

ALASKA LEGISLATURE SPECIAL COMMITTEE/SUBJECT FILE 8672
2054 SCOMM 78: SENATE SPEC. COMM. ON OIL & GAS, 1991-1992

Common Name: Sea Cucumber
Scientific Name: *Parastichopus californicus*

Adult/Juvenile Habitat: 0 to 80m.; <20m in SU to spawn
Reference: Mottet, 1976a; Cameron, 1985
Score SP: 1
SU: 3
FA: 1
WI: 1

Location of Larvae: same habitat as adult
Reference: Cameron, 1985
Score SP: 3
SU: 3
F: 1
W: 1

Location of Eggs: 4-11m MLW near where spawning occurs
Reference: Cameron, 1985
Score SP: 3
SU: 3
F: 0
W: 0

WA Population Conc.:
Reference: Mills & Solomon, 1983
Score: 1

Length of Spawning: late Su through Su
Reference: Mottet, 1976a; Cameron, 1985
Score SP: 1
SU: 1
FA: 0
WI: 0

Relative Signif. WA Pop.: B.C. to Mexico
Reference: Mottet, 1976a
Score: 1

Population Size in WA:
Reference:
Score: 1

Reproductive Potential: a guess
Reference:
Score: 3

Age at Sexual Maturity: 4+ years
Reference: Cameron, 1985
Score: 5

COMPOSITE RANKING

Spring: 80
Summer: 96
Fall: 8
Winter: 8

Common Name: Red Sea Urchin
Scientific Name: *Strongylocentrotus franciscanus*

Adult/Juvenile Habitat: typically 5-10 m.; up to 125m.

Reference: Mottet, 1976b

Score SP: 1

SU: 1

FA: 1

WI: 1

Location of Larvae: planktonic for 2 months

Reference: Mottet, 1976b

Score SP: 3

SU: 3

F: 0

W: 0

Location of Eggs: eggs have a floating stage

Reference: Mottet, 1976b

Score SP: 5

SU: 0

F: 0

W: 0

WA Population Conc.: rocky substrates with current/kelp

Reference: Mottet, 1976b

Score: 3

Length of Spawning: Spring

Reference: Mottet, 1976b; Cumbow, 1978

Score SP: 3

SU: 0

FA: 0

WI: 0

Relative Signif. WA Pop.: North Pacific; so. to Baja in EPac.

Reference: Mottet, 1976b

Score: 1

Population Size in WA: abundant; annual harvest >1 million lbs.

Reference: Cumbow, 1978

Score: 1

Reproductive Potential: 100,000 to 2 million

Reference: Mottet, 1976b

Score: 1

Age at Sexual Maturity: four to six months

Reference: Mottet, 1976b

Score: 1

COMPOSITE RANKING

Spring: 168

Summer: 6

Fall: 6

Winter: 6

Common Name: Green Sea Urchin
Scientific Name: *Strongylocentrotus droebachiensis*

Adult/Juvenile Habitat: to 70 fathoms

Reference: Mottet, 1976b

Score SP: 1

SU: 1

FA: 1

WI: 1

Location of Larvae: Planktonic for 2-3 months

Reference: Mottet, 1976b

Score SP: 3

SU: 0

F: 0

W: 3

Location of Eggs: eggs have a floating stage

Reference: Mottet, 1976b

Score SP: 5

SU: 0

F: 0

W: 5

WA Population Conc.:

Reference:

Score: 3

Length of Spawning: Winter or Early Spring

Reference: Mottet, 1976b

Score SP: 1

SU: 0

FA: 0

WI: 1

Relative Signif. WA Pop.: Circumpolar

Reference: Mottet, 1976b

Score: 1

Population Size in WA: abundant; dominant sea urchin in Puget Sound

Reference: Mottet, 1976b

Score: 1

Reproductive Potential: 100,000 to 2 million

Reference: Mottet, 1976b

Score: 1

Age at Sexual Maturity: four to six months

Reference: Mottet, 1976b

Score: 1

COMPOSITE RANKING

Spring: 60

Summer: 6

Fall: 6

Winter: 60

Common Name: Dungeness Crab
Scientific Name: Cancer magister

Adult/Juvenile Habitat: fished at depths of <60 fathoms
Reference: Monaco and Emmett, 1988
Score SP: 1
SU: 1
FA: 1
WI: 1

Location of Larvae: larval period 4 mo., with daily mig
Reference: Monaco and Emmett, 1988; Cumbow, 1978
Score SP: 5
SU: 5
F: 0
W: 5

Location of Eggs: eggs remain on females
Reference: Monaco and Emmett, 1988
Score SP: 0
SU: 0
F: 1
W: 1

WA Population Conc.:
Reference: Monaco and Emmett, 1988
Score: 1

Length of Spawning: late Winter to Spring
Reference: Ricketts et al., 1985
Score SP: 1
SU: 0
FA: 0
WI: 1

Relative Signif. WA Pop.: AK to So. CA
Reference: Ricketts et al., 1985
Score: 1

Population Size in WA: ave. yield, 36 million pounds
Reference: Monaco and Emmett, 1988
Score: 1

Reproductive Potential: up to 2.5 million
Reference: Monaco and Emmett, 1988
Score: 1

Age at Sexual Maturity: most at 3 years
Reference: Monaco and Emmett 1988
Score: 3

COMPOSITE RANKING

Spring: 42
Summer: 6
Fall: 6
Winter: 48

Common Name: Red (Rock) Crab
Scientific Name: Cancer productus

Adult/Juvenile Habitat:

Reference: Orensanz & Gallucci, 1988
Score SP: 3
SU: 3
FA: 3
WI: 3

Location of Larvae: larvae in bay shallow waters

Reference: Orensanz & Gallucci, 1988
Score SP: 0
SU: 5
F: 5
W: 5

Location of Eggs: eggs held on females that move deep

Reference: Orensanz & Gallucci, 1988
Score SP: 0
SU: 3
F: 3
W: 0

WA Population Conc.:

Reference:
Score: 1

Length of Spawning: Su and Fall

Reference: Orensanz & Gallucci, 1988
Score SP: 0
SU: 1
FA: 1
WI: 0

Relative Signif. WA Pop.: AK to Baja

Reference: Ricketts et al., 1985
Score: 1

Population Size in WA: not abundant enough for commercial

Reference: Ricketts et al., 1985
Score: 3

Reproductive Potential:

Reference:
Score:

Age at Sexual Maturity: < 1 yr. after settlement

Reference: Orensanz & Gallucci, 1988
Score: 1

COMPOSITE RANKING

Spring: 18
Summer: 66
Fall: 66
Winter: 18

Common Name: Spot Shrimp
Scientific Name: *Pandalus platyceros*

Adult/Juvenile Habitat:

Reference: Sloan, 1987

Score SP: 1

SU: 1

FA: 1

WI: 1

Location of Larvae: in shallower waters

Reference: Sloan, 1987

Score SP: 3

SU: 3

F: 3

W: 3

Location of Eggs: eggs held on female

Reference:

Score SP: 1

SU: 1

F: 1

W: 1

WA Population Conc.: commerc. densities only in Hood C.

Reference: Bumgarner, 1983

Score: 5

Length of Spawning: assuming spawning in Sp/early Su

Reference:

Score SP: 3

SU: 3

FA: 0

WI: 0

Relative Signif. WA Pop.:

Reference:

Score: 3

Population Size in WA: 95 mt harvested in '81 and '82

Reference: Bumgarner, 1983

Score: 3

Reproductive Potential:

Reference:

Score: 3

Age at Sexual Maturity:

Reference:

Score: 3

COMPOSITE RANKING

Spring: 130

Summer: 220

Fall: 10

Winter: 10

Common Name: Coon Stripe Shrimp
Scientific Name: *Pandalus danae*

Adult/Juvenile Habitat:

Reference: Wicksten, 1984
Score SP: 1
SU: 1
FA: 1
WI: 1

Location of Larvae: in shallower waters

Reference: Sloan, 1987
Score SP: 3
SU: 3
F: 3
W: 3

Location of Eggs: eggs held on female

Reference:
Score SP: 1
SU: 1
F: 1
W: 1

WA Population Conc.:

Reference:
Score: 3

Length of Spawning: assumming spawning in Sp/early Su

Reference:
Score SP: 3
SU: 3
FA: 0
WI: 0

Relative Signif. WA Pop.:

Reference:
Score: 3

Population Size in WA:

Reference:
Score: 3

Reproductive Potential:

Reference:
Score: 3

Age at Sexual Maturity:

Reference:
Score: 3

COMPOSITE RANKING

Spring: 130
Summer: 220
Fall: 10
Winter: 10

Common Name: Side Shrimp
Scientific Name: *Pandalopsis dispar*

Adult/Juvenile Habitat:

Reference: see other local shrimp species

Score SP: 1
SU: 1
FA: 1
WI: 1

Location of Larvae: in shallower waters

Reference: Sloan, 1987

Score SP: 3
SU: 3
F: 3
W: 3

Location of Eggs: eggs held on female

Reference:

Score SP: 1
SU: 1
F: 1
W: 1

WA Population Conc.:

Reference:
Score: 3

Length of Spawning: assuming spawning in Sp/early Su

Reference:
Score SP: 3
SU: 3
FA: 0
WI: 0

Relative Signif. WA Pop.:

Reference:
Score: 3

Population Size in WA:

Reference:
Score: 3

Reproductive Potential:

Reference:
Score: 3

Age at Sexual Maturity:

Reference:
Score: 3

COMPOSITE RANKING

Spring: 182
Summer: 308
Fall: 14
Winter: 14

Common Name: Pink Shrimp
Scientific Name: *Pandalus jordani* and *P. borealis*

Adult/Juvenile Habitat:

Reference: see other local shrimp species

Score SP: 1
SU: 1
FA: 1
WI: 1

Location of Larvae: in shallower waters

Reference: Sloan, 1987

Score SP: 3
SU: 3
F: 3
W: 3

Location of Eggs: eggs held on female

Reference:

Score SP: 1
SU: 1
F: 1
W: 1

WA Population Conc.:

Reference:

Score: 3

Length of Spawning: assumming spawning in Sp/early Su

Reference:

Score SP: 3
SU: 3
FA: 0
WI: 0

Relative Signif. WA Pop.:

Reference:

Score: 3

Population Size in WA:

Reference:

Score: 3

Reproductive Potential:

Reference:

Score: 3

Age at Sexual Maturity:

Reference:

Score: 3

COMPOSITE RANKING

Spring: 72
Summer: 126
Fall: 0
Winter: 0

DRAFT FINAL REPORT

**PETROLEUM TOXICITY RELATIONSHIPS
FOR THE WASHINGTON COMPENSATION SCHEDULE**

by

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March 11, 1991

This Draft Report is Under Review by the Oil Toxicity Subcommittee of the Oil Spill Compensation Schedule Scientific Advisory Board. Some changes to this report will be made, but the basic approach described for ranking oils will remain unchanged.

*Supporting document
for oil toxicity ranking
part of model.*

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Petroleum Toxicity Relationships
for the Washington Compensation Schedule

by

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I. Origins of the Washington Compensation Schedule

Washington and Alaska Legislative Contexts

In 1989, the Washington State Legislature created a new method for determining compensation for damages resulting from oil spills. Existing law had already provided that, in the case of any unlawful discharge of oil into waters of Washington (covered under Laws of Washington RCW 90.48.320), the responsible party is liable not only for a penalty for each incident, but must also pay compensation for any adverse environmental, recreational, aesthetic, or other effects caused by the spill (RCW 90.48.366). The new feature added in 1989 was that the amount of compensation could be determined in one of two ways: either by a detailed resource assessment or by use of a compensation schedule¹.

The purpose of the compensation schedule (now under development by the Department of Ecology) is to provide adequate compensation for "unquantifiable damages or damages not quantifiable at reasonable cost." The amount of compensation assessed is a per gallon charge of not less than one dollar and

not more than fifty dollars per gallon of oil spilled (RCW 90.48.366), to be determined by a formula based on the characteristics of the oil spilled and the sensitivity of the receiving environment (RCW 90.48.366(1)(2)). The compensation schedule is to take into account:

Characteristics of the oil spilled, such as toxicity, dispersibility, solubility, and persistence, that may affect the severity of the effects on the receiving environment, living organisms, and recreational and aesthetic resources [RCW 90.48.366(1)]

The sensitivity of the affected area as determined by such factors as: (a) the location of the spill; (b) habitat and living resource sensitivity; (c) seasonal distribution or sensitivity of living resources; (d) areas of recreational use or aesthetic importance; (e) the proximity of the spill to important habitats for birds, aquatic mammals, fish, or to species listed as threatened or endangered under state or federal law; and (f) other areas of special ecological or recreational importance, as determined by the department... [RCW 90.48.366(2)]

The model for this provision is a similar provision in a 1977 Alaska oil spill compensation law (AS 45.03.758)², and development of the Washington approach was influenced by a similar underlying philosophy. The legislative findings of the Alaskan statute assert in part that:

the exact nature and extent of oil pollution can be neither documented with certainty nor precisely quantified on a spill-by-spill basis; however, in light of the magnitude of harm which may be caused..., and the vital importance of (the natural resources) to the economic future of the state and its quality of life, ...substantial civil penalties should be imposed for the discharge of oil and to insure that the public does not bear substantial losses from oil pollution for which, because of its subtle, long-term or unquantifiable nature, compensation would not otherwise be received...[AS 45.03.758(a)]

Similarly the Washington legislature has found that:

oil spills can cause significant damage to the environment and natural resources held in trust by and for the people of

this state. Some of these damages are unquantifiable, and others cannot be quantified at a reasonable cost. Both quantifiable and unquantifiable damages often occur despite prompt containment and cleanup measures. Due to the inability to measure the exact nature and extent of certain types of damages, current damage assessment methodologies used by the state inadequately assess the damage caused by oil spills. (1989 Washington Laws, C. 388, Section 1).

The Alaska Dept. of Environmental Conservation (ADEC) was directed by its legislation to promulgate regulations establishing a schedule of civil penalties which vary in relation to the toxicity, degradability and dispersal characteristics of the oil, and the sensitivity and productivity of the receiving environment [AS 45.03.758 (b) and (d)]. ADEC ultimately developed a simple formula in which scores for an oil's relative toxicity, dispersibility and degradability are averaged and multiplied by a base charge rate (derived on a per-gallon basis and depending on the sensitivity of the receiving environment). This calculation is then multiplied by the volume of oil spilled but not recovered to determine a total charge for the spill (See Appendix I).

In applying this formula to crude oil spills ADEC adjusts the toxicity and degradability factors by an additional factor determined by the oil's specific gravity³. In applying the formula to spills of refined products the toxicity factor is adjusted by a second factor based on the oil's total content of aromatic hydrocarbons. Values for the unadjusted factors were pre-specified for relevant oil types by sorting a list of petroleum products utilized or produced in Alaska into categories of high, medium or low toxicity, degradability and dispersibility, and then assigning numerical values between 0 and

1 to each category. (See Appendix II, which is taken from Rubin [1989].)

As Rubin notes, whether or not the simple relationship among these factors utilized in the Alaska formula actually explains the relative differences in damages observed in different oil spills is an empirically testable question. No such evidence has been presented in support of the Alaska formula, however. A review of the extensive literature on oil spill fate and effects which has appeared since the Alaska law was developed (summarized below), indicates nevertheless that underlying physical and chemical properties like those identified in the Alaska approach can be associated in a general way with the propensity of oil spills to cause environmental harm.

Some Connections to Federal Law

Both the Alaska and Washington approaches have connections to ideas contained in federal law. The concept of relying on toxicity, degradability and dispersibility factors in scoring relative oil spill damage appears to come originally from the now superseded Federal Water Pollution Control Act (33 U.S.C. 1254) which stated that:

...[T]he owner or operator of any vessel, onshore facility, or offshore facility, from which there is discharged any hazardous substance determined not removable...shall be liable...to the United States for either one or the other of the following penalties...(aa) a penalty in such amount... based on the toxicity, degradability, and dispersal characteristics of the substance...[or] (bb) a penalty determined by the number of units discharged multiplied by the amount established for each such unit... [33 U.S.C. 1254 Sect. 1321(b)(2)(B)(iii)].

The idea of utilizing a unit charge approach as an alternative compensation mechanism to field-study based damage assessments continues to find support in federal law. CERCLA (The Comprehensive Environmental Response and Liability Act of 1980) specifies that:

standard procedures for simplified assessments requiring minimal field observations, including establishing measures of damages based on units of discharge or release or units of affected area [be developed, as well as]...alternative protocols for conducting assessments in individual cases to determine the type and extent of short- and long-term injury, destruction, or loss. Sec. 301(c)(2)].

More recently, NOAA, under authority granted by the 1990 Oil Pollution Act, has announced its intention to explore use of "a phalanx of [simplified natural resource damage assessment] procedures, including a schedule or table estimating damages based on certain parameters of the spill..." (Federal Register 55:53479, December 28, 1990). The Washington Compensation Schedule is a unit-of-discharge-based approach of this type. The remainder of this report is devoted to developing petroleum toxicity relationships for use in the Washington Compensation Schedule.

II. Elements of the Proposed Approach to Defining Petroleum Toxicity

Petroleum Products Shipped on Washington Waters

Production and shipping activities in the Washington petroleum industry are summarized in "Washington State Petroleum Markets Data Book," a 1989 publication of the Washington State Energy Office (WSEO).

The pattern of oil shipments on Washington waters over the past decade is such that a relatively small number of product classes capture the great majority of shipments which pose a risk of spills (See Table 1)

Table 1. Petroleum and Petroleum Products Accounting for the Great Majority of Shipments on Washington Waters
(Source: WSEO 1989; and Chadbourne and Leschine 1989)

-
- Alaskan crude (Prudhoe Bay)
 - finished motor gasoline
 - leaded and unleaded
 - distillate fuel oil
 - nos. 1, 2 and 4 fuel oils
 - nos. 1 and 2 diesel fuel oils
 - kerosene type jet fuel
 - residual fuel oil
 - no. 6 fuel oil (Bunker C)
 - "Navy Special" fuel oil (no. 5 fuel oil)
-

Eighty-five percent of all crude oil entering the state is Alaskan crude. Of the remaining 15%, two-thirds is from foreign sources, primarily Indonesia and Canada. Ninety-eight percent of all crude deliveries are by tanker. (Canadian crude generally is delivered via the Trans Mountain Pipeline.) 1988 vessel shipments of crude oil are practically fully accounted for as the sum of Alaskan shipments (141.1 million barrels) and Indonesian shipments (7.7 million barrels). The only other source of tanker shipments greater than 1 million barrels for 1988 was Australia (1.5 million barrels).

Total refinery production for the years 1981-1988 was dominated by unleaded gasoline (252 million barrels in total) followed by leaded gasoline (225 million barrels). Leaded gasoline production is falling but still significant (nearly twice as much unleaded gasoline was produced in 1988 as leaded). Distillate fuel oils (224 million barrels), residual fuel oil (160 million barrels) and kerosene-type jet fuel (144.5 million barrels) make up the vast majority of the remainder of liquid products production.

Most gasoline and distillate deliveries from Washington refineries to final markets or distribution terminals in the Northwest are via the Olympic Pipeline. But 1.6 million barrels of gasoline and 1.2 million barrels of distillates were delivered to regional destinations via tanker or barge in 1987. There are also minor foreign imports of these products to the Portland area, utilizing the Columbia River, and refined products are delivered via the Columbia as far as Pasco, in Eastern

Washington. The bulk of residual fuels can be assumed to leave refineries by tanker or barge. Also, fuels in all categories are exported to foreign countries by vessel. Of the 9.3 million barrels of refinery products exported in 1988, 3 million barrels were distillate fuels (principally to Japan), 2.2 million barrels were residual fuels (principally to Canada), 1.6 million barrels were jet fuels (divided between Japan and Canada), and 700,000 barrels were gasolines (also shipped to Japan and Canada). For the purpose of deriving oil spill scoring formulas it appears feasible to work with the following classes:

- Crude oil (Prudhoe Bay crude)

and four classes of refined products derived largely from Prudoe Bay/Alaska North Slope Crude:

- Gasoline (including both leaded and unleaded)
- Kerosene and jet fuel (including non-kerosene type jet fuels, and including no. 1 fuel oil)
- No. 2 fuel oil (including diesel)
- Residual fuel oil (including no. 5 fuel oil, Bunker C, gas oils)

Data in WSEO's Data Book indicate that in recent years the combined volumes of Prudhoe Bay crude oil (PBC), leaded and unleaded gasolines, kerosene-type jet fuel, distillate fuel oil and residual fuel oil has comprised some 90% of the crude oil and refined petroleum products shipped around Washington coastal waters. We propose to consider only these products in developing the compensation schedule. We also propose to treat leaded and

unleaded gasolines together as one product. In 1988 unleaded gas amounted to 2/3 of the total gasoline produced, and the percentage of leaded gasolines will continue to drop in future years. Furthermore, we know of no fundamental difference which would require treating them as two categories in this initial stage. As can be seen from the distillation diagram provided in Figure 1, these product classes cover well the full range of products derivable from crude oil through the refining process.

The Changing Nature of "Prudhoe Bay Crude". A series of chemical characterizations of Prudhoe Bay crude oil were completed during the mid 1970s when it became clear it would soon be tankered in large quantities into the lower 48 states. Analyses were made on a PBC sample supplied by the American Petroleum Institute (API), representing a 'typical' sample from the original production field. These analyses showed the PBC to be an intermediate gravity, high sulfur, high nitrogen oil that contains a relatively high percentage of aromatic hydrocarbons. Table 1 of McAuliffe (1987) [reproduced here as Table 2] shows that the concentrations of various aromatics in sea water equilibrated with PBC are greater than aromatic concentrations in waters equilibrated with several other crudes. Anderson et al. (1987) give concentrations of several aromatics in PBC and sea water soluble fractions of the PBC (Table 3). Earlier characterizations of the PBC are given by Clark and Brown (1977).

Predictions of a 1983 Oil & Gas Journal article were that by 1985 about 15% of the north Alaskan oil tankered south would

FRACTIONAL DISTILLATION DISTRIBUTION

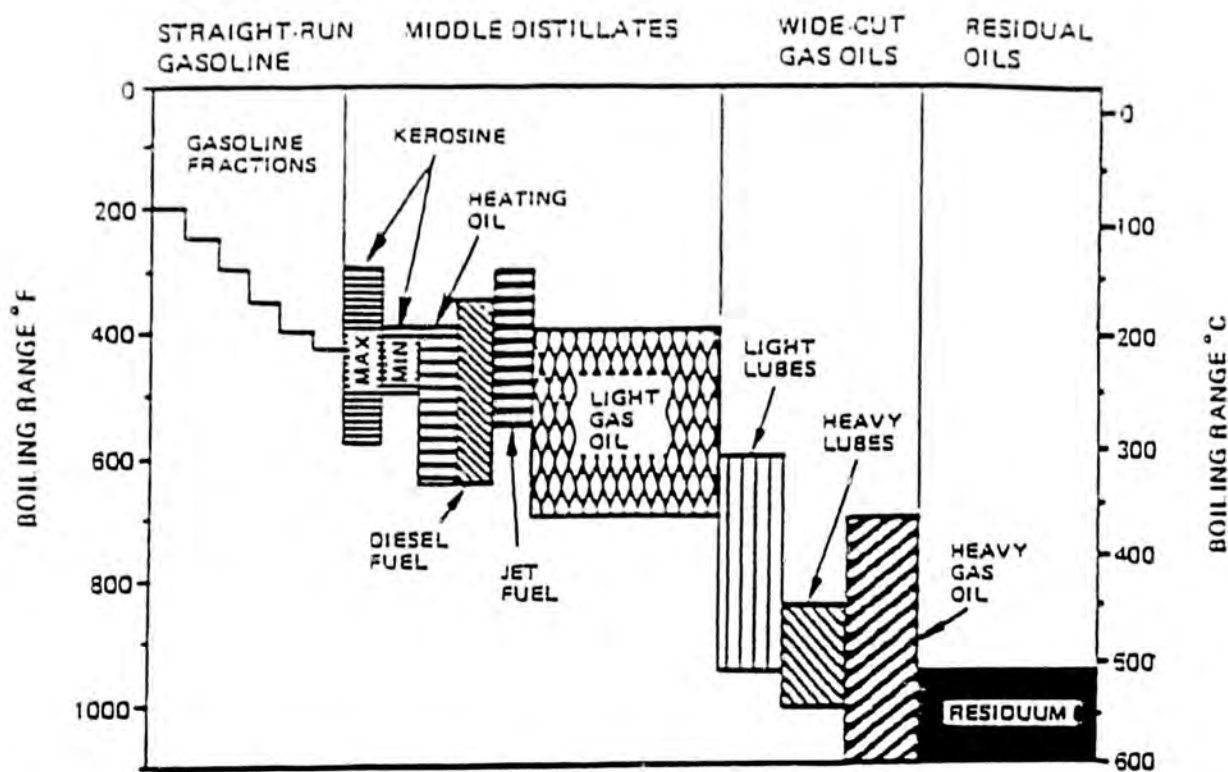


FIGURE 1 Boiling point range of fractions of crude petroleum.

NOTE: Bunker oil (not shown) is an oil of high viscosity used as a fuel oil. A given bunker oil may be a mixture of two or more of the distillate cuts shown in the figure or it may be a residual oil from a distillation run.

SOURCE: Adapted from Bureau of Naval Personnel by R.C. Clark and Brown (1977).

Table 2. Hydrocarbons dissolved in water equilibrated with oil samples
(concentrations in mg/L)

Crude oil Water salinity Produced source Hydrocarbons	Murcan Sea (McAuliffe ¹)	La Rosa Sea	South Louisiana 2% NaCl (Anderson et al. ¹)	Kuwait 2% NaCl	Cook Inlet Sea (Rice et al. ¹)	Prushoe Bay Sea
Methane	—	.26	—	—	.31	—
Ethane	.22	2.01	.34	.21	3.63	.01
Propane	2.15	3.65	3.01	3.30	10.70	.79
Isobutane	.30	.76	1.29	.90	1.90	.33
n-Butane	2.38	1.38	2.26	3.66	5.02	1.50
Isopentane	1.03	.60	.70	.98	1.02	.40
n-Pentane	1.34	.60	.49	1.31	1.11	.56
Hexanes + cyclopentane	.35	.50	.33	.59	.96	.50
n-Hexane	.50	.15	.09	.39	.21	.13
Methylocyclopentane	.35	.11	.11	.19	.63	.22
Benzene	6.08	3.30	6.75	3.26	3.10	9.30
Cyclohexane	.41	.19	—	—	.30	.24
n-Heptane	.33	.10	.06	.09	.16	.11
Methylocyclohexane	.33	.16	.11	.08	.42	.21
Toluene	6.16	2.80	4.13	3.62	4.10	6.58
Ethylbenzene	.82	.11	—	—	.15	.49
m-, p-Xylene	1.94	.34	1.56	1.58	1.06	1.58
o-Xylene	1.01	.15	.40	.67	.45	.52
Trimethylbenzenes	.75	.30	.76	.73	.29	.34
C ₇ -C ₈ Alkanes	8.43	9.48	8.79	10.38	24.19	3.59
C ₉ + C ₁₀ Saturates	2.67	1.57	.98	1.24	3.13	1.51
Total Saturates	11.10	11.11	9.77	11.62	27.37	5.10
Benzene + Toluene	12.74	6.10	10.88	6.98	12.20	15.88
Dimethylbenzenes (C ₈)	3.77	1.46	1.96	2.25	1.36	2.59
Trimethylbenzenes (C ₉)	.75	.30	.76	.73	.29	.34
Naftalenenes (Table 2)	—	—	.20	.07	—	—
Biphenyls, Fluorenes, and Phenanthrenes (Table 2)	—	—	.01	.01	—	—
Total Aromatics	16.76	7.86	13.60	9.96	14.25	18.81
Total Hydrocarbons	27.87	19.97	23.37	21.57	41.62	23.90
Benzene/hexane	12	22	75	12	39	72
Toluene/heptane	19	28	69	40	26	60
Benzene + toluene Total aromatics × 100	73	78	80	70	35	84
Benzene + toluene Total C ₇ + hydrocarbons × 100	64	66	75	62	70	78
Total aromatics Total hydrocarbons × 100	60	39	53	46	34	79

1. All analyses performed at Chevron Oil Field Research Company
2. Included with benzene
3. Included with m-, p-xylene
4. Saturated (alkane plus cycloalkanes)

SOURCE: McAuliffe (1987)

Table 3. Concentrations of C₁₂-C₂₄ n-Paraffins and Aromatic Hydrocarbons in Reference Oils and the 10% Water-Soluble fractions (WSFs) Prepared From Them

Name of Compound	S. Louisiana		Kuwait		No. 2 Fuel Oil		Bunker C		Pudhoe Bay	
	Whole Oil (%)	WSF (ppb)	Whole Oil (%)	WSF (ppb)	Whole Oil (%)	WSF (ppb)	Whole Oil (%)	WSF (ppb)	Whole Oil (%)	WSF ^a (ppb)
n-paraffins										^b
C ₁₄	0.44	10	0.46	<0.5	0.02	5.0	0.11	0.0	0.36	
C ₁₅	0.48	10	0.41	<0.5	1.06	7.0	0.11	0.9	0.37	
C ₁₆	0.54	12	0.43	0.6	1.20	8.0	0.15	1.2	0.36	
C ₁₇	0.41	9	0.42	0.8	0.98	6.0	0.12	1.9	0.34	
C ₁₈	0.30	7	0.28	0.5	0.60	4.0	0.10	1.0	0.30	
Total C ₁₂ -C ₂₄ n-paraffins	3.90	89	4.00	2.9	7.38	47	1.26	12	4.40	2.93
Aromatics										
Benzene	^c	6,750	^c	3,360	^c	550	^c	40	^c	36.1
Toluene		4,130		3,620		1,040		80	0.93	55.5
Alkylbenzenes ^d		760		730		970		110	3.19	53.8
Naphthalene	0.04	120	0.04	20	0.40	840	0.10	210	0.16	1.6
1-methylnaphthalene	0.08	60	0.05	20	0.82	340	0.28	190	0.21	2.4
2-methylnaphthalene	0.09	50	0.07	8	1.89	400	0.47	200	0.25	
Dimethylnaphthalenes ^d	0.36	60	0.20	20	3.11	240	1.23	200	0.80	1.4
Trimethylnaphthalenes ^d	0.27	8	0.19	3	1.84	30	0.80	100	0.40	0.6
Diphenyls ^d	<0.01	2	<0.01	1	0.16	20	<0.01	1	^c	^c
Fluorenes ^d	0.02	3	<0.01	3	0.36	20	0.24	11	^c	^c
Phenanthrenes ^d	0.06	4	0.04	3	0.53	20	1.11	23	0.39	0.3
Dibenzothiophenes ^d	0.02	1	0.01	1	0.07	4	<0.01	1	0.13 ^d	^c
Total aromatics	0.94	11,948	0.60	7,789	9.18	4,562	4.31	1,166	6.54	151.7
Total hydrocarbons measured	4.92	12,037	4.60	7,792	16.56	4,609	5.57	1,178	10.94	154.6
Total hydrocarbons present (IR analysis)		19,800		10,400		8,700		6,300		141

NOTE: Hydrocarbon concentrations in the oils are given as percent (g/100 ml.) and in the WSFs as parts per billion (µg/l.) in 20 o/oo seawater.

^a30 o/oo seawater in a flowing system.

^bIndividual n-paraffin concentrations were very low.

^cNot measured.

^dTotal of several isomers.

SOURCE: J.W. Anderson et al. (1974), R.D. Anderson (1975), and Dean et al. (1980).

consist of other than the oil from the original Sadlerochit formation:

Alaska North Slope production has recently been running at the rate of 1/6 million b/d. Almost all of this is vintage North Slope crude from the original discovery formation, the Sadlerochit. However, Kuparuk, a new crude stream of different quality, is blended with the North Slope at a rate of some 120,000 b/d at Trans Alaska Pipeline's pump station No. 1 in the Alaskan Arctic. At this rate Kuparuk hardly has a discernible effect on the North Slope stream from the refinery perspective, according to some operators. But the contribution of Kuparuk is scheduled to double by early 1985. ... Farther down the road another possible contributor to the North Slope stream is crude oil from the West Sak River sand, also in the Prudhoe Bay/Kuparuk area (Aalund 1983, p. 71).

This blending of oils from other formations may result in some modest changes in chemical composition, so we suggest using the term "Alaskan North Slope Crude" (ANSC) to distinguish current crude composition from that of the original pure Prudhoe Bay crude. Legal obstacles have tied up all data on composition of oil aboard the Exxon Valdez, and we know of no recent analyses. Although some more current chemical analyses of the actual 'typical' ANSC being delivered during the 1990s are desirable and should be encouraged, they are not mandatory before establishing an initial compensation schedule for unquantifiable damages.

Toxicity Relationships for the Washington Compensation Schedule: Overview

Leschine and Rubin (1989) outlined a general approach for scoring the relative propensity of an oil spill to cause environmental harm. The suggested approach was based on consideration of environmental sensitivity, oil toxicity,

resource values, and "the state of nature" at the time the spill occurred. To make such an approach consistent with the findings of oil spill fate and effects research, they suggested that several distinct categories of potential harm should be considered separately. Then the relative severity of effects in each category can be estimated, and the results combined to give a qualitative estimate of the spill's overall impact on the environment. This is the approach we develop in this report. A review of the literature on laboratory and field studies of marine oil spills suggests that as many as seven different types of adverse environmental effects could be considered (Table 4).

Table 4. Categories of Potential Injury for Oil Spills in the Marine Environment (adapted from Leschine and Rubin 1989)

Potential biological harms:

- mechanical toxicity (smothering, coating of wildlife)
- acute chemical toxicity
- persistence (proxy for chronic toxicity)
- tainting of marine food organisms
- bioaccumulation and biomagnification
- chemoreception interference

Potential non-living resource harm:

- fouling (shorelines, fixed structures, boat hulls, etc.)
-

The Washington Compensation Schedule (as proposed below) deals explicitly with three of the oil spill-related phenomena listed in Table 4: acute chemical toxicity, mechanical toxicity and persistence.

In modeling the relative importance of each of these three effects we have tried to identify, where feasible, those underlying physical and chemical characteristics which, other things being equal, appear to account best for differences among petroleum products in their relative propensities to cause each type of harm. These characteristics are treated in a way which allows us to locate specific petroleum product types of importance to commerce in Washington on a series of numerical scales, corresponding to each type of harm. When adjusted on the basis of habitat-related considerations and combined with environmental sensitivity measures, these scale values allow us to score, on a unit-of-discharge basis, particular spills with respect to the (unquantifiable) environmental harm they are likely to cause, as directed by RCW 90.48.366. The details are developed in subsequent sections of this document.

Categories of Injury not Considered

Because the mechanisms of shoreline fouling and mechanical toxicity appear to be similar, and because the potential for fouling also appears to be related to persistence, we do not develop any specific chemical or physical properties of petroleum products specific to their fouling potential. But relative habitat vulnerabilities are used to distinguish between

mechanical toxicity occurring on the sea surface and that which could occur along shorelines or in subtidal areas.

Other factors not treated explicitly are bioaccumulation and biomagnification, chemoreception interference and the tainting of marine food organisms. Scientists in recent years have grown more aware of the importance of chemical signals used by some marine organisms to locate food and/or mates, and to avoid predators (the phenomenon called 'chemoreception'). Concern has been raised that oil spills might interfere with salmon's ability to use these subtle chemical signals to return to their spawning streams. A series of studies on chinook salmon homing in fresh water and coho salmon homing in marine waters have been carried out, to determine whether or not short-term exposure to crude oil has any deleterious effect on homing success. The studies are summarized by McAuliffe (1987). The adult salmon showed a tendency to avoid the oil, and scientists noted no significant differences in percent return or return times between controls, oil, dispersed oil, or dispersant-treated groups of fish after forced exposure for short times at relatively high oil concentrations.

The tainting of marine food organisms following an oil spill is expected to be closely monitored by food and health agencies. Any losses of food resources due to tainting can be included in quantifiable damages, and so will not be considered in developing this compensation schedule for unquantifiable damages. In a similar vein, many higher trophic level marine organisms have shown the ability to biodegrade hydrocarbons rather rapidly (NAS,

1985), thus limiting possible biomagnification of the hydrocarbons. Lower trophic level organisms with little if any ability to degrade hydrocarbons, such as shellfish, may evidence biomagnification of concentrations. In such cases, noticeable tainting seems likely, and loss of the resource would then be included under quantifiable damages.

III. Procedures for Scoring Petroleum Products

In this section we present the numerical relationships we have developed to score the propensity of oils to cause acute or mechanical toxic effects, or to persist in the environment when spilled into marine waters.

Formula for Relative Acute Chemical Toxicity

The literature review we conducted (summarized in Sec. IV below) suggests that relative differences in the acute chemical toxicity of different crude oils and petroleum products are best explained by 1) differences in their contents of 1-, 2- and 3-ring aromatic hydrocarbon compounds; 2) apparent differences in the absolute toxicities of these classes of compounds; and 3) differences in the solubilities in seawater among these compounds. Since the empirical studies cited rely on direct exposure of test organisms to water soluble fractions (WSFs) of the oils, it appears reasonable to assume as a first approximation that the absolute toxicities of 1-, 2- and 3-ring aromatic fractions are the same, and that relative differences in observed toxicities of the parent oils are explained by relative differences in their aromatic contents and in the aqueous

solubilities of these aromatic compounds. These assumptions lead directly to the computation of relative scores for acute toxicity for the parent PBC and for each of the four petroleum product classes identified earlier.

The approach we take involves calculating the weighted average of the portions of whole oil composed of 1-, 2- and 3-ring aromatic compounds (percent-weight), with weighting defined by aqueous solubility. That is, letting

SOL_i = solubility in seawater of i-ring aromatic hydrocarbons,

and

$PCT-WT_i$ = percent-weight of i-ring aromatic hydrocarbons in crude oil or refined product, $i = 1, 2, 3$,

then

$$(1) \text{ Relative Acute Toxicity} = SOL_1 \cdot PCT-WT_1 + SOL_2 \cdot PCT-WT_2 + SOL_3 \cdot PCT-WT_3.$$

The rationale for this approach is captured in a general way in the National Academy's 1985 report:

The simplest aromatic compounds are...among the most toxic compounds of crude and refined oil, and as they are also the most soluble, their impact on the marine environment is greater than simple mass balance considerations would imply (NAS 1985, p. 278).

Following the findings of the numerous laboratory studies reviewed, solubility in seawater appears to be the most appropriate factor to apply in modifying the mass-balance relationship among aromatic compounds, given the objective of reflecting relative differences in observed acute toxicity.

Aqueous Solubility. The relationship between aqueous solubility and number of carbon atoms in hydrocarbon compounds is

well-illustrated in Fig. 2, from McAuliffe (1987). In general, the solubilities of individual compounds will vary with temperature, salinity and organic matter content of the waters in which they are dissolved. Mackay et al. (1983) note furthermore that seawater solubility will generally be 70-80% of freshwater solubility. The values for the solubility of particular aromatic hydrocarbons which we apply in calculations based on formula (1) [see Table 5] are those of McAuliffe (1987; see Fig. 2).

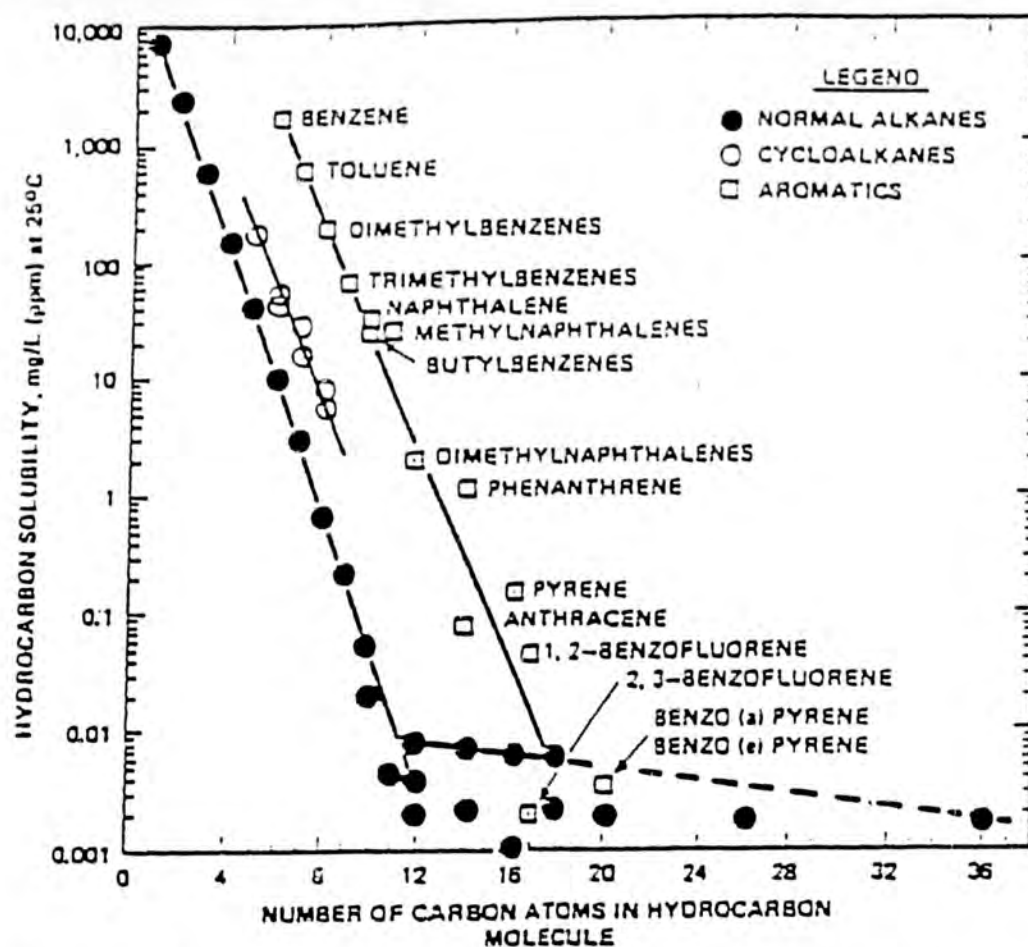


FIGURE 2 Solubilities of normal alkane, cycloalkane, and aromatic hydrocarbons in water (data from McAuliffe, Baker, Wauchope and Getzen, Sutton and Calder, Button, Eganhouse and Calder, Price, Schwartz and Wasik, and Mackay and Shiu).

SOURCE: McAuliffe (1987)

Table 5. Aqueous Solubilities (mg/L at 25°C) for Key Constituents of Lower Molecular Weight Aromatic Hydrocarbons Found in Petroleum Products [source: McAuliffe 1987, Fig. 1]

<u>Aromatic Hydrocarbon Type</u>	<u>Aqueous Solubility (mg/L)</u>	<u>Vapor Pressure¹ (atm @ 25°C)</u>
Monoaromatics		
benzene	1,100	.125
toluene	500	.374
Diaromatics		
naphthalene	30	.0001
Triaromatics		
phenanthrene	1.2	9×10^{-7}
4-Ring Compounds		
pyrene	<.2	-

¹ Values taken from U.S. DOI 1987, Vol. II, Appendix C.

The value for pyrene is reported to underscore the rapid diminution which solubilities undergo as molecular weight increases. Although higher molecular weight compounds may also be highly toxic in an absolute sense, they are not likely to be present in high concentrations in water soluble fractions due to their low solubilities. Because compounds which are highly soluble are also highly volatile (see Table 5), under most conditions the acute toxic effects of concern are likely to be of importance for time periods ranging from only hours to days. They also may tend to be highly localized in that actual concentrations of dissolved hydrocarbons under oil slicks in open waters (and away from the slick interface) are likely to be quite low (McAuliffe 1987).

Aromatic Hydrocarbon Content. Aromatic hydrocarbon contents of PBC, Bunker C, and no. 2 fuel oils are reported by Clark and Brown (1977) (see Table 6). Coleman et al. (1984), who conducted chemical assays on the water soluble fractions of gasoline and kerosene, find that extremely high concentrations of lower molecular weight aromatics occur in the WSFs of these products (37 - 95% by weight of compounds in the unleaded gasoline WSF tested, and 99% by weight for the WSF of the kerosene tested). They, like other authors, caution however that the contents of gasolines and kerosenes can be highly variable depending on the raw source, and the degree of processing and blending. Also, the products they tested are unlikely to have been refined from PBC. Finally, it should be noted that gasolines themselves are

Table 6. Physical characteristics and chemical properties of several crude oils

Characteristic or Component	Crude Oil		
	Prudhoe Bay ^a	South Louisiana ^b	Kuwait ^b
API gravity (20°C) (*API)*	27.8	34.5	31.4
Sulfur (wt %)	0.94	0.25	2.44
Nitrogen (wt %)	0.23	0.69	0.14
Nickel (ppm)	10	2.2	7.7
Vanadium (ppm)	20	1.9	28.
Naphtha fraction ^c (wt %)	23.2	18.6	22.7
Paraffins	12.5	8.8	16.2
Naphthenes	7.4	7.7	4.1
Aromatics	3.2	2.1	2.4
Benzenes	0.3 ^d	0.2	0.1
Toluene	0.6	0.4	0.4
C ₈ aromatics	0.5	0.7	0.8
C ₉ aromatics	0.06	0.5	0.6
C ₁₀ aromatics	--	0.2	0.3
C ₁₁ aromatics	--	0.1	0.1
Indans	--	--	0.1
High-boiling fraction ^e (wt %)	76.8	81.4	77.3
Saturates	14.4 ^f	56.3	34.0
n-paraffins	5.8 ^g	5.2	4.7
C ₁₁	0.12	0.06	0.12
C ₁₂	0.25	0.24	0.28
C ₁₃	0.42	0.41	0.38
C ₁₄	0.50	0.56	0.44
C ₁₅	0.44	0.54	0.43
C ₁₆	0.50	0.58	0.45
C ₁₇	0.51	0.59	0.41
C ₁₈	0.47	0.40	0.35
C ₁₉	0.43	0.38	0.33
C ₂₀	0.37	0.28	0.25
C ₂₁	0.32	0.20	0.20
C ₂₂	0.24	0.15	0.17
C ₂₃	0.21	0.16	0.15
C ₂₄	0.20	0.13	0.12
C ₂₅	0.17	0.12	0.10
C ₂₆	0.15	0.09	0.09
C ₂₇	0.10	0.06	0.06
C ₂₈	0.09	0.05	0.06
C ₂₉	0.08	0.05	0.05
C ₃₀	0.08	0.04	0.07
C ₃₁	0.08	0.04	0.06
C ₃₂ plus	0.07	0	0.06
Isoparaffins	--	14.0	13.2
1-ring cycloparaffins	9.9	12.4	6.2
2-ring cycloparaffins	7.7	9.4	4.5

Characteristic or Component	Crude Oil		
	Prudhoe Bay ^a	South Louisiana ^b	Kuwait ^b
3-ring cycloparaffins	5.5	6.8	3.3
4-ring cycloparaffins	5.4	4.8	1.8
5-ring cycloparaffins	--	3.2	0.4
6-ring cycloparaffins	--	1.1	--
Aromatics (wt %)	25.0	16.5	21.9
Benzenes	7.0	3.9	4.8
Indans and tetralins	--	2.4	2.2
Dinaphthenobenzenes	--	2.9	2.0
Naphthalenes	9.9	1.3	0.7
Acenaphthenes	--	1.4	0.9
Phenanthrenes	3.1	0.9	0.3
Acenaphthalenes	--	2.8	1.5
Pyrenes	1.5	--	--
Chrysenes	--	--	0.2
Benzothiophenes	1.7	0.5	5.4
Dibenzothiophenes	1.3	0.4	3.3
Indanothiophenes	--	--	0.6
Polar materials ^h (wt %)	2.9	8.4	17.9
Insolubles ⁱ	1.2	0.2	3.5

NOTE: These analyses represent values for one typical crude oil from each of the geographical regions; variations in composition can be expected for oils produced from different formations or fields within each region.

^aAdapted from Thompson et al. (23) and Coleman et al. (24).

^bFrom Pancirov (25).

^cFraction boiling from 20° to 205°C.

^dReported for fraction boiling from 20° to 150°C.

^eFraction boiling above 205°C.

^fReported for fraction boiling above 220°C.

^gPrudhoe Bay crude oil weathered 2 weeks to duplicate fractional distillation equivalent to approximately 205°C n-paraffin percentages from gas chromatography over the range C₁₁-C₃₂ plus for the Prudhoe Bay crude oil sample only (R. C. Clark, Jr., unpublished manuscript, 1966).

^hPolar materials: clay-gel separation according to ASTM method D-2007 (10; part 24) using pentane on unweathered sample.

ⁱInsolubles: pentane-insoluble materials according to ASTM method D-893 (10; part 23).

*API gravity = 141.5/ (specific gravity at 60°F or 16°C) - 131.5.

SOURCE: R.C. Clark and Brown (1977). Numbers in parentheses in footnotes above are reference numbers in R.C. Clark and Brown (1977).

currently undergoing reformulation as a result of air pollution concerns. As the Western States Petroleum Association noted in a recent publication, "Many of the reformulated gasolines feature lower volatility ... and higher oxygen content [achieved] by adding the oxygenate, methyl tertiary-butyl ether" (WSPA 1990). Lacking better data at this time however, we utilize the values Coleman et al. report in Table 7 below.

Acute Toxicity Scores. The values listed in Tables 5 and 7 lead directly to relative acute toxicity scores for each of the five products listed in Table 7, computed by means of Formula (1) above. These are listed in Table 8 below.

Table 7. Percent Weight Composition of 1-, 2-, 3- and Higher than 3-ring Aromatic Hydrocarbon Compounds in Selected Petroleum Products.

<u>Aromatic hydro- carbon type</u>	<u>PBC¹</u>	<u>Bunker C¹</u>	<u>No. 2 Fuel Oil¹</u>	<u>Gasoline²</u>	<u>Kerosene^{2,3}</u>
Monoaromatics	8.4	6	22.2	48.6	13.7
Diaromatics	10.0	3.3	5.9	1	5.7
Triaromatics	3.1	11.6	-	-	-
Greater than 3-ring	4.5	3.2	.9	-	-

1. Calculated from Tables 4 and 6 of Clark and Brown (1977). Reported values of aromatic contents of some of the products listed vary to some extent from source to source.
2. Taken from Coleman et al. (1984), Table 3.
3. Values for JP-5 jet fuel derived by Sink et al. (1984) in a separate study are similar to those reported for kerosene. But for reasons explained in the test we treat jet fuels as equivalent to gasoline in acute toxicity potential.

Table 8. Relative Scores for Acute Toxicity Based on Product Type.

<u>Product Type</u>	<u>Raw Score</u> ¹
PBC	95.4
Bunker C	67.1
No. 2 Fuel Oil	246.0
Gasoline	534.9
Kerosene	152.4
Kerosene-type Jet Fuel	NA

¹ Calculated from Formula 1 in text and data in Tables 5 and 7.

The scores in Table 8 reflect, on the basis of an empirical theory which is developed in some detail below, expected relative differences in the acute toxicities of different product types. The theory, laid out briefly above, relates expected acute toxicity to the relative abundances of certain classes of compounds in the spilled oil. It is still necessary however to relate these scores to the level of injury from acute toxicity expected to occur following a spill of each type of product, all other things being equal. To do this, we utilize the scale for toxic effects developed by Dethier in a separate study for DOE, with slight modifications:

<u>Habitat Class No.</u> ⁴	<u>Expected Level of Injury</u>
5	Destruction of most or all susceptible organisms in the area affected by the spill
4	Death or significant population decline of a large proportion of the susceptible organisms
3	Death or loss of a moderate proportion of these organisms, or broad sublethal effects
2	Moderate, mostly sublethal effects
1	Little injury
0	Spill of a non-acutely toxic substance (e.g. vegetable oil)

To convert the raw scores in Table 8 to the scale values above, we first associate 0 raw score points with 0 on the scale above. Then, based on the findings of field and laboratory studies noted elsewhere, we assign gasoline (535 points in Table

8) to toxicity class 5. Simiarly, based on the reports of jet fuel spills into Des Moines Creek, Washington discussed below, we assign kerosene-type jet fuel (no raw score) to toxicity class five. The other product types are then assigned to acute toxicity classes on the basis of linear interpolation. The results appear in Table 9.

Table 9. Acute Toxicity Class Assignments for Petroleum Products
(see text for derivation.)

<u>Product Type</u>	<u>Rescaled Value</u>	<u>Class Assignment via Upward Rounding</u> ¹
PBC	.89	1
Bunker C	.63	1
No. 2 fuel Oil	2.30	3
Gasoline	5.00	5
Kerosene	1.42	2
Kerosene-type Jet Fuel	5.00	5

1. For specification of the marine and estuarine habitats associated with each habitat class in relation to their sensitivity to the acute toxic effects of spilled oil see M. Dethier (1990). We assign marine open waters not adjacent to shorelines and without significant bird populations to habitat class 4. The rating is based on effects on planktonic organisms, and was developed in consultation with Dethier.

Scale for Mechanical Toxicity

Following the conclusion of our review of the literature on mechanical toxicity (see below), we use API gravity to scale the five classes of petroleum products with respect to their relative propensity to cause mechanical toxicity to wildlife. Smith (1968) classified more than 7,000 crude oils with respect to their API gravities and other properties. The resulting distribution (Fig. 3) suggests that a scale ranging from 10 to 65 degrees API gravity is sufficient to cover most crude and refined petroleum products likely to be spilled in Washington waters. By this scaling, the lower the API gravity (i.e., the higher the specific gravity), the more likely the product is to cause mechanical toxicity. Representative API gravity values for the five classes of products treated in this report are presented in Table 10.

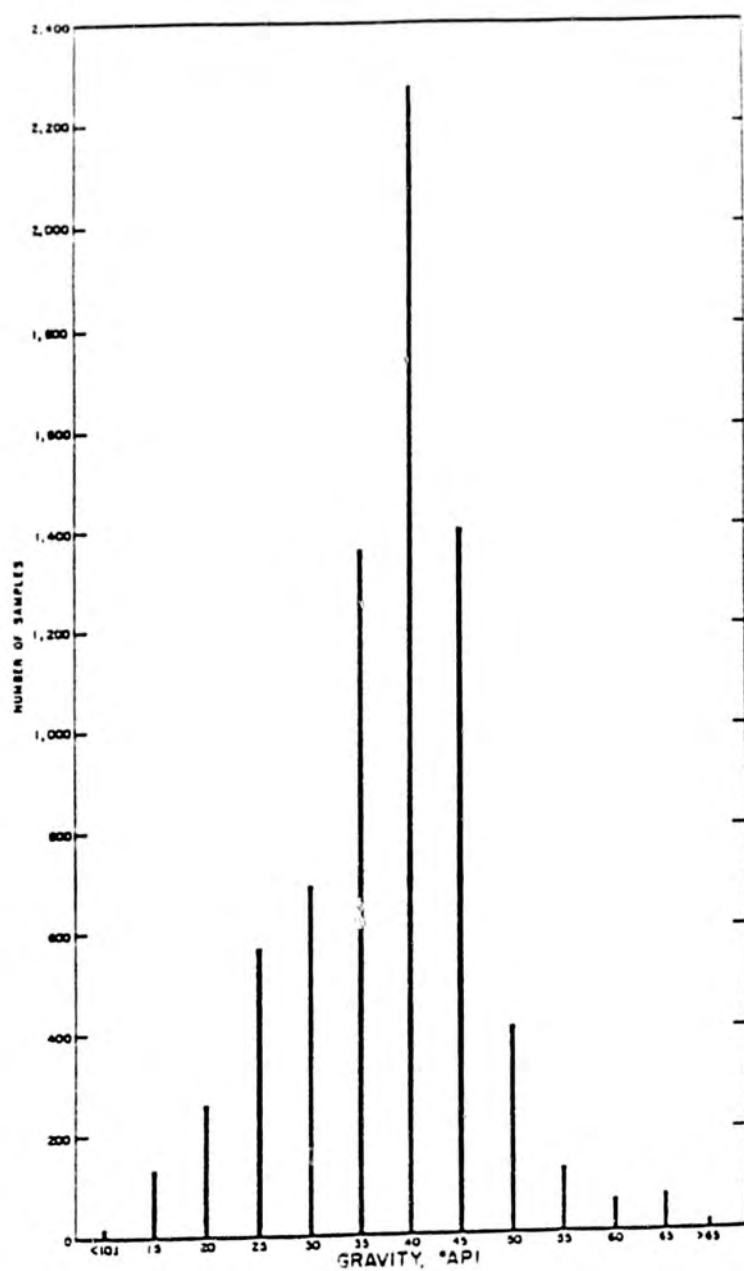


FIGURE 3 Frequency Distribution of API Gravity of Crude Oils (7,386 samples).

SOURCE: Smith (1968)

Table 10. Representative API Gravities for Petroleum Product Classes Hauled in Washington Waters.

<u>Product</u>	<u>API Gravity</u> ¹
Prudhoe Bay Crude	27.8
Bunker C	13.0
No. 2 fuel oil	31.6
Kerosene	41.5
Gasoline	62.4
Kerosene-type jet fuel	35.8 - 56.7

¹ Values for PBC, no. 2 fuel oil and kerosene from Clark & Brown (1977). Value for Bunker C is an average of four values reported by Bobra (1989). Gasoline value is reported as "typical" for unleaded gas by Bobra, who is also the source for the range of values for jet fuel.

As with acute toxicity, it is still necessary to associate the values in Table 10 with the level of injury from mechanical toxicity which we would expect to result from a spill of each type of oil. This is done by reference to the same five-point scale of injury used for acute toxicity.

As a glance at Table 10 shows, a Bunker C spill would be expected to have the greatest potential (all other things being equal) for mechanical toxicity, while a gasoline spill would be expected to exhibit the least such potential. On the basis of the extreme volatility and very low density of gasoline, we judge spills of gasoline (or still lighter products) to exhibit essentially no mechanical toxicity and assign them to toxicity class 1.

To determine the appropriate assignment for the upper end of the mechanical toxicity scale (i.e., for products with API gravity equal to or lower than that of Bunker C) we make reference to the 1988 Nestucca spill off Grays Harbor, in which some 225,000 gallons of Bunker C oil were spilled. As is well known, sea birds are among the most susceptible of wildlife populations to the effects of mechanical toxicity. Although the actual bird mortalities resulting from the Nestucca spill are as of this writing still subject to some dispute, it is known that nearly 9,000 dead birds were recovered. This number is about one-fourth the number of dead bird recoveries made following the Exxon Valdez crude oil spill, even though the spill was only about 2.5% as large. This justifies a 5 rating for spills of Bunker C or heavier oils in our judgment. Having thus bounded

the ends of the scale, the other class assignments can then be determined by linear interpolation (see Table 11).

Table 11. Mechanical Toxicity Class Assignments for Petroleum Products

<u>Product Type</u>	<u>Rescaled Value</u> ¹	<u>Class Assignment</u> via <u>Upward Rounding</u> ³
PBC	3.56	4
Bunker C	5	5
No. 2 fuel Oil	3.24	4
Kerosene	2.44	3
Gasoline	1	1
Kerosene-type jet fuel	2.44 ²	3

1. Values calculated by a two-step process. First degrees API were converted to specific gravity (S.G.) via the formula $^{\circ}\text{API} = 141.5/\text{S.G.} - 131.5$. Then linear interpolation was used to rescale results to a 1-5 scale.
2. The API gravity value for kerosene is taken as a representative value for kerosene-type jet fuel.
3. For specification of the marine and estuarine habitats associated with each habitat class in relation to their sensitivity to the mechanical effects associated with spilled oil see M. Dethier (1990). We assign marine open waters not adjacent to shorelines and without significant bird populations to habitat class 3, in consultation with Dethier. Definitions of scale values appear in the text.

Persistence Scale: Overview

We reviewed available data on the persistence of several types of oil products spilled around the Washington coast and the literature on the persistence of the main oil product types transported around Washington when spilled in other temperate coastal regions (see below). We propose a scale for persistence which ranges from a few hours to a few days for gasolines, kerosenes and jet fuels, to several months to several years (ultimately to more than a decade) for no. 2 fuel oils, for Alaskan North Slope crude oil, and for residual, heavy, Bunker C or no. 5 and no. 6 fuel oils (see Figure 4). For the products heavier than jet fuels, interaction with sediments becomes important; for this reason we develop multiple ranges of persistence to account for different habitat types. At the minimum, one could have two ranges of persistence, a shorter range for open, exposed, high energy rocky coastal areas and a longer range for more protected, low energy fine sediment areas like bays and marshes. Use of the information developed by M. Dethier on differences in the propensity for oil to persist in relation to habitat type makes it feasible to distinguish among five different ranges of persistence on the basis of habitat type.

Unlike the treatment we accorded to chemical and mechanical toxicity above, we utilize a purely judgmental approach to generate a numerical scale to represent relative differences in oil persistence. Limitations in available data do not permit us to focus on specific classes of compounds present in oils and to

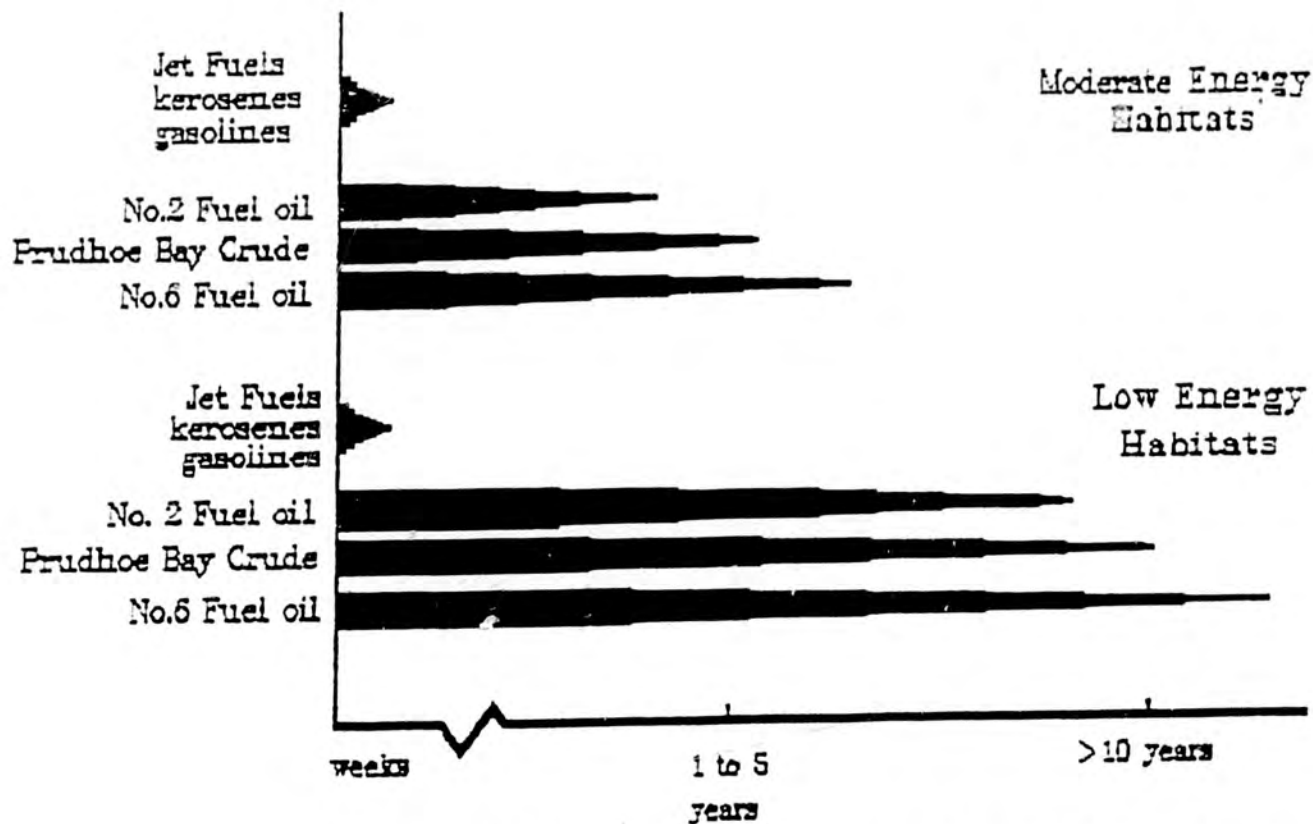


FIGURE 4 Schematic Representation of Spilled Oil Persistence

base the scaling on the relative abundances of these compounds in parent oils and in refined petroleum products, as we did for acute toxicity. While the heavier weight aromatic and aliphatic compounds, with their correspondingly low solubilities and vapor pressures, are found in post-spill studies to be the compounds which persist longest in the environment, analytical difficulties hamper accurate characterization of their abundance in whole oils. Such data as we have been able to glean from published analyses are suggestive of the general relationships among oils in their tendencies to persist as indicated by our review, but are neither complete nor definitive enough to justify their use in numerical scaling.

Clark and Brown (1977) provide a breakdown of the heavier weight chemical constituents in the oil types most likely to persist in the environment following spills (represented in our classification scheme by PBC, no. 2 fuel oil, and Bunker C). Other literature we reviewed suggests that the most persistent hydrocarbon compounds will be the aromatics with 3 or more rings, the straight-chain n-paraffins in the C₂₂ and greater range (Clark et al. 1978), the branched non n-alkane compounds in the C₂₅ and greater range (Cretney et al. 1978), and such non-aromatic compounds as the cycloparaffins of 3 or more rings. As a general rule, cyclic and branched compounds could be expected to persist longer than straight-chain compounds and aromatics would be expected to persist longer than aliphatics.

A partial listing of persistent hydrocarbon compounds found in PBC, no. 2 fuel oil and Bunker C is presented for illustrative

purposes in Table 12. But a great many nitrogen, sulfur, oxygen and other non-hydrocarbon compounds not shown here are also found in oil (Clark and Brown [1977] and NAS [1985]), many of which are also quite persistent. We note that the ordering implied in Table 12: no. 2 fuel oil, PBC, Bunker C, in order of increasing propensity to persist in the environment, is nevertheless consistent with that suggested by the literature review, presented in Sec. IV below.

Table 12. Percent-Weight Composition in Oils of Some Higher Molecular Weight Compounds Likely to Persist in the Marine Environment (Source: Clark and Brown, 1977)

<u>Hydrocarbon Compound Type</u>	<u>No. 2 Fuel Oil</u>	<u>PBC</u>	<u>Bunker C</u>
3-ring and greater aromatics	0.9	7.6	14.8
C ₂₂ and greater n-paraffins	0	1.47	0.65
3-ring and greater cyclo- paraffins	4.5	10.9	7.9
TOTAL	5.4	19.97	23.35

Scale for Persistence. In order to account for the effects of habitat type in determining the relative propensity of oils to persist in the marine environment, we again utilize Dethier's classification scheme for the marine and estuarine habitats of Washington. In addition to providing the toxicity ratings utilized above, she also sorts the 35 habitat types she describes into five classes on the basis of their propensity to retain oil once it enters as the result of a spill. Dethier defines these classes by their expected oil retention time (assuming an undefined mixed-cargo spill) as follows:

<u>Habitat Class No.</u>	<u>Expected Oil Retention Time</u>
5	more than 10 years
4	5 - 10 years
3	1 - 5 years
2	1 month to 1 year
1	days to weeks

The extremes in this classification are represented by an exposed sandy beach (the only habitat type in Dethier's class no. 1), where no oil would be expected to persist beyond a few weeks, and protected mudflats, muddy bays, deep subtidal muds, estuarine lagoons and the other habitat types grouped into Dethier's class no. 5, where highly persistent oils would be expected to persist for more than 10 years. Generally speaking, it is the habitat energy regime that defines the differences among these classes, which are taken to be independent of the type of oil spilled.

In order to integrate this numerically scaled information on habitat-specific differences in the propensity to retain oil with qualitative information on relative differences in the propensity of different petroleum products to persist in the environment, it is necessary to scale the latter information as well. To do this we define a second, habitat-independent scale for oil persistence as follows:

Associated Persistence Time Under
the Most Scale Value Unfavorable
Environmental Circumstances

5	more than 10 years
4	5 - 10 years
3	1 - 5 years
2	1 month to 1 year
1	days to weeks

Using this scale, we can now assign numerical values to each petroleum product class on the basis of its habitat-independent propensity to persist in the environment once spilled:

<u>Oil Type</u>	<u>Points for Persistence</u>
gasoline, kerosene, jet fuel	1
no. 2 fuel oil	2
PBC	5
Bunker C	5

The two 1-5 scales, and the rules we use in combining the scales in Table 13, are intended basically to reflect the following assumptions:

- 1) The very low persistence of gasoline, kerosene and jet fuel is unaffected by habitat type;
- 2) On exposed sandy beaches (habitat class 1) the persistence of all oils is on the order of days to weeks, with gasoline persisting for perhaps only hours, and with PBC and Bunker C persisting for weeks.
- 3) In all but the most energetic environments, no. 2 fuel oil is less persistent than PBC, which is in turn less persistent than Bunker C. PBC is more like Bunker C in persistence than no. 2 fuel oil is like PBC; and
- 4) When persistence is determined by the interaction between habitat type and oil type (habitat classes 2-5 and oil types PBC, no. 2 fuel and Bunker C) the significance of persistence for any oil type increases as a multiple of habitat class.

The process of combining the habitat-dependent scores with the oil type-dependent (and habitat-independent) scores is basically one of multiplication, with the exception of the circumstances described in Assumption 1 (for oils in the lowest habitat-independent persistence class) and Assumption 2 (for habitats in the lowest persistence class). See Table 13.

Table 13. Scale Values for Persistence of Oils in Various Marine and Estuarine habitat types.

<u>Habitat Class</u> ¹	<u>OIL TYPE</u>			
	Gasoline, Kerosene jet fuel	No. 2 fuel oil	PBC	Bunker C
1	1	1	1	1
2	1	4	10	10
3	1	6	15	15
4	1	8	20	20
5	1	10	25	25

¹ For specification of the marine and estuarine habitat types associated with each class in relation to their tendencies to retain oil within them, see M. Dethier (1990). Open water areas not adjacent to shorelines are assigned to habitat class 1.

A Note on Combining Toxicity Scores with Other Resource Values

Three types of detrimental effects associated with oil spills -- acute and mechanical toxicity and persistence -- have now been subjected to numerical scaling intended to represent differences in the degree of each effect observed in the field and in laboratory studies. The result permits differentiation among petroleum products with respect to their potential to cause acute or mechanical toxic effects, and differentiation among combinations of petroleum products and habitat types with respect to the tendency for particular petroleum products to persist in particular habitat types once spilled.

Before the goals outlined by the legislation can be met, these results must be combined with the results of other efforts underway within or under sponsorship of DOE to attach similarly scaled values to the marine and estuarine resources of Washington which are sensitive to oil spill damage.

We have already alluded to the work of M. Dethier, which was used extensively in the development of the persistence ratings. Dethier's work also includes other measures not utilized in the present analysis, such as habitat sensitivity to acute and mechanical toxicity and ratings of habitat types on the basis of such factors as their primary and secondary productivity support value. In addition, DOE personnel are now developing a number of indicators of the value of various zones within the state with respect to the support they provide for marine birds and mammals, fin and shell fisheries, recreation, and other resources.

While the final formula for assigning an overall score to a spill could have many possible forms, the idea underlying this work is basically that of extending the approach taken in developing the persistence scores above to other elements of this ongoing work. In essence, a score for 'persistence potential' of the oil spilled (on a 1-5 scale) is multiplied by a score representing the propensity of oil to persist in the habitat type in which the spill occurs (also on a 1-5 scale). The resulting scores range in theory from a low value of 1 to a high value of 25.

The suggested extension of this approach is to multiply scaled resource values in each class (on 1-5 scales) by the value representing the type of toxicity which most affects each resource type. Thus fishery values (on 1-5 scales) would be multiplied by acute toxicity scores, while marine mammal and bird values (also on 1-5 scales) would be multiplied by mechanical toxicity scores. The results would then be added across categories⁵. Situations where multiple habitat types were affected or where resources were thought to be sensitive to both types of toxic effects could be handled by appropriate averaging or by allocation of the total spill volume.

To illustrate, a simple hypothetical example is presented. It includes a proposed method for translating the final scores into the dollars-per-gallon scale required by the legislation. The final transformation to dollars involves linear scaling, but there is no a priori reason why this last step should follow a linear model. The underlying value function should represent the

underlying value society places on avoiding spills of increasing severity on a per-gallon basis⁶. A variety of non-linear forms could be utilized, including logarithmic exponential, or logistic forms.

EXAMPLE:

- 1) Crude oil is spilled in zone X during season Y.
- 2) It affects a single habitat type H, which has the following sensitivities (after Dethier):

	<u>Classification</u>
Propensity of oil to persist	3
Propensity for acute toxic effects	4
Propensity for mechanical effects	5

- 3) In zone X during season Y, the resource values are (after DOE):

Birds	5
Fisheries	3
Marine mammals	4
Recreation	2

- 4) The crude oil spilled is rated as follows (after this document):

Acute toxicity potential	1
Mechanical toxicity potential	4
Persistence potential	5

To score the spill, we assume that birds, mammals and recreation are affected primarily by mechanical toxic effects, while fisheries are affected primarily by acute toxicity. The score for the spill is then computed as

$$\text{SCORE} = [\text{BIRD VALUE} + \text{MAMMAL VALUE} + \text{RECREATION VALUE} + \text{HABITAT MECH INJURY POT'L}] * \text{MECH TOX POT'L} + [\text{FISH VALUE} + \text{HABITAT ACUTE TOX INJURY POT'L}] * \text{ACUTE TOX POT'L} + \text{PERSIST POT'L} * \text{PERSIST}$$

PROPENSITY =

$$[5+4+2+5]*4 + [3 + 4]*1 + 5*3 = 86 \text{ points.}$$

In theory, the spill could have scored as few points as 7 points (all values set to 1) or as many as 175 points (all values set to 5). Using a linear transformation which maps 7 points to \$1/gallon and maps 175 points to \$50/gallon, we can calculate that this spill would cost out at about \$24/gallon.

IV. Potential Injury to Marine Environments Associated with Oil Spills: A Review of the Literature

In this section we review the literature on harmful effects associated with oil spills, as background to the scoring systems developed above for dealing with these effects in the Washington Compensation schedule.

Acute Chemical Toxicity

Toxicities of various crude oils and refined products to marine organisms have been examined in numerous laboratory and field studies. The literature is reviewed by Neff (1979); Rice et al. (1979); Neff and Anderson (1981); National Academy of Sciences (NAS 1985); McAuliffe (1987) and Anderson et al. (1987). Our sense of the voluminous literature which has been devoted to documenting the acute toxic effects of oil is that a reasonable scientific consensus has been reached supporting the summary of Anderson et al. (1987) who state:

Indirect evidence from a number of sources strongly indicate that the single class of compounds producing mortality at the lowest concentration is the diaromatics referred to as naphthalenes. Phenanthrenes (triaromatics) are equally toxic, but much lower concentrations are found in water extracts or mixtures of dispersed oil (water phase). While

monoaromatics have been shown to be less toxic than naphthalenes, they are found at much higher concentrations in fresh crude oils and their WSF. Therefore, the compounds likely to produce most of the toxicity when oil is mixed with water are the mono and diaromatics (Anderson et al. 1987, p. 235).

This summary is similar to that of the 1985 NAS report:

Toxic effects from petroleum exposure vary widely and for reasons that are not well understood. Certainly these have to do with the complexity of its chemical composition, with different products or even crude oils differing markedly in their chemical makeup. Another factor is the variability in sensitivity to oil found among marine organisms, differing not only with the species (Figure 5-1; [included here as Fig. 5] but even for life-cycle stages (Figure 5-2). While it is generally true that the younger stages of organisms are more sensitive to petroleum hydrocarbons, there are exceptions. Unfortunately, not many studies have compared the sensitivity of organisms at various life stages under identical experimental conditions for any one species.

While the absolute toxicity of petroleum hydrocarbons appears to be greater for the higher-molecular-weight compounds (for example, 3- and 4-ring aromatics), most of the toxic effect of petroleum in water is thought to be due to the lower-molecular-weight (C_{12} - C_{24}) n-paraffin compounds and to the monoaromatic fraction, for the simple reason that these compounds are the most water-soluble (Chapter 3, Table 3-4; [included here as Table 3]). From examinations of the concentrations present in water-soluble fractions (WSF), it is clear that the contribution of compounds higher in molecular weight than the alkylnaphthalenes is very small and may be insignificant in terms of producing acute toxicity (NAS 1985, p. 372).

We propose that, if data from field or lab studies of toxicities of Prudhoe Bay crude and products derived from it are not available, predictions or rankings of expected toxicities should be made based on estimates or measurements of the concentrations of one-, two- and three-ringed aromatic hydrocarbons present in each product.

Despite the importance of tanker shipments of Prudhoe Bay crude oil, we note that the toxic effects data listed for it in

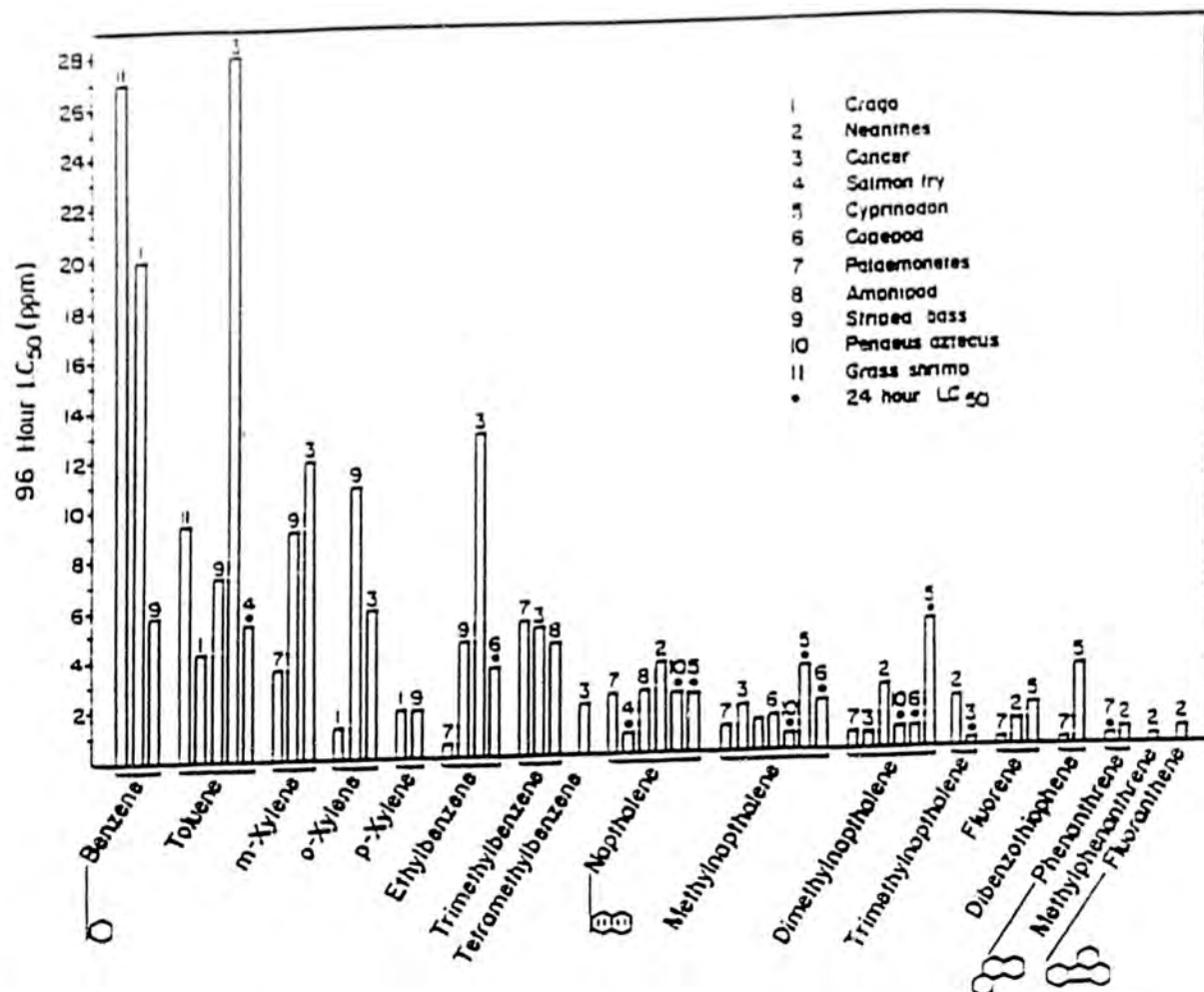


FIGURE 5 Acute toxicity (24- and 96-hour LC_{50} static tests) of some aromatic hydrocarbons for selected marine macro-invertebrates and fish

SOURCES: Caldwell et al. (1977), Benville and Korn (1977), Neff et al. (1976), R.E. Thomas and Rice (1979), Young (1977), Rossi and Neff (1978), Ott et al. (1978), and W.Y. Lee and Nicol (1978).

the CERCLA "Type A" damage assessment procedures are actually data measured by Rice et al. (1979) for the response of 39 species of Alaskan marine organisms to Cook Inlet Alaskan crude oil, which has lower aromatic content (Table 2). Data on the toxicity of PBC to Pacific Northwest organisms from studies following the Exxon Valdez spill have been tied up in legal proceedings and are unlikely to be available to the public for several more years.

Toxicities of Prudhoe Bay crude oil to a variety of marine species have been determined previously under laboratory conditions. Pearson et al. (1985) studied the effect of PBC and chemically dispersed oil on Pacific herring egg fertilization, hatching and larval abnormalities. Anderson et al. (1987) determined the relative toxicities of fresh PBC and dispersed PBC oil fractions to the shrimp Pandalus danae and the fish Ammodytes hexapterus (sand lance). McAuliffe (1987) summarizes many API-sponsored bioassays and behavioral studies of effects of PBC or fractions of it on a variety of marine organisms. Particular attention was paid to possible effects on salmon species.

A number of studies report the toxicities of water soluble fractions (WSF) of PBC (or ANS) to a variety of marine organisms. We know of no studies of toxicities of WSFs of any refined petroleum products derived from the PBC. There are several reasons for using the WSF instead of a crude oil itself. Operationally, studies are easier to reproduce when one is not contending with variable losses of oil itself to container walls, with variable extents of emulsions/droplets/supersaturations,

etc. Second, toxicities of oil components are related to their water solubilities -- due at least in part to the fact that marine organisms have large quantities of water passing over their gills and other vulnerable surfaces. Also, the high lipid/water partition coefficients of hydrocarbons favor rapid hydrocarbon transport from the aqueous phase into lipid rich components like the biological membranes or other lipid pools in organisms. It is therefore generally believed that the dissolved hydrocarbons cause immediate toxic effects on marine and fresh water organisms (McAuliffe 1987).

Non-experts must realize however that hydrocarbon concentrations in WSFs depend upon how the WSF was produced--in static or flow-through systems, by what degree of mixing, etc. So, comparison of hydrocarbon contents of WSFs prepared in different studies are usually not valid. As Neff and Anderson (1981) note:

It should be recognized that the WSF is a purely artificial mixture and is not meant to precisely simulate the conditions of hydrocarbon composition and concentration in the water column under oil spilled in the marine environment. Equilibration conditions in nature are quite different from those used to produce the WSF. The WSF represents a compromise. It is a means of generating a highly reproducible oil-in-water mixture and therefore is extremely useful for comparing the relative toxicity of different crude and refined petroleum to marine organisms. (Neff and Anderson 1981, p. 17).

It must be noted further that recent studies have suggested that water column toxicity per se, particularly for crude oil spills in the open ocean, is unlikely to be as important as sediment (acute) toxicity and, when oil comes into direct contact with seabirds, marine mammals or other vulnerable organisms, the

effects of mechanical toxicity. Table 3 (from McAuliffe 1987) shows for example that actual hydrocarbon concentrations under oil slicks tend to be several orders of magnitude lower than the LC_{50} s for the organisms tested in laboratory studies. But acute toxic effects wherever and whenever they occur are likely to be mediated by the same underlying factors, and as Rice et al. (1979) note, concentrations can increase dramatically in semi-enclosed environments and in waters at the slick interface.

Prudhoe Bay Crude. Table 2 shows that water soluble fractions of North Slope Alaskan crude oils contain several times higher amounts of benzenes, toluene and dimethyl benzenes than WSFs of five other crude oils. Table 6 (from Clark & Brown 1977) shows that the PBC has several times higher concentrations of benzenes, naphthalenes & phenanthrenes as do the API South Louisiana and Kuwait reference crude oils.

Data given in Malins and Hodgins (1981, p. 1277) showed flatfish sand sole embryos and larvae developed high percentages of abnormalities when exposed to fresh and weathered PBC in various ways at concentrations of several hundred ppb. Results of other exposures of PBC to marine organisms are given by Anderson et al. (1987) and by McAuliffe (1987).

The relatively high total and 1- and 2-ring aromatic hydrocarbons and high sulfur contents plus exposure tests lead us to rule out a low toxicity ranking for PBC. Most probably a medium-range ranking is appropriate.

Gasoline, Kerosene and Jet Fuel. Quantitative information linking gasoline toxicity to marine organisms to underlying product compositional characteristics appears to be generally lacking. The Alaskan Penalty Table (See Appendix I) lists gasoline, kerosene and several common jet fuels as highly toxic. The National Contingency Plan does not list gasoline but does accord kerosene and benzene its highest toxicity rating. The CERCLA Type A model appendices (U.S. DOI 1987, Vol. II) assign identical toxicities to all petroleum products however, based on Rice et al.'s studies of Cook Inlet crude oil. Clark and Brown (1987; p. 23) describe the gasoline fraction from PBC as composed of 15.9% aromatics and 36.8% naphthenes (percent volume).

In November of 1985 and again in April of 1986, Des Moines Creek, which flows into Puget Sound, experienced jet fuel spills causing serious fish kills. On November 28, 1985 a 31,000 gallon discharge of Jet A fuel from the Olympic Pipeline Company facility killed all of the salmon and trout in Des Moines Creek from the discharge site to the mouth of the creek - 2.5 miles (Kittle 1986). On April 6, 1986 7,000-8,000 gallons of Jet A fuel were discharged from the Northwest Orient Airlines fuel farm near the headwaters of Des Moines Creek. The damage assessment indicated that all the salmon and trout in the creek were killed for a distance of 3 miles downstream from the discharge (Kittle and LeVander, 1986). These spills support a high toxicity rating for jet fuels.

Distillate Fuel Oils (taken as equivalent to no. 2 fuel oils).

The Alaskan penalty table gives this category of oil products the highest toxicity -- 1.0 on scale of 0.25 to 1.0. Rice et al. (1979), in the extensive study whose data form the basis for numbers in the CERCLA Type A model tables, found no. 2 fuel oil to be consistently more toxic to a variety of marine organisms than Cook Inlet crude oil (although the particular no. 2 tested was probably not derived from Cook Inlet crude). Rice et al. say "Observed toxicity of the no. 2 fuel oil was probably caused by small concentrations of highly toxic di-aromatic hydrocarbons."

Neff and Anderson (1981; p. 20) showed that the total naphthalenes and toxicity of the water soluble fraction of four API oils both decreased in order: no. 2 fuel oil, Bunker C residual oil, South Louisiana crude oil and Kuwait crude oil.

Table 6 (from Clark & Brown 1977) shows the initial PBC to be high in content of 2- and 3-ring aromatics compared to API South Louisiana and Kuwait crudes, and Table 3 (from McAuliffe 1987) shows that the water soluble fraction of PBC contains more aromatics than WSFs of five other crudes. We would therefore expect no. 2 fuels derived from PBC to be relatively high in both aromatics and toxicity. We know of no data on toxicity of No. 2 fuel oils derived from PBC, but the detailed compositional data of Coleman et al. (1973) show that distillation cuts of PBC in the no. 2 fuel oil boiling range are indeed rather rich in aromatics. A well-documented no. 2 fuel oil spill in Buzzards Bay, Massachusetts proved to be toxic to intertidal organisms for several years (Sanders et al. 1980).

Residual Fuels (no. 6 Fuel Oil, Bunker C, etc.) The Alaskan penalty table assigns this product category a rating of 0.5 on scale of 0.25 to 1.0. There is no ranking in the National Contingency Plan.

We could find no data on chemical composition or biological effects of any residual fuel derived from PBC -- all effects data seem to be from the API Bunker C fuel oil derived from Venezuelan crude (composition given in Clark and Brown 1977) and an apparently different API reference Bunker C whose composition is given on p. 144 of NAS (1985).

Neff and Anderson (1981, p. 20) reported for the four API reference oils that total naphthalene concentrations in WSFs and relative toxicities both decreased in the same order: no. 2 fuel oil, Bunker C residual oil, South Louisiana crude and Kuwait crude.

Table 3 lists concentrations of some n-paraffins and aromatic hydrocarbons in these four reference oils and compares them with concentrations in fresh PBC, but gives no data for composition of any Bunker C derived from PBC. The residual oil composition listed by Coleman et al. (1983) for PBC derived fractions shows the residual to have both high sulfur and naphtheno-aromatic content.

Given that the PBC starting crude is enriched in aromatics vs. other crudes and that the heavier aromatics will be enriched in the residual fuels, we feel the residual fuels derived from

PBC will most likely be at least as toxic as the API Bunker C "standard."

Mechanical Toxicity - Smothering, Coating, etc.

This type of harm to biota is most important for seabirds, certain mammals, and intertidal or subtidal organisms in the aftermath of large spills or when oil enters protected coves and bays.

The importance of mechanical toxicity (principally in the coating of waterfowl, seabirds and marine mammals by oil directly or by oil-water emulsifications) was underscored by the 1989 Exxon Valdez spill. As many as 300,000 seabirds may have perished, along with more than 1,000 sea otters out of a population estimated at 13,000 (Nichols 1990). The potential for significant and costly-to-remove shoreline fouling was also demonstrated by the spill. The biggest single expenditure of the \$2 billion Exxon spent in post-spill response appears to have been the cost of deploying cleanup crews and equipment to deal with the nearly 1,000 miles of oiled shoreline left by the spill.

We propose to use scales for this effect based on API gravity or viscosity of the products spilled, for several reasons:

- (1) API gravity and viscosity are properties routinely specified for all oil products;
- (2) Other properties which affect this sort of harmful action can be at least semi-directly related to these properties (see below); and
- (3) The physical and chemical nature of an oil product changes rapidly in the several days following a spill, with evaporation/dissolution of lighter, more soluble

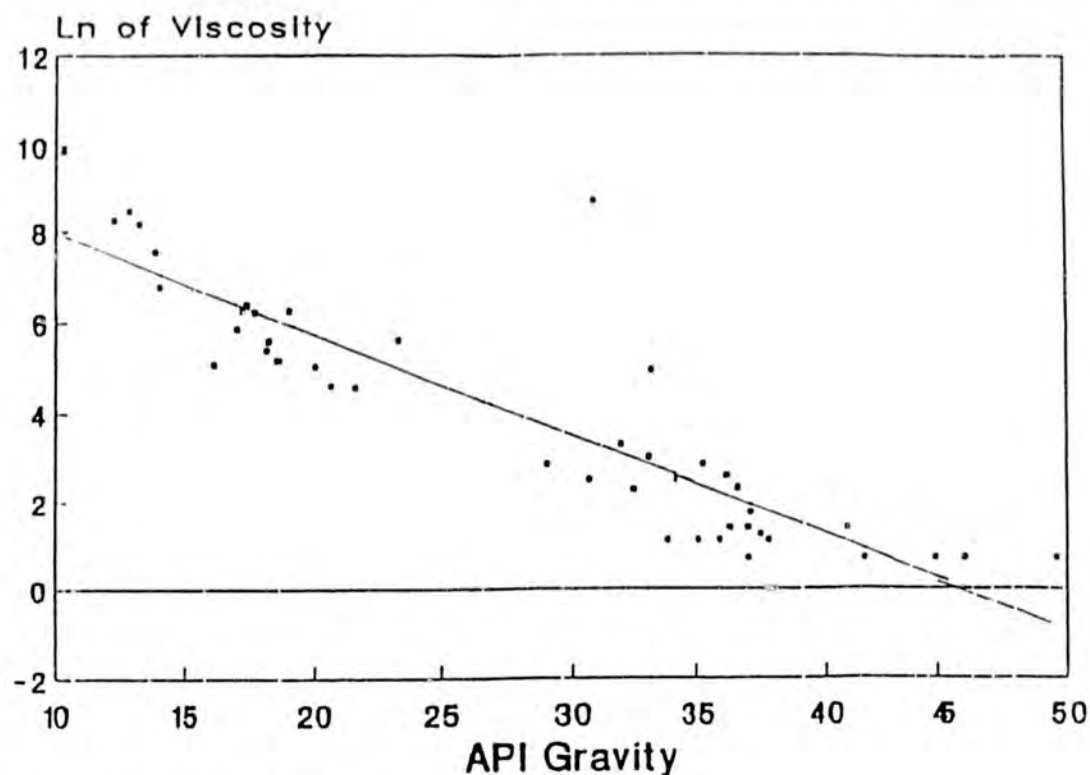
or biodegradable components. These changes with time tend, to first approximation, to affect both viscosity and density in similar ways. For example, loss of lighter, more soluble components tends to increase both viscosity and density of the remaining oil.

Figures 6 and 7 show empirically a relationship between API gravity or density and viscosity of a variety of crude oils and refined products. The API gravity scale definition is such that more dense oils have lower API gravity numbers (around 10), while less dense oil products have larger API gravities (around 60 for gasolines). The corresponding density or specific gravity range is from around 0.7 to somewhat more than 1 gram/cm³ for gasolines to heavy residual fuels -- a range of only 0.5 units.⁷

Surface tension is a property of oils which affects its movement and coating behavior, but is not routinely determined (surface tension of pure water is 75 dynes/cm², while the surface tension of pure benzene is 31.6). However, standard physical chemistry equations show that surface tension is directly proportional to density of the liquid. So, surface tension should increase as API gravity decreases. Jordan and Payne (1980, p. 5) note that the oil spreading coefficient varies inversely with molecular weight. Thus the oil spreading coefficient should vary directly with density and increase with decreasing API gravity. It also seems reasonable to assume that, as a first approximation, oil persistence and propensity to cause mechanical coating and harm would increase with products of increasing viscosity and increase with products of greater density (or smaller API gravity).

FIGURE 6

Oil Viscosity and API Gravity for Crudes with High API Gravity or Pour Pt.

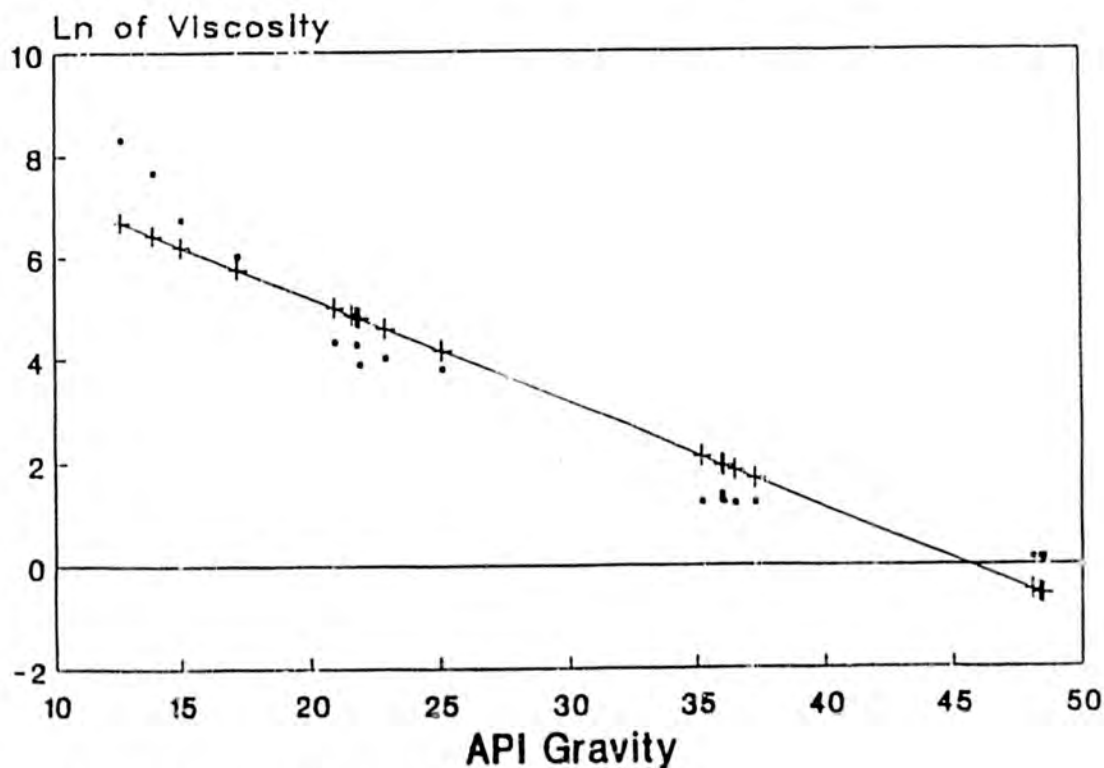


Slope of regression line = -0.22 , $R^2 = 0.79$

SOURCE: Jonathan Rubin

FIGURE 7

Refined Oil Viscosity and API Gravity



Products include: Kerosine, light gas oil, heavy gas oil, and residual. Slope of Regression line = -0.20 , $R^2 = 0.92$

SOURCE: Jonathan Rubin

We therefore suggest using scales based on viscosity and API gravity to rank various oil products as to the mechanical toxicity/physical coating harm they might cause. Such rankings might prove misleading if one were to create, from some unusual combination of feedstocks, products of high viscosity but very short persistence, products of low viscosity but very long persistence, or perhaps products with low API gravity but short persistence. Although this might be possible with unusual oil mixtures, we do not feel it likely for products shipped through Washington waters, which are predominantly derived from reasonably well-defined ANS crude.

Injury to Birds and Mammals. Clear evidence of the harm mechanical coatings can do to a variety of sea birds and mammals comes primarily from dead body counts made along beaches or through aerial surveillance after spills. Legal, ethical and logistical problems will always limit scientists ability to carry out rigorous experiments on how much of what kinds of oils it takes to coat and harm large, active, legally protected creatures like seabirds, sea otters and other mammals. It seems pointless to quibble over details -- the general mechanisms of the harmful effects associated with mechanical coatings are now abundantly clear.

Parmenter (1989) gives an excellent summary of the abundance of different types of sea birds and mammals around the Washington coast, and the likelihood that each type might be harmed by oil coatings. The majority of the dead birds killed by the Exxon

Valdez spill were murres, grebes and loons, with the remainder including cormorants, scoters and puffins. Most of the birds drowned, starved or died of hypothermia. In contrast with the over 1,000 dead sea otters collected, only a few seals or sea lions were killed, because unlike otters, they rely on a subcutaneous fat layer instead of fur for insulation, and they do not groom.

After the much smaller Arco Anchorage spill of ANS crude in Port Angeles harbor, 1,917 birds were found dead on beaches or collected oiled but alive and taken to bird treatment centers (Lindstedt-Siva et al. 1987). Grebes comprised 58%, ducks 25% and alcids 12% of the totals. 80% of the captured oiled birds died despite treatment. No mention was made about harm to marine mammals, probably because sea otters are found in only a few small colonies on the open Washington coast off Olympic National Park.

In the 1989 Nestucca spill off Grays Harbor, Washington, 231,000 gallons of no. 6 fuel oil (Bunker C) were spilled (Kittle, 1989). Approximately 10,000 oiled birds were collected during the search and rehabilitation efforts (primarily murres and scoters). About 9,000 of the birds died. It is assumed that many more birds were killed than were collected. There was no evidence of harm to marine mammals, but there was concern about possible harm to raptors that could suffer from feeding on oiled carcasses (DOE, 1989).

Injury to Intertidal Organisms. The relatively small, sessile organisms that live on beaches between high and low tide lines are especially susceptible to being smothered and killed by a blanket of oil washing ashore. Such organisms include seaweeds, eelgrass, starfish, snails, sea urchins, barnacles, and a variety of bivalves (clams, mussels, oysters). We note the great importance of the recreational and commercial harvest of several of these shellfish species in Washington State. Washington produces some 38% of the total U.S. supply of oysters, and clams, geoducks and other shellfish are objects of increasingly popular commercial and recreational harvest. We have the impression that such inter- or subtidal species are more valued in Washington than in Alaska, which seems primarily concerned with protecting salmon, halibut and herring resources. The approximately ten times larger Washington human population and greater accessibility of the coast also suggests great values on recreational use of beaches and on pleasure boating, both of which are affected when beaches, marinas or boats are fouled with a coat of oil.

We know of no scientifically rigorous studies to define exactly how much of different types of oil are needed to smother, foul or coat different intertidal creatures. Studies of the aftermath of the Amoco Cadiz crude oil spill and others show intertidal organisms are certainly susceptible to being harmed by coating of oils. It seems intuitively likely that lighter, more volatile, less persistent, less viscous oil products will cause less mechanical harm than more viscous, denser and more

persistent products. For example, bivalves can close up tightly for the few hours necessary to survive a coating by a short-lived gasoline-like fuel, but could not remain closed long enough for a coating of no. 2 fuel oil or some even more viscous product to disappear. Clams and other intertidal species inside Ediz Hook were found to be narcotized - a potentially injurious condition - by oil from the Arco Anchorage spill (Geselbracht, 1989, p. 34).

Persistence of Oils in the Marine Environment

A combination of reports from short-term field investigations of actual spills and, more rarely, longer-term studies of the fate of oil spills, provides a rationale for the scaling applied to the relative propensity of different oils to persist in the marine environment developed above. A review of the scientific literature, and where appropriate, reports of short-term spill investigations, follows.

Gasolines, Kerosenes and Jet Fuels. The environmental persistence of these products is determined primarily by their rate of evaporation and only secondarily by rates of dissolution and biodegradation. Rates of evaporation are governed by a combination of several compound-specific properties (Henry's law constant, molecular weight, mass transfer coefficient/diffusion coefficient, etc.) and the key environmental variables water and air temperatures and wind speeds and turbulence.

Evaporation rates for the low molecular weight (mostly C₆-C₁₂) compounds predominant in gasolines, kerosenes and jet fuels have been examined under a variety of conditions and shown to be

typically a few hours to a couple of days (Jordan and Payne, 1980; Payne et. al., 1983; numerous references in NAS, 1985; McAuliffe, 1989; Mackay et al., 1983). We know of no detailed scientific studies of evaporation rates of these oil product types specifically from Washington coastal waters (typically 5-15°C), but we feel the local rates can reasonably be expected to be in the range quoted above. This conclusion is supported by the disappearance within a few days of the highly toxic jet fuel which was spilled into Des Moines Creek in 1985 and again in 1986 (Kittle 1986; Kittle and LeVander 1986).

No. 2 Fuel Oils. For the heavier no. 2 fuel oils which are not as rapidly evaporated, dissolution, biological degradation and sedimentation processes all have important impacts on how long the oil persists in the environment.

One spill of about 5,000 barrels of a no. 2 fuel oil (not derived from Alaska North Slope Oil) occurred on 26 April 1971 at a fuel loading dock at Anacortes, Washington (Vagners, 1972). Because this was the first relatively large oil spill in the Washington coastal zone, scientists, regulatory agencies and response teams were all poorly prepared. Studies of the spill fate and effects were poorly organized, incomplete and lacking any actual chemical characterizations. There are no hard data from this spill which can be used to predict the persistence of no. 2 fuel oils in Washington coastal zones. From a few haphazard visual observations, the oil seemed to disappear from shorelines within several weeks.

The most detailed chemical studies of the aftermath of spills of no. 2 fuel oils in a coastal zone are undoubtedly those carried out around Buzzards Bay and Falmouth, Massachusetts (Blumer and Sass, 1972; Teal et al., 1973; Hampson and Moul, 1978; Mayo et al., 1978; Sanders et al., 1980). In these relatively protected intertidal and subtidal mud and salt marsh-type environs, at least traces of the no. 2 fuel oil and effects persisted for 10 years after the spills (Sanders et al., 1980). These studies all stressed the importance of the nature of the sedimentary environment in affecting oil persistence. In contrast to relatively rapid removal of the oils from exposed beaches, once the oil is sedimented or buried, degradation is inhibited due to lower O_2 concentrations and reduced biological activity, and mechanical removal is very slow. The crude oil source for the no. 2 oils spilled in Massachusetts areas was not ANS crude, but these data provide probably the closest analogy in the literature as to what one might expect for no. 2 fuel oil persistence in protected, low energy environs around Washington State. Such areas are to be found in Willapa Bay, Grays Harbor, Nisqually Delta, Padilla Bay, Skagit Bay, and many small bays and harbors within Puget Sound. Persistence of several years up to a decade seems likely in such areas.

Prudhoe Bay Crude. The best predictor for likely persistence of Prudhoe Bay crude oil in the Washington coastal zone comes from observations following the spill of some 5,700 barrels of Alaska North Slope oil from the tanker Arco Anchorage in Port Angeles

Harbor on December 21, 1985. Studies of the aftermath of this spill showed that for the relatively coarse/sandy/open beach areas of Ediz Hook and nearby areas where considerable cleanup agitation was accomplished, most residues and effects of ANSC had disappeared from the sediments within 2-3 years (Miller, 1989; Mancini et al., 1989; Blaylock and Houghton, 1989; Lindstedt-Siva et al., 1987).

Observations of ANSC oil spilled in Prince William Sound from the tanker Exxon Valdez show significant decrease in amounts of visible oil along beaches after one year, but with some oil buried beneath mud and cobbles likely to persist for several years. One important fact evident from the follow up observations however, is the important role bacterial degradation has in degrading the oil, and that one of the best cleanup procedures, although still experimental, may be to 'seed' areas with 'cocktails' of oil-degrading bacteria and enhanced nutrients nitrogen and phosphorous. Microbial degradation of ANSC by water samples from a commercial harbor, oil tanker dock area, and a pristine area of Washington State have been studied by Fedorak and Westlake, 1981).

Compositional changes in ANS crude oil mixed with sediment from near Sequim, Washington were followed for four months by McCain et al. (1978). After an initially rapid decrease of oil contents, changes slowed and amounts seemed to stabilize after four months at about half the initial amounts.

By eight years after the 1978 Amoco Cadiz oil spill, the hydrocarbon content of the sediments had returned to background

levels in all but the most heavily impacted areas. The residues of weathered Amoco Cadiz oil that remained were in the final stages of degradation (Page 1989).

Residual Fuels Equivalent to No. 5, 6 or Bunker C Oils. These heavier, higher density residual oils remain after lighter compounds are distilled off. These residual oils are relatively rich in larger molecules with high boiling points, higher density, very low water solubility, slower bacterial degradation rates and higher amounts of aromatic hydrocarbons with 3 or more aromatic rings. They are expected to tend to sink, accumulate in sediments, and to persist at least as long as their parent crude oil. While generally low in short-term acute toxicity, they may be the major cause of chronic contamination and effects.

There have been four spills of this type of residual oil fraction around the Washington Coast: the wreck of the towed troopship General M.C. Meigs off the open northwest coast on January 9, 1972; the spill from the tanker Mobiloil in the Columbia River on March 19, 1984; the sinking of the MCN #5 barge near Anacortes on January 1988 and the holing of the barge Nestucca off Grays Harbor, Washington in December 1988. Only in the aftermath of the Meigs accident were rigorous chemical studies carried out to define the persistence of the spilled oil (Clark et al., 1978).

Clark et al. reported that "Observations of animal and plant populations and their petroleum hydrocarbon uptake patterns showed early evidence of contamination and the persistence of the

oil spill throughout the study period" (5 years). Only the aliphatic hydrocarbon trends were observed, but the heavier 3-ring and larger aromatic hydrocarbons would be expected to persist even longer.

The sinking of the MCN #5 barge near Anacortes, Washington released some 47,000 gallons of a heavy residual fuel oil which was denser than sea water and which sank upon release. The aftermath of this spill is described by Geselbracht (1989) and by Yaroch & Reiter (1989). Initial visual observations noted that the oil sank out of sight and appeared to cause no major biological harm in the immediate spill area. With little evidence of damage to commercially or recreationally important species, staff of the Washington State Department of Ecology decided not to invoke the MRDA (Marine Resources Damage Assessment) procedures and no large scale study was initiated. Scientists from the Shannon Point Marine Center near Anacortes did collect some specimens of red sea cucumber (a commercially harvested benthic species) from the area of the oil spill, which were oiled externally. They also carried out some preliminary investigations which showed marine sediments from the spill area were contaminated with oil, possibly from the MCN #5 spill. NOAA apparently subsequently provided some funds for further sediment sampling and analysis and a few bioassays, but none of these chemical results are available to us. All we can say is that as expected, some of this heavy residual oil did sink to the sea floor and accumulate in sediments near the spill site.

The tanker Mobiloil ran aground in the Columbia River and released three types of oil: a heavy residual oil; a no. 6 low sulfur fuel oil; and an industrial fuel oil (JRB Associates, 1985). The oil eventually reached Pacific coastal areas as far as 100 km north of the Columbia River mouth. Washington State Department of Ecology staff did activate the MRDA procedures in this case, and supported several studies focused on efforts to determine which resources had been exposed to the spilled oil and whether this exposure has damaged any of the biological resources. Most of these studies could not verify if damage to biological resources had occurred or not (Geselbracht, 1989; JRB Associates, 1985). Krahn et al. (1986) did however clearly show from analyses of metabolites in bile of sturgeon from the Columbia River that these large bottom feeding fish in the river had indeed incorporated hydrocarbons from the oil spill.

JRB Associates (1985) summarize results of chemical analyses of environmental samples performed to see if petroleum in the samples could be chemically fingerprinted to match that originally carried by the Mobiloil. Matches were found at numerous sites in the Columbia River system downstream of the spill site and on the coast as far north as Copalis Beach, 90 km north of the river mouth, for samples collected in March-May 1984. However, neither intertidal samples nor samples more exposed to atmospheric weathering collected in February 1985 conclusively showed the Mobiloil fingerprint. No samples from the subtidal were collected, so the length of persistence in subtidal coastal sediments remains unknown.