}$ values is shown in Table 13-3. The low probabilities associated with Channels 1 and 4 are the result of the enormous volume of vessel movements in those channels.

TABLE 13-3: SHIP COLLISION VALUES FOR 1970

V_T = 15 KNOTS

	Lower Bound		Upper Bound	
Channel	$\bar{C}$ collision/yr.	P(C)	$\bar{C}$ collision/yr.	P(C)
1	.2	4.0×10^{-8}(est.)	.8	1.6×10^{-7}
2	.1	6.9×10^{-6}	.4	2.76×10^{-5}
3	.1	1.2×10^{-6}	.4	4.9×10^{-6}
4	.4	5.7×10^{-8}	1.6	2.3×10^{-7}
5	.1	6.0×10^{-8}	.4	2.4×10^{-6}

The data in Figure 13-2 also gives the probability of a collision given a collision situation, $P(C|C_o)$. This figure is a constant in each individual channel regardless of the number of vessel movements or their velocity. Basically it is dependent on the actual dimensions of the channel. For the five channels chosen in this study these probabilities expressed as ratios follow:

Channel	Number of resulting collisions per 10,000 collision situations
1	12
2	34
3	44
4	41
5	56

These figures give some indication of the ship's ability to avoid a collision once it finds itself in a collision situation.

D. Exceptions

As mentioned earlier, two areas of the Sound have been excluded from the analysis using the Sperry model. In these waters, vessels exhibit more or less a random movement, as contrasted with the more predictable lanes in the five designated channels. Thus, a system analogous to two dimensional free gas model can be used to predict the probability of a collision in these two bodies of water. Unfortunately, there is insufficient information to estimate the number of collisions per year, as was done in the above analysis. Nevertheless, the probability values derived below can be used as a basis to evaluate behavior in these two waterways in the face of increasing commerce over the next twenty years.

$$P(X) = \frac{n\,a}{A}$$

where

P(X) = probability of collision between objects in the waterway
n = number of objects (vessels) in the body at any instant
a = area occupied by vessel
A = area of the body of water

It is essential here that collisions between vessels predominate over groundings, due to the physical characteristics.

For the large body of water east of the Strait of Juan de Fuca, vessels can move in five directions. Table 13-4, below, lists these paths, the length of travel, and the width of the waterway exposed to the vessel, plus the number of vessel movements. This later set of figures are based on those presented in the earlier channel analysis:

TABLE 13-4: INTER CHANNEL PATHS

Path	Length of Path (miles)	Width of Path (miles)	Number of Vessels
Channel 1-2	21	25	12,000
Channel 1-3	42	25	36,000
Channel 1-4	30	42	177,000
Channel 2-4	25	42	14,000
Channel 3-4	16	25	42,000
			281,000

The width of this body of water is the weighted average of the widths confronted by the vessels. The mean distance traveled within this area is likewise the weighted average.

TABLE 13-5: COMPUTATION OF WEIGHTED DIMENSIONS

Path	Weighting factor	Weighted Length (miles)	Weighted Width (miles)
Channel 1-2	4.3%	.9	1.1
Channel 1-3	12.8%	5.4	3.2
Channel 1-4	63.0	18.9	26.5
Channel 2-4	4.9	1.2	2.1
Channel 3-4	15.0	2.4	3.8
		28.8 miles	36.7 miles

The value 36.7 miles is the solution for W in the probability equation.

At any instant, the number of vessels in the channel, n, is dependent on the entrance and exit frequency, the speed, and the time spent in the channel. Using a velocity of 15 knots, and the weighted distance of 28.8 miles, the average time spent in this body of water by a vessel is 2.2 hours. Thus

$$n = (\text{\# of vessels per year}) \times \frac{(\text{hrs. in channel})}{\text{hrs. per year}} = \frac{(281{,}000)(2.2)}{8760}$$

$$= 71 \text{ vessels}$$

The weighted cross sectional area of a vessel is assumed to be the sum of the weighted width and length, since these are the areas exposed to potential collisions. Using values 75 ft. and 300 ft. for the dimensions, a is equal to 22,500 sq ft, or 8×10^{-4} sq miles. The weighted area is the product of the weighted length and width of the body of water. Thus,

$$P(X) = \frac{na}{A} = \frac{71(.0008)}{(28.8)\ (36.7)} = 5.35 \times 10^{-5} = .0000535$$

The results show five chances out of 100,000 for a collision in the body of water east of the Strait of Juan de Fuca. This assumes only random movements. Given that ship navigators exercise care in piloting their vessels, the chances are even less. A detailed study of vessel movements in this area is needed to yield more accurate estimates than those presented here.

For the Strait of Georgia, only vessels from Channels 2 and 3 are considered as sources or sinks. Their destination and weighting factors are as follows:

TABLE 13-6: INTERCHANNEL PATHS IN STRAIT OF GEORGIA

Path	Length (miles)	Width (miles)	Number of Vessels
Channel 2-B.C.	16	15	12,000
Channel 2-Sandy Pt.	14	19	0
Channel 3-B.C.	23	13	11,000
Channel 4-Sandy Pt.	12	13	25,000
			48,000

The weighted Strait dimensions are thus:

TABLE 13-7: WEIGHTED DIMENSIONS - STRAIT OF GEORGIA

Path	Weighting factor	Weight Length	Weighted width
Channel 2-B.C.	25%	4.0	3.8
Channel 3-Sandy Pt.	23%	3.2	4.4
Channel 3-B.C.	52%	6.2	6.7
		13.4 miles	14.9 miles

The deadweight ton (DWT) deflators give an indication of how much the average vessel size has increased each 5 year period. This can be determined as (1 - DWT deflator). The purpose of the deflator is to reduce the total vessel movements in any given 5 year period to an amount, comparable period by period. That is, a growth in commerce will occur indicating more vessel movements, however, the size of the vessels will also increase requiring a deflation of the percentage again in total movements. Table 13-8, below, shows values for tankers (T) and freighters (F):

TABLE 13-8: DWT DEFLATORS

Year	DWT_F	DWT_T	Deflator F	Deflator T
1970	8000	45,000	1.0	1.0
1975	8500	60,000	.94	.67
1980	8800	78,000	.96	.70
1985	9000	85,000	.98	.91
1990	9300	90,000	.97	.94

An assumption is made here that the projected growth in freighter and tanker sizes is representative of the expected growth in size of all types of vessels engaged in commerce. That is, the average size vessel carrying general cargo will increase in size approximately 16 percent over the next 20 years while the typical vessel moving bulk oil will double in size over the same period of time.

Applying the DWT deflators to the percent growth in tonnage, an approximation for the percentage growth in the number of vessel movements can be estimated.

TABLE 13-9: GROWTH RATES MODIFIED BY DWT DEFLATORS, FREIGHTERS

Year	% Growth Tonnage (Other)	DWT Deflator F	% Growth Vessel Movements (F)
1970	0	1.0	0
1975	7.4%	.94	6.9%
1980	8.9%	.96	8.5%
1985	16.0%	.98	15.7%
1990	14.9%	.97	14.4%

TABLE 13-10: GROWTH RATES MODIFIED BY DWT DEFLATOR, TANKERS

Year	% Growth Tonnage (Bulk Oil)	DWT Deflator T	% Growth Vessel Movements (T)
1970	0	1.0	0
1975	23.6%	.67	15.8%
1980	16.3%	.70	11.4%
1985	14.4%	.91	13.1%
1990	14.0%	.94	13.2%

The total percentage growth in the number of vessel movements is found by taking a weighted average of the two individual growths. The weighting factors are the percentages of the total tonnage comprised of bulk oil and other commerce, with one modification.

On the average, the ratio of DWT of freighters to tankers in each of the 5 year periods is:

1970	.18
1975	.14
1980	.11
1985	.105
1990	.103

When applying the weighting factors to the percentage growth for numbers of vessels, the factors must be the weighted for growth in numbers, not tonnages. Therefore, it is necessary to modify the total tonnage weighting factors with the relative DWT ratios as follows:

TABLE 13-11: COMPUTATION OF WEIGHTING FACTORS FOR NUMBER OF VESSELS

Year	(Total Commerce) % Tanker	x	DWT Relative Ratio	=	Weight Factors Tankers	Weight Factors Freighters
1970	43		.18		.075	.925
1975	46		.14		.065	.935
1980	48		.11		.053	.947
1985	47		.105		.05	.95
1990	48		.103		.05	.95

The weighting factor for 1970 compares favorably with the ratios of numbers of tankers and freighters over 1000 net tons entering Puget Sound in 1970.

The time to travel through this body of water at 15 knots is 0.78 hours, and the resultant number of vessels in these waters at any instant, is

$$\frac{48{,}000\ (0.71)}{8760} = 4.3 \text{ vessels}$$

assuming the same vessel area, 8×10^{-4} sq. miles

$$P(X) = \frac{(4.3)\ (8 \times 15^{4})}{(13.4)\ (14.9)} = 1.71 \times 10^{-6}$$

Thus, for this body of water there is less than two chances in one million of having a collision, assuming random movements.

E. Projected Growth in Vessel Movement

To project the growth in traffic for each channel, a basic assumption was made that the base mix (allocation) will not change over time. This assumption requires approximately equal growths for all areas of Puget Sound. The total commerce projections as well as the increasing vessel size was used to arrive at a percentage rate of growth per five year period. This percentage of growth is then applied to the base number of vessel movements to obtain the projection desired.

The percentage growth per five year period in other commerce is calculated as follows:

Year	Historical Trend Projection (Short Tons)	Percent Growth
1970	28,200,000	0
1975	30,300,000	7.4%
1980	33,000,000	8.9%
1985	38,000,000	16.0%
1990	44,000,000	14.9%

The percentage growth per five year period in bulk oil commerce is calculated as follows:

Year	Historical Trend Projection (Short Tons)	Percent Growth
1970	20,800,000	0
1975	25,700,000	23.6%
1980	29,900,000	16.3%
1985	34,200,000	14.4%
1990	39,000,000	14.0%

Of the 2,485 vessels in the Sound, 235 were tankers, yielding 9.5% of the total number or .095 for vessels over 1000 net tons as compared to .075 for all vessels as determined above.[5]

The resultant weighted average growth ratio is now computed by multiplying the growth rate of each type of vessel (Table 13-9 and 13-10) by its respective weighting factor (Table 13-11).

TABLE 13-12: AVERAGE GROWTH RATES USED IN COMPUTER MODEL

Year	Total Commerce % Tanker	Total Commerce % Freighter	Weighted Average % Growth of Vessel Movements
1970	7.5%	92.5%	0
1975	6.5%	93.5%	7.5%
1980	5.3%	94.7%	8.7%
1985	5.0%	95%	15.6%
1990	5.0%	95%	14.4%

The average growth rate for the number of vessel movements is approximately 2.3% increase per year or 11.5% per 5 year interval.

Now that the percentage growth rate is established, the future number of vessel movements can be determined by applying the percentage growth figures to the 1970 base of vessel movements. The results are as follows:

TABLE 13-13: PROJECTED NUMBER OF VESSELS IN PUGET SOUND CHANNELS

Growth Factor	(1.00)	(1.075)	(1.087)	(1.156)	(1.144)
Channel:	1970	1975	1980	1985	1990
1	152,300	164,720	177,960	205,770	235,340
2	12,300	13,220	14,370	16,610	19,000
3	37,000	39,775	43,235	49,980	57,180
4	233,500	251,010	272,840	315,403	360,820
5	46,600	50,095	54,450	62,950	72,015

F. Projected Ship Collision Occurrences

In order to see what effect the increased commerce in each of the channels will have on the number of vessel collisions in these channels/year the number of collisions per encounter is multiplied by the new encounter rates in succeeding years and is shown as follows:

TABLE 13-14: PROJECTED NUMBER OF COLLISIONS FOR THE GIVEN YEAR

Channel		1970	1975	1980	1985	1990
1	Lo	0.20	0.23	0.27	0.36	0.48
	Hi	0.8	0.92	1.09	1.46	1.92
2	Lo	0.10	0.12	0.14	0.18	0.24
	Hi	0.40	0.46	0.55	0.73	0.95
3	Lo	0.10	0.11	0.13	0.18	0.23
	Hi	0.40	0.46	0.55	0.73	0.95
4	Lo	0.40	0.46	0.55	0.73	0.96
	Hi	1.60	1.87	2.20	2.90	3.90
5	Lo	0.10	0.12	0.14	0.19	0.24
	Hi	0.40	0.47	0.55	0.74	0.97
Total Puget Sound:						
	Lo	0.90	1.34	1.23	1.64	2.15
	Hi	3.60	4.28	4.94	6.56	8.69

Thus, the total number of collisions in each channel can be predicted in this fashion.

G. Projected Oil Spill Occurrence

One last step remains to arrive at the final objective - the probability of an oil spill. Again, by necessity, some assumption must be made concerning the number of vessels that collide. Some estimate of the conditional probability that a ship involved in a collision will spill oil is necessary. At the risk of being arbitrary, this probability is estimated by dividing the number of bulk oil vessels by the total number of vessels on the Sound. Two further assumptions are:

1. In every collision involving bulk oil carriers the vessel scantlings will be damaged such that oil is spilled from the vessel, and
2. In collisions resulting in penetration of the fuel oil tanks will not cause oil to spill.

These conditional probabilities are as follows:

Year	Probability of Collision Involving Bulk Oil Carrier
1970	.075
1975	.065
1980	.053
1985	.05
1990	.05

Finally, the number of collisions/year that will result in oil being spilled in the Puget Sound region waters over the next 20 years by channel is shown below:

TABLE 13-15: NUMBER OF COLLISIONS HAVING OIL SPILLS FOR A GIVEN YEAR

Channel		1970	1975	1980	1985	1990
1	Lo	.0150	.0156	.0143	.0180	.0340
	Hi	.0600	.0600	.0575	.0730	.0960
2	Lo	.0075	.0075	.0072	.0091	.0120
	Hi	.0300	.0300	.0290	.0365	.0475
3	Lo	.0075	.0073	.0071	.0089	.0116
	Hi	.0300	.0300	.0290	.0365	.0475
4	Lo	.0300	.0300	.0290	.0365	.0480
	Hi	.1200	.1220	.1170	.1450	.1950
5	Lo	.0075	.0076	.0073	.0093	.0120
	Hi	.0300	.0305	.0290	.0360	.0485
Total Puget Sound:						
	Lo	.0675	.0680	.0649	.0818	.0176
	Hi	.2700	.2725	.2615	.3270	.4445

The results are interesting and several observations can be made. First, the number of collisions involving the spillage of oil does not show an increase until nearly 1985, in spite of the fact that the number of total collisions is increasing in this same period. The reason for this is the result of a predicted increase in average tank vessel size which effectively reduces the ratio of tank vessels to the total number of vessels. Secondly, the total predicted number of collisions resulting in oil spills can be obtain by summing the number of collisions per year over the 20 year period. For the first 10 years, 1970-1980, the expected collisions involving oil spillage are:

Lo 0.67 collisions over 10 year period.
Hi 2.69 collisions over 10 year period.

That is, on the low side 0.67 expected collisions will occur in the next ten years which spill oil, on the high side 2.69 collisions are predicted. For the second 10 years, 1980-1990, the corresponding figures are:

Lo 0.84 collisions per 10 year period.
Hi 3.40 collisions per 10 year period.

The numbers for the 1970-1980 period compare favorably with the probable number of tank vessel collisions predicted in a study by Honeywell. This study predicted 2.4 collisions when a 3% growth rate was considered.[6]

To give some indication of the number of collisions involving oil spillage in each channel/year the values are listed in matrix form below.

TABLE 13-16: PREDICTED NUMBER OF OIL SPILL COLLISIONS PER CHANNEL

Channel		10 Years (1970-1980)	10 Years (1980-1990)
1	Lo	.152 collision	.185 collision
	Hi	.594	.749
2	Lo	.074	.093
	Hi	.300	.374
3	Lo	.074	.093
	Hi	.300	.374
4	Lo	.300	.375
	Hi	1.200	1.500
5	Lo	.074	.093
	Hi	.3	.374

This matrix indicates that the channel likely to produce the greatest number of oil spills from vessel collisions is channel 4 (Point Wilson to Elliot Bay). In the next 10 years the expected number of collisions on the low side is .300 and on the high side is 1.2. The remaining channels can be viewed in a similar manner.

H. Probability of Future Collision With the Free Gas Model

For the two bodies of water analyzed by the free gas model, the increase in vessel movements is assumed to behave similarly as for the channels. In addition, the weighted length of vessels is assumed to increase linearly from 300 ft. in 1970 to 500 ft. in 1990, while the width of vessels remains fixed. Since the geographic characteristics will not change, the only influencing factors in P(X) are n and a. Therefore, the following probabilities for collisions result:

TABLE 13-17: PROBABILITY OF COLLISION

	P(X) for Large Body Inland of Straits	P(X) for Strait of Georgia
1970	5.35×10^{-5}	1.71×10^{-6}
1975	6.77×10^{-5}	2.16×10^{-6}
1980	8.10×10^{-5}	2.58×10^{-6}
1985	1.08×10^{-4}	3.48×10^{-6}
1990	1.38×10^{-4}	4.4×10^{-6}

The probability of an oil spill resulting from a collision P(Y) is the product of P(X) and the conditional probabilities for collision involving bulk oil carries defined earlier. Thus,

TABLE 13-18: PROBABILITY OF COLLISION RESULTING IN AN OIL SPILL

	P(Y) for Body of Water Inland of Straits	P(Y) for Strait of Georgia
1970	4.0×10^{-6}	1.3×10^{-7}
1975	4.4×10^{-6}	1.4×10^{-7}
1980	4.3×10^{-6}	1.4×10^{-7}
1985	5.4×10^{-6}	1.7×10^{-7}
1990	6.9×10^{-6}	1.7×10^{-7}

These results show that the larger body of water is 3 times more susceptible to an oil spill than the Strait of Georgia. It must be emphasized that the results presented for this free gas model cannot be directly compared to the results of the Sperry model for the 5 channels.

The objectives of the free gas model presentation were to show a relationship between two bodies of water and to estimate the further trends in oil spills for ship collisions.

I. Summary Comments

It is recognized that, in the development of these predictions, many simplifying assumptions have been made as well as estimates of very pertinent data. The allocation process as to the allotment of vessel movements to each channel surely is not completely accurate, and open to question. In addition to these shortcomings one cannot even say 'let the the results speak for the model,' for all that can be compared is historical data, and what is being attempted is to predict the future. So where does this leave us? Perhaps not any better off than before the analysis! This is not exactly true. For no matter how crude the analysis may be, there is now some measure of the predicted relative collision frequencies in various areas of the Puget Sound region. These measures can be improved, perhaps significantly, through a relaxation of some of the constraining assumptions, more accurate input data as well as improved computational techniques. After all, the effectiveness of any model is dependent on its representation of the real world, and the input data. In this model, the representation of the real world (i.e., behavior of vessels) is also dependent on the input data. This input data includes the detailed information of any ship entering Puget Sound waters. Vessel dimensions, type of cargo, destinations, timetable of arrivals and departures, unusual incidents, and their causes are some of the inputs that are necessary for all vessels. In the end, it is imperative that the measures be accurately known so as to efficiently distribute the scarce resources at command in combatting future oil spills resulting from vessel collisions.

J. Endnotes for Appendix 13

1. Honeywell Marine Systems Center, A Proposed Automated Marine Traffic Advisory System for Puget Sound, Document K03/70, Appendix A, November 6, 1970.
2. Sperry Piedmont Co., Final Report Lookout Assist Device Feasibility Studies, Vol. I, Section 3, Contract #MA-3374, August 1965.
3. Unpublished data provided by Commander G. K. Greiner, Jr., of the 13th Coast Guard District.
4. U. S. Army Corps of Engineers, Waterborne Commerce of the United States, Calendar Year 1967, Part 4.
5. Seattle Chamber of Commerce, Ship Movements and Petroleum Transportation in Puget Sound Area, State of Washington, A White Paper, 1971.
6. Honeywell.

APPENDIX 14

CHARACTERISTICS OF OIL IN THE ENVIRONMENT

This appendix is included in the report to give some insight on the complexity oil behavior technology. The initial two sections provide a glossary of terms used in describing oil and a conversion table to relate various report methods as oil production, shipment, or transfer. The last three parts document a literature suming on the effects of oil in the environment, including short and long term biological effects. No attempt was made by the Study Group to prove or disprove the published information. The sole purpose of including this data is to demonstrate the critical need for development of a coordinated program for a comprehensive study of the subject. Government agencies have the authority and funding mechanism, while industry and academic institutions have the technology. For a study to be as complete as possible, a sustained joint effort is key.

A. Glossary of Terms[1]

API Gravity: An empirical scale for measuring the density of liquid petroleum products, the unit being called the "degree API".

Ash: Inorganic residue remaining after irnition of combustible substances determined by definite prescribed methods.

Asphalts: Black, solid or semisolid bituments which occur in nature or are obtained as residues during petroleum refining.

Bilge Oil: Waste oil which accumulates, usually in small quantities, in the lower spaces in a ship, just inside the shell plating. Usually mixed with larger quantities of water.

Blowout: A sudden violent escape of gas and oil from an oil well when high pressure gas is encountered and preventive measures have failed.

Boiling Point: The temperature at which the vapor pressures of a liquid is equal to the pressure of the atmosphere.

Bunker "C" Oil: A general term used to indicate a heavy viscous fuel oil.

Bunker Fuel: A general term for heavy oils used as fuel on ships and in industry. It often refers to No. 5 and 6 fuel oils.

Bunkering: The process of fueling a ship.

Coker Feed (or Fuel): A special fuel oil used in a coker furnace, one of the operating elements of a refinery.

Crude Oil: Petroleum as it is extracted from the earth. There may be several thousands of different substances in crude oil, some of which evaporate quickly, while others persist indefinitely. The physical characteristics of crude oils may vary widely. Crude oils are often identified in trade jargon by their regions of origin. This identification may not relate to the apparent physical characteristics of the oil. Commercial gasoline, kerosene, heating oils, diesel oils, lubricating oils, waxes, and asphalts are all obtained by refining crude oil.

Demulsidility: The resistance of an oil to emulsification, or the ability of an oil to separate from any water with which it is mixed. The better the demulsidility rating, the more quickly the oil separates from water.

Density: Density is the term meaning the mass of a unit volume. Its numerical expression varies with the units selected.

Emulsion: A mechanical mixture of two liquids which do not naturally mix as oil and water. Water-in-oil emulsions have the water as the internal phase and oil as the external. Oil-in-water emulsions have water as the external phase and the internal phase is oil.

Fire Point: The lowest temperature at which an oil vaporizes rapidly enough to burn for at least 5 seconds after ignition, under standard conditions.

Flash Point: The lowest temperature at which an oil gives off sufficient vapor to form a mixture which will ignite, under standard conditions.

Fraction: Refinery term for a product of fractional distillation having a restricted boiling range.

Fuel Oil Grade: Numerical ratings ranging from 1 to 6. The lower the grade number, the thinner the oil is and the more easily it evaporates. A high number indicates a relatively thick, heavy oil. No. 1 and 2 fuel oils are usually used in domestic heaters, and the others are used by industry and ships. No. 5 and 6 oils are solids which must be liquified by heating. Kerosene, coal oil, and range oil are all No. 1 oil. No. 3 fuel oil is no longer used as a standard term.

Innage: Space occupied in a product container.

In Personam: An action in personam is instituted against an individual, usually through the personal service of process, and may result in the imposition of a liability directly upon the person of a dependent.

In Rem: An action in rem is one in which the vessel or thing itself is treated as offender and made defendent without any proceeding against the owners or even mentioning their names. The decree in an action in rem is enforced directly against the res by a condemnation and sale thereof.

Load on Top: A procedure for ballasting and cleaning unloaded tankers without discharging oil. Half of the tanks are first filled with sea water while the others are cleaned by hosing. Then oil from the cleaned tanks, along with oil which has separated out in the full tanks, is pumped into a single slop tank. The clean water in the full tanks is then discharged while the freshly-cleaned tanks are filled with seawater. Ballast is thus constantly maintained.

Oil Films: A slick thinner than .0001 inch and may be classified as follows:

Standard Term	Gallons of Oil per Square Mile	Appearance
"barely visible"	25	- barely visible under most favorable light conditions
"silvery"	50	- visible as silvery sheen on surface water
"slightly colored"	100	- first trace of color may be observed

Standard Term	Gallons of Oil per Square Mile	Appearance
"brightly colored"	200	- bright bands of color are visible
"dull"	666	- colors begin to turn dull brown
"dark"	1332	- much darker brown

Note: Each one-inch thickness of oil equals 5.61 gallons per square yard of 17,378,709 gallons per sq. mile.

Outage: Space left in a product container to allow for expansion during temperature changes it may undergo during shipment and use. Measurement of space not occupied.

pH: Term used to express the apparent acidity or alkalinity of aqueous solutions; values below 7 indicate acid solutions and values above 7 indicate alkaline solutions.

Pour Point: The lowest temperature at which an oil will flow or can be poured under specified conditions of test.

Residual Oil: A general term used to indicate a heavy viscous fuel oil.

Scuppers: Openings around the deck of a vessel which allow water falling onto the deck to flow overboard. Should be plugged during fuel transfer.

Sludge Oil: Muddy impurities and acid which have settled from mineral oil.

Specific Gravity: The ratio of the weight of a given volume of the material at a stated temperature to the weight of an equal volume of distilled water at a stated temperature.

Spontaneous Ignition Temperature: (S.I.T.): The temperature at which an oil ignites of its own accord in the presence of air oxygen under standard conditions.

Stoke: The unit of kinetic viscosity.

Tonnage: There are various tonnages applied to merchant ships. The one commonly implied is gross tonnage although in these days tankers and other bulk carriers are often referred to in terms of deadweight.

Gross Tonnage - 100 cubic feet of permanently enclosed space is equal to one gross ton - nothing whatever to do with weight. This is usually the registered tonnage although it may vary somewhat according to the classifying authority or nationality.

Net Tonnage - The earning capacity of a ship. The gross tonnage after deduction of certain spaces, such as engine and boiler rooms, crew accommodation, stores, equipment, etc. Port and harbor dues are based on this tonnage.

Displacement Tonnage - The actual weight in tons, varying according to whether a vessel is light or in loaded condition. Warships are always spoken of by this form of measurement.

Deadweight Tonnage - The actual weight in tons of cargo, stores, etc. required to bring a vessel down to her load line, from the light condition. Cargo deadweight is, as its name implies, the actual weight in tons of the cargo when loaded, as distinct from stores, ballast, etc.

Ullage: The amount which a tank or vessel lacks of being full. (See also Outage.)

Viscosity: The property of liquids which causes them to resist instantaneous change of shape, or instantaneous rearrangement of their parts, due to internal friction. The resistance which the particles of a liquid offer to a force tending to move them in relation to each other. Viscosity of oils is usually expressed as the number of seconds at a definite temperature required for a standard quantity of oil to flow through a standard apparatus.

Viscous: Thick, resistant to flow, having a high viscosity.

Volatile: Evaporates easily.

B. Conversion Table for Oil

Approximate Conversions:

Material	Barrels per Ton (long)
Crude oils	6.7 - 8.1
Aviation gasolines	8.3 - 9.2
Motor gasolines	8.2 - 9.1
Kerosenes	7.7 - 8.3
Gas oils	7.2 - 7.9
Diesel oils	7.0 - 7.9
Lubricating oils	6.8 - 7.6
Fuel oils	6.6 - 7.0
Asphaltic bitumens	5.9 - 6.5

1 barrel = .154 short tons (rule of thumb)
= 42 gallons (U.S.)
= 34.9726 gallons (Imp)
= 5.6146 cu ft.
= 158.984 litres
= .137 long tons (rule of thumb)
= 308 lbs. (rule of thumb)
=
=

C. Behavior of Oil in the Environment

The change of the oil properties once it is exposed to the environment is a complex chemical reaction. The time dependent behavior of oil in water is speculated by Dean:

Evaporation:

> "There is no doubt that the one big change which occurs rapidly when oil is spread on the sea is the evaporation of the light fractions. The rate at which this occurs is very uncertain and undoubtedly very variable, depending on the nature of the crude oil, the rate of thinning of the film, violence of wave action, strength of the wind, temperature, etc., etc. However, it seems probable that, after a few days on the sea, the amount of the oil left will be of the order of that of the residue greater than 370°C. (700°F.)."

Solution:

> "It is known that the lower hydrocarbons, e.g. methane, butane, heptane and benzene, have finite solubilities in water. Undoubtedly, with increase in molecular weight there is a decrease in solubility but, on the other hand, we are considering very large volumes of sea water. At a solubility of the order of 1 ppm. the whole cargo of the TORREY CANYON could have been dissolved in a patch of sea 20 miles square and 500 feet deep."

Oxidation:

> "Hydrocarbons are generally considered resistant to oxidation but, in actual fact, when oxygen is readily available and oxidation inhibitors are absent, they oxidize quite rapidly. This is particularly true when irradiated by light of short wavelengths of less than 4,000 Angstroms. Moreover, many of the sulphur compounds in crude oils are inhibitors of this oxidation although, in the process of inhibition, they are themselves converted to water soluble materials. Some of the metallocompounds present in the crude oils are, on the other hand, promoters of oxidation, thus it is an understatement to call the problem complex."

Another factor to consider is the biological oxidation of oil. A good review of this phenomena is by Holcomb.[2]

> "Bacteria found in open seas tend to degrade only straight-chain hydrocarbons of moderate molecular weight so branched-chain hydrocarbons of high molecular weight in the form of tarry chunks may persist for a long time. In still waters, a series of complex events results in almost complete degradation. In 1950, Soviet microbiologists showed that, after the lighter fractions of oil spilled on the Moskva River evaporated, the remaining oil was absorbed by particles and sank. Bottom-dwelling microorganisms produced a new mixture of organic substances that were carried to the surface with bubbles of methane and other light gases. The new compounds again were absorbed, sank, and the cycle was repeated. A number of cycles, repeated over several months, were necessary to degrade most of the oil.
>
> Studies on the thoroughness of degradation have produced conflicting results. Research at Terrebonne Bay, Louisiana, in 1966 showed that essentially complete degradation occurs within a period of several months. Oil has been a consistent pollutant in the Bay since the 1930's, but analysis of bottom mud showed that significant concentrations of petrochemicals could be found only in areas that had received oil relatively recently. However, studies in the French Mediterranean, which will be discussed later, indicate that important chemicals are persistent in bottom sediments.

> There is now a considerable body of literature on the interactions of microorganisms and petroleum products, most of it based on laboratory studies and much of it dating back to Soviet work in the 1930's and American work in the 1940's. However, these studies are scarcely past the descriptive stage, and, even when combined with field studies, they are not adequate for predicting the course of degradation of an oil spill."

Even less well understood is the tendency of some oils to form 'water-in-oil' emulsions. Dean notes that:

> "The consideration given to the significance of these emulsions has not been nearly sufficient. Even the reason for and the mode of formation of these emulsions is obscure. Are they stabilized by the products of bacterial action or by collecting plankton from the surface of the sea? Why do they not readily revert to the oil-in-water emulsion which is so desirable for dispersal?"

These emulsions tend to retain their identity in the marine environment. Their formation is therefore significant with respect to the long term effects of a spill.

Persistent 'lumps' of oil have been observed by Horn[3] and co-workers. These may be connected with the formation of stable emulsions. Horn reports:

> "Lumps of crude oil residue floating on the sea surface have been observed widely. Samples were taken with surface-skimming nets in the Mediterranean Sea and eastern North Atlantic Ocean; their displacement volumes were as large as 0.5 milliliter per square meter. An isopod, Idotea metallica, appears to be associated with the lumps, and a barnacle, Lepas pectinata, grows upon them. Lumps were found in stomachs of Scomberesox saurus, a surface-feeding fish important in ocean food webs. Films on the lumps, presumably consisting mostly of bacteria, consumed oxygen at the rate of 4 cubic millimeters per hour per square centimeter of lump surface. Chemical analysis suggested that certain lumps had been at large for only a few weeks; data from barnacle size and growth rate suggested that other lumps were at least two months old."

D. Short Term Biological Effects of Oil and Oil Spills

Any discussion of the effects of an oil spill should distinguish between the damage done by the oil and the damage done by subsequent spill treating agents. Once this distinction is made, further division of the short and long term consequences of the spill is meaningful.

In order to assess the effects of an actual spill, there must be knowledge of local marine life existing prior to the spill. Although this knowledge is available in part, it is fragmented among many different interest groups. Coordination and compilation of this information has not been attempted successfully. Therefore, it is strongly suggested that this information be gathered for Puget Sound. Section II-A of this report presents a preliminary inventory on marine life.

1. Oil Spill Treating Agents
   a. Toxic Effects

Studies following the Torrey Canyon spill emphasize the danger of dispersing agents to varied forms of marine life. Since that time, a large amount of information on the toxicity of spill treating agents has been gathered by various institutions. Some of those groups active in this data collection are the FWQCA's Edison Water Quality Laboratory and National Marine Water Quality Laboratory, the Licensing Division of the California Fish and Game Department, the Richland Labs of Battelle Northwest, and various universities.

A review of the toxicity of various spill treating agents was sponsored by the American Petroleum Institute and completed by Battelle in May of 1970.[4] This review included over 70 commercially available treating agents and accompanying toxicity tests when available.

Battelle also made recommendations where appropriate on test procedures for determining toxicity. Those commercial agents listed, whose toxicity is unknown or questionable, should undergo tests such as those outlined by Battelle. Before this is done, this list should be updated to 1971 (something which Battelle is currently doing) and new data from any of the above institutions should be incorporated. When this is done, a more informed statement can be made on what treating agents should be used during various conditons.

   b. Sub-Lethal Effects

Although much attention has been given to the acute toxic effects of treating agents, relatively little attention has been given to the long term toxic and sub-lethal effects. This is mainly due to the fact that these effects must be determined under field conditions rather than in the laboratory. The following discussion is taken from the Battelle report:[5]

> "Recently, long-term studies have been conducted where low levels of toxicant have been maintained over critical periods in the life cycle of selected organisms. The results have demonstrated that the application factors to be applied to 96 hr TL_m values to indicate safe concentrations during chronic or continuous exposure are not adequate to protect aquatic life. Application factors in current use, as recommended by The National Technical Advisory Subcommittee on Water Quality Requirements for Fish, Other Aquatic Life and Wildlife, range from 1/10 to 1/100 of the 96 hr TL_m value.
>
> While ultimately research should be conducted to determine absolute toxicity of many such materials on the diversity of both fresh-water and marine organisms, it is recommended that the following problem areas be given priority:
>
> 1. Short-term bioassay studies to identify the most sensitive species and the most sensitive life stage to a selected toxicant.
>
> 2. Long-term bioassay studies with those species and life stages which are the most sensitive to a particular toxicant to determine the following:
>
> a. The consequential effects of non-lethal damage at any stage on successive stages in the life cycle.
>
> b. The effects on all life stages of sub-lethal exposures during the most sensitive stages.
>
> c. Comparative studies of the effects of exposure during the most sensitive stages and of exposures during the entire life cycle.
>
> 3. Related to investigation of the long-term effects of selected toxicants, the following studies should be undertaken:
>
> a. Determination of the mode of toxicity, of the selected toxicant, their metabolities and degradation products.

> b. Determination of the interaction of two or more toxicants; both synergistic and antagonistic effects, and those materials with similar modes of action."

The report goes on to recommend a currently possible approach to the measurement of sub-lethal effects:

> "For the determination of sub-lethal effect or chronic exposure, it is perhaps more important to examine the communities in the environment, either aquatic or terrestrial, than it is to examine the individual organisms within the community.
>
> The community is modified as a result of pollution, in structure and in size, numbers of species tend to shift their relative frequency; or they can be eliminated entirely. It is the community of organisms that reflects the total effect of contamination over the protracted period of time."

Currently, however, due to the lack of universally accepted measurement techniques, studies concerned with the problem of these effects have not been conclusive. They include those conducted by the Warren Spring Laboratory after the Torrey Canyon spill, and those conducted by the U.S.Geological Survey and the University of Southern California following the Santa Barbara spill. The main conclusion from all of these studies was that the effects of the treating agents were difficult, if not impossible, to separate from the effects of the oil and all other phenomena. Yet, for now, the acute effects of those treating agents that have been studied in the laboratory should be the important variable in determining use.

Despite the lack of complete data, it is felt that the use of dispersants and sinking agents is to be avoided. The State DOE prohibits use of chemical dispersants in combatting oil spills.[6] It is recommended that use of absorbing and biological agents have been shown to be safe to Pacific Northwest marine species. If toxicity data on these agents does not include tests on Puget Sound species (and in most cases id does not cover many), use of absorbing and biological agents otherwise shown to be safe are recommended. However, these agents should only be used when the spill is heading toward a high priority area. (See Section III-B, part 2.) If the decision is made to direct a spill to an available sandy beach relatively sterile in marine life, avoiding the use of treating agents is stronly recommended.

2. Oil

The least studied and least understood consequence of an oil spill is the effect of the oil itself on marine life. Research on this aspect of the problem is really just beginning to develop. For the purposes of this report, initial effort has been directed to current literature and to current unpublished studies. These data raise more questions than they answer as is the case with most research in a new area.

As described earlier, the interaction of oil with the marine environment is highly complex and variable. For this reason, a quantitative prediction of what would occur if a certain oil were mixed with waters of a given area is not possible. Those reactions which are known to occur under controlled laboratory conditions may not occur in the rapidly changing environment of the sea. Even if one could say that certain classes of reactions would occur, this fact alone would not be enough to describe the toxic and sub-lethal effects of oil on marine organisms. Our limited knowledge of the mechanisms of toxicity to various marine organisms and of the range of sub-lethal effects that actually occur restricts our ability to predict the consequences of known chemical reaction.

For these reasons, the most useful data are the measured effects of actual spills. Unfortunately, these measurements have not been made in the past due to limited interest, facilities, and techniques. Only in the past few years has there been any reliable investigation of the sub-lethal effects of oil. We are just now beginning to interpret the results of these studies with the result that the direction of future research is as yet unclear. The recent grant to Battelle from Standard Oil to study the effects of oil, oil with treating agents, and treating agents alone, is another step in the right direction, but is by no means the ideal scientific investigation. Battelle's initial constraint will be time, which is one constraint that should be eliminated in any study of long term effects.

Although we can't accurately predict all of the effects, we can infer some of the effects characteristic of the general chemical classes. This has been done by Clark, et. al... and is quoted below:

> "Low-boiling, saturated hydrocarbons are related to the fat-soluble anaesthetics and have a narcotic effect on a wide variety of animals. In lower animals at low concentrations they often cause cell damage and death, especially in larval and juvenile stages of marine organisms. The solubility of these low-molecular weight hydrocarbons in water is of the order of 0.1 to 1.0 grams per liter, comparable to that of many drugs (Goldacre, 1968).
>
> Higher-boiling, saturated hydrocarbons occur naturally in many organisms and, while probably not toxic at low levels, they may interfere with chemical communications used by some organisms for locating food, as sex attractants, and as indicators of migration routes (Blumer, 1969).
>
> Olefinic hydrocarbons are not generally found in crude oils but are plentiful in gasolines and other refined products. The fate of olefins in the marine environment is poorly understood but this class of compounds is quite reactive and will combine readily with hydrogen, oxygen, chlorine, sulfur and other elements to produce toxic substances. Also, once incorporated into organisms, olefins are stable.
>
> Aromatic hydrocarbons comprise the most dangerous of petroleum fractions. The low-boiling aromatics are acutely poisonous to man and marine organisms alike. Benzene, toluene and phenols, such as found in crude oil, produce in man reactions similar to those of alcohol. The initial reaction is restlessness, then excitement, inebriation, drowsiness, depression and sleep. Death may follow from respiratory failure as the concentration rises (Goldacre, 1968). Chronic exposure to low concentrations of some aromatics, especially benzene, may cause bone marrow aphasia, chromosome aberration and leukemia (Finkel, 1960).
>
> The higher-boiling aromatics are suspected of having carcenogenic properties. Benzpyrene, 1, 2-benzanthracene and aklylbenzanthracenes have been isolated from crude oils and their carcenogenic effects on animals and man demonstrated. Some years ago, a high incidence of skin cancer in some refinery personnel was observed. The cause was traced to prolonged skin contact by these persons with petroleum and with refinery products. Better plant design and education, aimed at preventing the skin contact, have since reduced or eliminated this hazard (Eckart, 1967). However, these incidents have demonstrated that oil and oil products can cause cancer in man."

Non-Hydrocarbons: "In their behavior and toxicity, the non-hydrocarbon components of crude oil (nitrogen, oxygen, sulfur, and metal compounds) closely resemble the corresponding aromatic compounds (Blumer, 1969)."
(From "Environmental Statement on the Proposed Leasing of Puget Sound Shorelands and Beds of Navigable Waters for Oil and Gas Exploration." Dolan, Savage and Clark. Oct. 1970.)

a. Direct Effects

A good summary of research in this area up until November, 1967, is found in Battelle's literature search study.[7] Due to the length of this search, a summary of the important effects is presented here.

Due to a lack of detailed information on the relative effects of various crude oils, all crude oils have been grouped together. Possible exceptions to this general category include those crudes which have been mixed with an unusual amount of water soluble and high boiling components.

Similar reasoning leads to a second grouping of more highly refined products. Possible variation of effects within this group could be attributed to the variation in chemical structures. Kerosene and gasoline are mainly composed of saturated straight and branched chains, whereas the jet fuel and other highly refined products have a large portion of ring structured (aromatic) components.

Some oils do not readily fall into either category. The heavy residual oils approach the crude oils in physical properties, but are not necessarily similar chemically. This is due to the mixing of high and low boiling components to achieve the desired properties of handling and combustion, as is done with Bunker C. The distillate oils contain more refined components which are more water soluble and low boiling than the heavier components. Yet, their physical properties do not compare as closely with the more refined products, and they tend to be more persistent physically in the marine environment.

At the time of the survey done by Battelle, the most complete before and after study of an oil spill was reported by

W. J. North of California Institute of Technology.[8] He studied the effects of the oil spilled by the Tampico, near Baja, California. He reports:

> "The cargo of about 60,000 barrels of diesel oil began leaking from the stricken ship and spread along the shore, carried by wind and waves. The hull of the Tampico formed a breakwater across the cove, reducing the oxygenation of these waters from breaking waves. The luxurious submarine gardens in this cove and along the surrounding beaches perished. Soon the shore was littered with piles of seaweed and dead and dying animals.
>
> Only a few animal species survived. One was a tiny snail, the periwinkle Littorina planaxis. This creature inhabits rocks well above the high water mark and depends on spray from waves to satisfy its water requirements. Unfavorable conditions apparently did not extend up to the periwinkle's domain. Several large green anemones, Anthopleura xanthogrammica, were found alive in the tidepools. These animals, which sometimes grow in salt water lines of oil refineries that use seawater as a coolant, are believed to be very tolerant of oil pollution. Among the dead species were lobsters, abalone, sea urchins, starfish, mussels, clams, and hosts of smaller forms.
>
> We have visited the area each year since catastrophe struck this little cove, recording plants and animals at a dozen different locations. Gradually the various forms of life returned. Sixty-nine species of animals have recently been observed, compared to only two species immediately after the shipwreck. Among plants the tally is fifty-seven now, versus four a month after the accident. In spite of the reestablishment of lost species, the cove is still not the same as we believe it was before the wreck. Many species have just appeared within the last year or two and often only one or two specimens have been seen. Prior to the wreck these species must have been abundant, judging from the numbers cast up on shore after the accident. Conversely, other species are now plentiful, of which only a few individuals were present before the wreck."

Another good summary of the current thinking at that time is found in a collection of papers edited by Arthur and Carthy.[9] This collection begins to indicate that the sub-lethal effects of spilled oil should be investigated. The following excerpts from Goldacre's paper point out this fact:

> "The lower members of the paraffin hydrocarbons have nevertheless a strong effect on living material. ...Changes produced in the cell membrane by hydrocarbons may plan an important part in causing malignant change. The cell membrane of cancer cells is different from that of the corresponding normal cell (Ambrose, 1967) (and) the work of Sonneborn (1964) has shown that it is possible for membrane changes to be inherited without any change in the nucleus. Hence hydrocarbon carcinogens could cause permanent changes in the cell membrane leading to a breakdown in cell-cell communication and to cancer."

Clark summarizes another paper in this collection by Arthur:

> "In the marine environment, oil pollution at low levels, where direct toxicity cannot be measured, is believed capable of interfering with biological function in two ways: (1) by blocking chemoreceptor organs and (2) by producing fake stimuli leading to unproductive behavior. Oil pollution at higher levels can cause death of many organisms in the food chains of higher animals such as birds and fish, causing an upset in the ecological balance. Oil brings about the death of tiny organisms when the oil coats their surfaces either by preventing molecular exchange across cell membranes or by causing incorporation of toxic components of the oil into the tissue (Arthur, 1968)."

At that time (July 1968) very little work on these sub-lethal effects had been done, although other researchers starting with Mallet (1964) had known about the carcinogenity of the heavier oil fractions and their presence in sediments. Then in late 1969 a spill occurred about six miles from Wood's Hole Oceanographic Institute. This led to the continuing work of Dr. Max Blumer and his co-workers on the sub-lethal effects of a spill. They were fortunate to have a documented biological baseline of Buzzard's Bay and the facilities to conduct sensitive analytical measurements. The first report appeared in January 1970 and the latest report updates that study by eight months (The West Falmouth Oil Spill-persistence of the Pollution Eight Months After the Accident - September 1970.) As the title implies, this latest study emphasizes that the oil has persisted in the ecosystem causing a wide variety of sub-lethal effects.

The abstract from the first report[10] is quoted below:

> "A spill of 650,000 to 700,000 l of No. 2 fuel oil has contaminated the coastal areas of Buzzards Bay, Massachusetts (USA). Gas chromatography demonstrates the presence of this oil in the sediments of the affected area. Two months after the accident, essentially unchanged oil is still being released from the sediments. The presence of the same pollutant is demonstrated in whole oysters Crassostrea virginica and in the adductor muscle of the scallop Aeguipecten irradians. A presumably biochemical modification leads to a gradual depletion of the straight chain and, to a lesser extent, of branched chain hydrocarbons. This does not result in detoxification, as the more toxic aromatic hydrocarbons are retained in the organisms several months after the accident. Scallops from an uncontaminated area contain hydrocarbons in lesser amounts and of very different molecular weight and type distribution; they are accountable entirely from biological sources."

The report itself details the precision and care of the measurement system - a precision not used before in other spill areas.

Portions of Dr. Blumer's congressional testimony[10] reflect the findings eight months later:

> Persistence and Spread of the Pollution:
>
> "Oil from the accident has been incorporated into the sediments of the tidal rivers and marshes and into the offshore sediments, down to 42 feet, the greatest water depth in the sea.
>
> The #2 fuel oil involved in the spill is a relatively volatile oil product. In spite of this, volatilization has been minimal and the oil remains in the marshes, exposed to air, and in the offshore areas, 10 months after the accident.
>
> The pollution has been spreading on the sea bottom and now covers at least 5000 acres offshore and 500 acres of marshes and tidal rivers. This is a much larger area than that affected immediately after the accident.
>
> Bacterial degradation of the oil is slow; degradation is still negligible in the most heavily polluted areas and the more rapid degradation in outlying, less affected, areas has been reversed by the influx of less degraded oil from the more polluted regions.

The kill of bottom plants and animals has reduced the stability of marshland and sea bottom; increased erosion results and may be responsible for the spread of the pollution along the sea bottom.

Bacterial degradation first attacks the least toxic hydrocarbons. The hydrocarbons remaining in the sediments are now more toxic, on an equal weight basis, than immediately after the spill.

Oil has penetrated the marshes to a depth of at least 1-2 feet; bacterial degradation within the marsh sediment is still negligible eight months after the accident."

Biological Effects of the Pollution:

"Where oil can be detected in the sediments there has been a kill of animals; in the most polluted areas the kill has been almost total. Control stations outside the area contain normal, healthy bottom faunas.

The kill associated with the presence of oil is detected down to the maximum water depth in the area.

A massive, immediate kill occurred offshore during the first few days after the accident. Affected were a wide range of fish, shellfish, worms, crabs and other crustaceans and invertebrates. Bottom living fishes and lobsters were killed and washed up on the beaches. Trawls in 10 feet of water showed 95% of the animals dead and many still dying. The bottom sediments contained many dead clams, crustaceans and snails.

Fish, crabs, shellfish and many other animals were killed in the tidal Wild Harbor River; and in the most heavily polluted locations of the river almost no animals have survived.

The affected areas have not been repopulated, nine months after the accident.

Mussels that survived last year's spill as juveniles have developed almost no eggs and sperm.

(From: Hampson and Sanders, 1969; Sanders and Hampson, 1970; Sanders and Hampson, personal communication.)

Effect on Commercial Shellfish Values:

"Oil from the spill was incorporated into oysters, scallops, soft-shell clams and quahaugs. As a result, the area had to be closed to the taking of shellfish.

> The 1970 crop of shellfish is as heavily contaminated as was last year's crop. Closure will have to be maintained at least through this second year and will have to be extended to areas more distant from the spill than last year.
>
> Oysters that were removed from the polluted area and that were maintained in clean water for as long as six months retained the oil without change in composition or quantity. Thus, once contaminated, shellfish cannot cleanse themselves of oil pollution.
>
> The tidal Wild Harbor River, a productive shellfish area of about 22 acres, contains an estimated four tons of the fuel oil. This amount has destroyed the shellfish harvest for two years. The severe biological damage to the area and the slow rate of biodegradation of the oil suggest that the productivity will be ruined for a longer time.
>
> The presence or absence of an "oily smell" is no clue for the presence of oil pollution in fish or shellfish. Only a small fraction of petroleum has a pronounced odor; this may be lost while the more harmful long-term poisons are retained. Boiling or frying may remove the odor but will not eliminate the toxicity."

Many of these effects have not been reported elsewhere because of the difference in precision of various sampling techniques. Perhaps if Dr. Blumer and his co-workers would have been monitoring the Santa Barbara spill, the following would not have appeared in U.S. News and World Report:[11]

> "This study, by Dr. Dale Straughan of the Allan Hancock Foundation of the University of Southern California, was released on Jan. 19, 1971. It confirmed many of the findings of the Geological Survey report ... In conclusion, said Dr. Straughan: "Three main points emerge from assessment of the data: (1) It is often difficult to isolate the effects of oil pollution from other phenomena. (2) Damage to flora and fauna in the Santa Barbara Channel was much less than predicted. (3) The area is recovering well."

Holcomb[12] reports the ensuing conflict:

> "Dr. Robert Holmes, the first director of a major study after the Santa Barbara blowout, has stated that plankton populations were unaffected, and, although his remark was

> challenged at the Massachusetts Institute of Technology symposium where it was made, it is generally agreed that visible damage to organisms other than birds has been relatively light."

b. Indirect Effects

i) One important indirect effect of spilled oil is the increased concentration of pesticides dissolved in stable oil sediments.

In May, 1970, Hartung and Klinger[13] report:

> "In the Detroit River, areas containing near 1% sedimented oils reach p,p'-DDT concentrations near 1 p.p.m. The combined levels of chlorinated hydrocarbon insecticides approach levels similar to those reached in insecticidal applications. These areas are also devoid or very deficient in benthic arthropods (Vaughan and Harlow, 1965).
>
> Since sedimented polluting oils are a significant constituent in aquatic environments in areas with a history of oil pollution, the partitioning behavior of these oils must be taken into account when one seeks to evaluate the impact of pollutants on benthic organisms, or the food-web that is supported by this benthos."

In March, 1970[14] similar findings are reported:

> "Pesticide concentrations 10,000 times greater than those found in surrounding waters have been discovered in oily surface slicks in Florida's Biscayne Bay. According to Drs. Eugene F. Corcoran and Douglas B. Seba of the University of Miami's Rosenstiel School of Marine and Atmospheric Sciences, the slicks are natural oceanographic phenomena that appear as calm streaks or patches on the rippled surface of the open oceans, lakes, or coastal waters. ...said Dr. Corcoran. "In Biscayne Bay, for example, we have observed gulls and pelicans diving into surface waters to feed on the dense schools of small fish that feed on plankton concentrated in the slicks. Since these sea birds eat many times their weight in fish, they eventually have more pesticide concentrated in their tissues than the fish did."

The growth of the bottom area contaminated by oil sediments (as previously reported by Blumer) and the presence of stable oil sublayers magnifies the importance of these findings. Evidence of the presence of a stable oil sublayer below the surface where these pesticides could concentrate is described in an unpublished report by the National Marine Fisheries Service. This report describes oil coated specimens fished up from 10 to 50 fathoms by the research vessel Aruba.

ii) Another important indirect effect is the disruption of the marine food chain. Clark summarizes this interaction:

> "A marine shoreline has a series of zones relating to exposure to different combinations of environmental conditions (waves, currents, surge, desiccation, light, substrate, etc.). Within each zone, ecosystems are composed of populations of primary producers (attached algae), browsers and grazers (herbivores) and predators (carnivores and omnivores), delicately balanced with respect to the environmental conditions prevailing within the zone (Bellamy and Whittick, 1968). If one step in the food chain is eliminated by oil pollution, the balance of the entire ecosystem is destroyed."

Holcomb[15] elaborates on this delicate web, emphasizing the concentration of carcinogens and pesticides in higher life forms through this process.

> "Pollutants tend to enter the food chain more easily and to pass through it with fewer changes in aquatic environments than they do in terrestrial environments. They can be introduced in solution through bottom sediments and even in dispersed droplets that are ingested by the numerous filter feeders that constitute an important part of aquatic food.
>
> The presence of DDT in Lake Michigan's coho salmon drew public attention to the fact that some hydrocarbons pass through the aquatic food chain relatively unchanged. Work at Woods Hole has demonstrated that the ratios of olefinic hydrocarbons in zooplankton to those in livers of basking sharks and herring that feed on the plankton are so constant that they can be used to determine the feeding grounds of these species.
>
> Obviously, studies should be conducted to see what concentrations of 3,4-benzopyrene and other potentially dangerous hydrocarbons must be in seawater or sediments before they are introduced into the food chain and whether the chemicals persist as they pass through the chain."

iii) Yet, another indirect effect arises from the chemically stimulated behavior of certain marine species. Holcomb summarizes the findings of Blumer:[16]

> "Blumer points out that very small amounts of certain chemicals are used by many species of sea animals as behavior signals in the vital activities of food finding, escaping from predators, homing, and reproduction. He has shown, for example, that starfish are attracted to their oyster prey by chemicals in concentrations of a few parts per billion. The responsible chemicals have not been identified, but Blumer believes that in many cases they may resemble the high-boiling, saturated hydrocarbons found in petroleum products. Because of the extreme sensitivity of the response and the similarity of the animal and petroleum chemicals, he thinks it is possible that pollution interferes with chemically stimulated behavior "by blocking the taste receptors and by mimicking natural stimuli."

iv) Other indirect effects to be considered include:

- Exposure of the marine ecosystem to possible cancer causing chemicals.
- Consumption of dissolved oxygen by degrading oil.
- Evaporation of volatile components can degrade short term air quality.

c. Long Term Effects

Long range effects of oil pollution are often difficult to detect, even more so to determine precise effects. Effects such as decreased growth, decreased viability, tumor initiation may have obscure complex causes which are difficult to determine. The additions of petroleum products to water may not be directly harmful but they may initiate other changes which are detrimental.

Life in the marine environment is very complex. One species during its life cycle can live in many environments and thus have varying vulnerability to oil pollution. The adult English sole, for instance, is a bottom dwelling species living at a depth of 20-50 fathoms. Its eggs float free in the water column at varying depths. The young spend their first year in very shallow water, often in the intertidal zone. The adults may be considered to be relatively safe from surface oil but the eggs and young are very susceptible.[17]

The richness of the Puget Sound biota is well known. The biological basis of this richness lies in the plankton that covers the waters. It is this segment from zero to 5 cm. deep that appears to be most sensitive to damage by an oil spill. In addition to being in an area where contact with oil is most likely, plankton has the disadvantage of not being able to move a sufficient distance to avoid the oil. The sensitivity of many of these organisms to oil is very great. Certain zooplankton, for example, die in 24 hours at a concentration of 0.1 ppm crude oil. A concentration of 0.01 ppm oil is sufficent to kill in 72-96 hours. In addition to direct mortality, oil may have effects by altering reproduction and growth rates.[18] Diatoms, for example, experience a reduced reproductive capacity when exposed to sub-lethal amounts of oil.[19] It is not known if this occurs in other groups of organisms that comprise the plankton of Puget Sound.

In addition to algae and zooplankton, the larvae of many economically important organisms such as crabs, clams, and some fish, are found at or near the surface of the water. In addition to being in a more vulnerable position to oil, the larvae appear to be more sensitive than the adults to oil pollution. This is probably due to the smaller size of the larvae. Very roughly, the larval stages appear to be 100 times more sensitive to oil than the adults. Plaice larvae, exposed to oil at 0.1 to 0.01 ppm experienced a 40-100% deformity upon development.[20]

Larger, stationary plants such as kelp play a crucial role in the ecology of Puget Sound. They provide food and shelter to many organisms. Since many of these plants reach to the surface of the water, they may easily become coated with oil which may have detrimental consequences though not immediately evident. A 0.02 mm. film of diesel oil on kep beds has little effect for 24 hours. However, after 72 hours photosynthetic activity is completely halted. Emulsions of oil are much more harmful to plants than surface oil. An emulsion of 1.0% oil reduces photosynthesis in kelp 73% in 24 hours and 100% in 77 hours. An emulsion of 0.01% diesel oil has some inhibitory effects in 72 hours. The oil appears to act on fatty constituents of the cytoplasmic membrane. Irreversible damage occurs after 6-12 hours of exposure to emulsified oils. In addition, the phenols and cresols are very toxic to plants, a concentration of 0.1 ppm being fatal.[21]

In addition to the more immediate effects of oil on plants, there are long term effects that are not understood. In one experiment, 65% of plant mortality, due to oil, occurred two months to one year after exposure to oil.[22] This effect could have very important ramifications both biological and economical.

Oil, when it remains in water for any length of time is oxidized by bacteria, or undergoes autoxidation, leading to end products of carbon dioxide in water. However, this breakdown of oil requires a tremendous amount of oxygen. One gm. of oil requires approximately 3.3 gm. of oxygen. One liter of oil would require all of the oxygen from 400 cubic meters of saturated sea water at 15° C.[23] At the surface, this huge oxygen demand would present no problem. However, sunken or emulsified oil could deplete the surrounding waters of their oxygen. Indeed, anerobic conditions are fairly common in areas such as loading docks that have chronic oil pollution. Such a situation could perhaps develop near the proposed Cherry Point refinery, an area which is a biological preserve for juvenile flatfish.

The rate of breakdown of oil depends to a great extent on the temperature. Below 10°C., the rate is very slow. In Puget Sound, the water temperature may be below 10°C. for months at a time which could have detrimental effects and increase the amount of time the oil remains.

When bacteria oxidize petroleum products, they assimilate a great deal of the material. Approximately 30-40% of the oxidized hydrocarbons are stored in the bacteria. This provides the hydrocarbons an entry into the food chain. It is very possible that these compounds are concentrated by the organisms as they pass through the food chain, very similar to the chlorinated hydrocarbon pesticides. The effect of such a concentration is not known. Even if it is not lethal or harmful to the fish, it may give their flesh an oil texture and thus decrease their economic value which could have far reaching effects on the Puget Sound economy.

It has been suggested that petroleum products may initiate cancerous growths in fishes. Tumors may be initiated by 4 and 5 ring aromatic hydrocarbons similar to those found in oils.[24] While such action by oil is yet to be proven, even the possibility may be enough to depress the values of fish taken from oil polluted waters.

Besides the direct delitarious effects of oil on fishes, there may be other effects. Large scale oil spills could disrupt migrations of fish, especially salmon. Spawning or feeding areas could be lost. Chemical senses play an important role in the lives of aquatic organisms and the addition of hydrocarbons could disrupt these sensory mechanisms. Many fish attract mates by chemical clues. These mechanisms are very sensitive and the fish are able to sense chemicals at less than 1 ppb.[25] The effects of large amounts of oil dissolved on the water are not known but they almost certainly would be detrimental to these chemical sensory mechanisms.

The greatest potential hazard from oil pollution would be a change in the equilibrium of species now present. By selectively destroying or decreasing the viability of certain species on a large scale, changes would occur in the abundance of almost all organisms. Organisms which are seemingly unaffected may find a vital food source gone and they themselves disappear; or a predator may decrease, and the prey increase in abundance accordingly. Such effects would be almost impossible to predict. This would probably occur only in localized areas with heavy, chronic pollution and poor water circulation. It would be accompanied by decreased species diversity and hence decreased stability of the system.

The possible long range effects of oil pollution are many and it is very difficult, if not impossible, to determine the full extent of the damage done by an oil spill. Table 14-1 presents a summary of known effects of oil on marine life. In the long run, the costs of an oil spill may be much greater than any benefits the importation of oil may have.

TABLE 14-1: KNOWN EFFECTS OF OIL POLLUTION IN THE MARINE ENVIRONMENT[26]

	Crude Oil	Refined Products	Dispersants + Oil
Plankton/ Bacteria	Toxic to some and utilized by others.	Toxic to some and utilized by others.	Inhibits some larval development, bacterial degradation.
Fish	Suffocation, surface fouling, hemorrhaging or capallaries, non-fatal tainting, disruption of food chain.	Carcenogenic tumors (refinery wastes), increased apparent toxicity of oil with a decrease in oxygen, non-fatal tainting loss of equilibrium.	Loss of equilibrium and orientation, destruction of gills and olfactory epithelium, breakdown of protein, inhibits reproduction.
Shellfish	Surface and ingested tainting, suffocation, poisoning, incorporation of oil into egg yolks, breaks down protective mucous coating of gill epithelium.	Tainting, suffocation, incorporation of carcenogenic compounds, changes in amino acid content.	Breaks down protective mucous and water coatings, inhibits growth and normal development.
Marine Plants	Suffocation, inhibition of flowering, leaf damage during photoinductive period.	Breakdown of fatty constituents of cytoplasmic membrane.	Increases the toxic effects of the oil and the rate of uptake of the oil.
Sediments	Incorporation of oil into sediments causes long-term tainting of shellfish and bottom-dwelling organisms, high concentration of chlorinated pesticides in oil-rich muds.	Same as for crude oil.	Incorporation of oil into sediments is enhanced by most dispersants and sinking agents.
Waterfowl	Physical coating, poisoning, starvation, destruction of protective habitat.	Poisoning by ingestion during preening, possible changes in reproduction (thin egg shell), concentration of certain fractions from contaminated food chain organisms (deposited in fatty tissues).	Removes natural protective oily body coatings, increases susceptibility to pneumonia.

E. Endnotes for Appendix 14

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