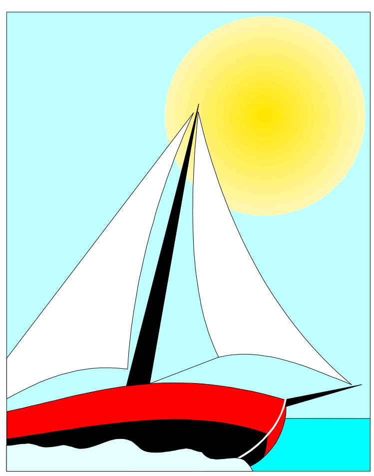
Environmental Impacts of Pleasure Craft Oil Spills

with Special Reference to Southern California Coastal Marinas



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Abstract

This report was prepared to answer two questions, “What are the environmental impacts of pleasure craft oil spills in Southern California coastal marinas?” and “On which pleasure craft operations should spill prevention programs be focused?” Environmental impacts were first placed in the context of socio-economic impacts. The boating industry contributes $11.0 billion to the California Gross State Product and generates 183 thousand jobs, including recreational boating and sport and commercial fishing by 876,965 registered and documented boat owners. Boating also provides important social welfare benefits of recreation and aesthetic enjoyment of time spent on the water. However, the federal Oil Spill Liability Trust Fund expended $865 thousand to clean up pleasure craft and commercial fishing vessel oil spills in California during 1996 and 1997; in 1997, 93% of this cost was due to groundings of vessels. Private parties and state and local governments expended an additional, but unknown, amount on spill cleanup.

Nationally, pleasure craft spilled less than 1% of the total volume of oil and fuel reported to the United States Coast Guard for 1993. In Southern California, pleasure craft spills accounted for 1% - 3% of the volume reported to Coast Guard Marine Safety Offices in 1996 and 1997. Diesel oil accounted for the largest volume of reported oil spills in Southern California, followed by gasoline, lubricating oil and waste oil. Primary, known causes of pleasure craft spills reported in San Diego were sinking, fueling and bilge pumping. These statistics indicate that education on safe boat handling, regular maintenance, fueling system redesign, bilge and waste oil management, and proper fueling practices would be effective in reducing spills. Bilge water pumpout facilities may provide larger boats an effective means of bilge oil management.

Pleasure craft fuels and oils are relatively light weight petroleum products that are released repeatedly in small quantities. They do not have the smothering effect of large, crude oil spills, but may accumulate in confined waters. Refined oils are generally more toxic than crude oil. The primary chemicals of environmental concern in pleasure craft oil and fuel are polycyclic aromatic hydrocarbons (PAHs). PAHs become adsorbed onto particles in marine water and sediment. They may cause behavioral changes, physiological and reproductive effects, reduced growth and feeding, deformity, cancers, mutations and ecological changes in marine species. Three stations in Southern California harbors are among the top 25 sites in the United States for PAH contamination. Marinas with storm drains have higher levels of PAHs and other organic compounds. It is difficult to determine the specific effects of boating activities on marine ecosystems, in part because it is difficult to separate their contributions from those of storm drains to petroleum hydrocarbon contamination of marinas and harbors. Outboard motors and atmospheric discharges of marine engines are also concerns, but were not the focus of this report.

Recommendations for action include: conduct and also foster boating community leadership of environmental stewardship and pollution prevention education programs; encourage redesign of vessel fueling systems and engine spaces; promote regular maintenance and safe boat handling; establish effective oil recycling systems; encourage watershed management, spill reporting, and reduction of disincentives for reporting; encourage a uniform system of regional reports on pleasure craft spills and their causes and make annual data readily available; install bilge water pumpout stations if appropriate; and encourage focused studies on pleasure craft oil spills.

Introduction

This report summarizes the results of an extensive literature search that was conducted to answer two questions, "What are the environmental impacts of pleasure craft oil spills in Southern California coastal marinas?" and "On which pleasure craft operations should spill prevention programs be focused?" Many of the 120 sources that were reviewed pertained to large spills of crude oil and so were not cited. Information used in the report was gleaned from a variety of sources, interpretations were made, and conclusions drawn based on sources that provided the best insights for understanding and preventing pleasure craft oil spills.

To manage the environmental impacts of pleasure craft oil spills effectively, it is important to determine their volume, causes and context, as well as the nature and severity of their effects on aquatic habitats and organisms. Pleasure craft tend to spill small amounts of refined petroleum products repeatedly in marinas and harbors, whose waters are generally confined, have poor circulation and flushing (Hollin et al., 1998), and are agitated by propellers and hull movements, that may contribute to dispersion of these products into the water column. Environmental impacts of refined petroleum discharges associated with pleasure craft bilge pumping, oil changing, and fueling are confounded by the frequent proximity of storm drains, that carry contaminated runoff, habitat alterations that occurred when harbors were developed, and the influence of other pollutants on marine species and ecological communities.

McMahon's (1989) report on Australian marinas illustrates the effect of flushing, fuel docks, and storm drains on water and sediment quality of marinas and the difficulty of separating the influence of runoff from marina activities. Three of the marinas sampled were designed as "embayments" and the fourth was near a river mouth with water flowing through it. An elevated level of petroleum in the water column was found in only one sample, taken near a fuel dock during refueling activity. He found higher petroleum levels in sediments of two embayment-type marinas with fuel docks and upland drainage, but not in sediment of an embayment-type marina with no fuel dock or upland drainage, nor in sediment of the flow-through type marina.

According to Coast Guard and other personnel, many pleasure craft spills go unreported or are included under "unknown" sources in government statistics. Some indicated that informants interviewed during spill investigations perceived pleasure craft spills as common and that boaters were reluctant to report each other. Some facility managers have expressed frustration that their commitment to diligent reporting has sometimes resulted in agency perceptions that their facility has an unusually high spill rate. Podlich and Pereira (1998) found that marina managers around the Gulf of Mexico feared stiff fines and penalties when they followed proper procedures by reporting spills. Olsson (1994) reported that small oil spills and slicks were considered normal and necessary to marina and boat operations on the Washington coast. Thus, pleasure craft almost certainly spill an unknown, larger volume of oil than is reported. Boat owner perceptions and disincentives, such as fines and penalties, apparently contribute to under-reporting.

Reports of relative contributions of automatic bilge pumping, sinking and fueling activities to the total volume of pleasure craft oil and fuel spills could only be obtained for the San Diego, California area and coastal waters of Washington state. Profiles of spill causes varied among regions and years. It is also difficult to isolate impacts of pleasure craft spills from impacts of spills by larger sources. For example spills by the Navy comprised about 60-90% of the annual volume of oil reported spilled in San Diego area harbors during 1996-1998 (USCG 1998c). Freight ships, platforms and facilities spills in Los Angeles and Long Beach area harbors varied annually, but were generally the major sources (USCG 1998b). Commercial fishing vessels contributed 67% of total oil spilled along the Texas coast in 1997 (Smith et al., *in press*). Nationally, recreational and marina sources contributed less than 1% of total gallons spilled in 1993 (USCG 1998a) Despite limitations of the data, it can provide insights for educators and agencies on how to focus spill reduction programs.

The effects of occasional, massive spills of crude oil, especially those that have occurred along the open coast are well-documented. There are also numerous reports on outboard motor exhaust, especially the effects of the fuel additive MTBE (methyl-*tert*-butyl ether). However, there are relatively few reports on the effects of small, chronic discharges of oily bilge water, waste oil spilled during oil changes and disposal, small amounts of fuel spilled during refueling operations, and sinkings of vessels occurring in marinas and harbors. Agency documents, anecdotal accounts, theses and dissertations comprise much of this literature. The National Research Council (1985; 81) dismissed pleasure craft oil spills in its 600-page report, *Oil in the Sea: Inputs, Fates and Effects*, stating "While inputs from pleasure craft may be locally significant, we believe that the total amount of this input would not be on the same scale with the other inputs considered," and devoting its attention to other spill sources. More recently, the international Joint Group of Experts on the Scientific Aspects of Marine Pollution reported in *The State of the Marine Environment*, that the primary, global impact of oil spills was in the form of tar balls that fouled beaches and affected tourist economies (GESAMP, 1990; 3).

Thus, the goal of this report is to examine locally significant inputs of petroleum discharges related to small craft, their context, fates, and effects in the confined waters of coastal marinas and harbors. Given the limitations on available data, insights will be gleaned and adapted from analyses of crude oil effects, reports on refined petroleum from pleasure craft and other sources in this and other geographic areas, and agency reports based in part on limited data.

This report will consider selected economic and social benefits and costs, context and volume of pleasure craft oil spills, national and regional spill profiles, implications for spill prevention programs, types of oil spilled, and environmental impacts of pleasure craft oil spills. It will also draw conclusions and make recommendations for actions that could reduce spills and improve our ability to assess their incidence and impacts.

As will be shown, data on pleasure craft spill volumes and environmental impacts are not detailed enough to support exact measurements of their effects on marina and harbor ecosystems. However, there is sufficient information to provide a general picture, make inferences, and suggest types of data that would be needed to determine the effects of pleasure craft oil spills in marinas and nearby harbor areas. These insights will hopefully guide scientists and funding agencies who wish to improve our understanding of pleasure craft oil spills, as well as assist educators in designing programs to foster an increased sense of environmental stewardship among boaters and to provide them with information on how to prevent oil and fuel spills.

Benefits and Costs of Recreational Boating

Recreational boating stimulates economic activity and benefits society by providing recreational and aesthetic benefits. Pleasure craft oil spills affect aquatic habitats, degrade water quality and aesthetics, and generate costs to society for containment and cleanup. It is important to balance the benefits and the environmental costs created by recreational boating but difficult to compare them on a quantitative, objective basis (GESAMP, 1990). A detailed study of benefits and costs provided to society by recreational boating activities and the pollution they generate is beyond the scope of this report. However, a few statistics can provide a general illustration.

A recent study by the California Department of Boating and Waterways (Rust and Potepan, 1997) reported that the boating industry contributed $11.0 billion to the Gross State Product (GSP). This included contributions by recreational boating and commercial fishing, because data for these two sectors are lumped in reports of some expenditures, such as fishing equipment and gear. Rust and Potepan reported that 183,000 jobs, state government revenues of $344.1 million, and local government revenues of $244.6 million were generated by the entire boating industry.

Social welfare benefits include opportunities to enjoy aquatic sports, fishing, and the aesthetically pleasing experience of relaxing outdoors on the water. In 1995 a total of 857,477 vessels were registered and 19,488 vessels were documented in California, testifying to the attractions of recreational boating (Rust and Potepan, 1997).

Each of these 876,965 boats is a potential opportunity for oil and fuel spills, that require the expenditure of public and private funds for cleanup and containment. For example, if a responsible party cannot be identified, or does not clean up an oil spill satisfactorily, claims may be submitted to the federal Oil Spill Liability Trust Fund (OSLTF). The Fund covers direct costs for spill clean-up, some Coast Guard costs, for example if the Federal On Scene Coordinator determines that special equipment is needed for direct cleanup by the Coast Guard, other costs by federal, state and local agencies, and liability claims by other parties whose operations were affected by the spill. They do not include expenditures incurred by responsible parties, their insurers, or Coast Guard staff time. (NPFC, 1998a) Thus, OSLTF data provide insights on some of the extended costs for some spills. In 1996 and 1997 the OSLTF paid $25,535 to clean up pleasure craft spills and $839,630 to clean up commercial fishing vessel spills in California. Three vessels accounted for $743,696, or 89% of federal funds spent on commercial fishing vessel spill remediation in those years. (NPFC, 1998b) The State of California spent over $1 million on all "mystery" spills and tarball incidents in seven years (*personal communication*, Dana Michaels, California Department of Fish and Game, Oil Spill Prevention and Response).

Coast Guard personnel in the Los Angeles/Long Beach Marine Safety Office reported that the Cities of Los Angeles and Long Beach generally remediate municipal marina spills. However, the OSLTF is sometimes used to pay for cleanup of spills occurring in marinas of smaller cities in the San Luis Obispo to Orange County area, that are unable to cover cleanup costs.

In the San Diego region the OSLTF spent about $243 thousand in 1996 and 1997 to clean up oil and fuel spills not generated by the Navy. Interestingly, two sunken, derelict vessels (one each year) accounted for about $193 thousand, or 79%, of federal funds spent on non-Navy oil spill cleanup in those two years. (USCG, 1998c) Also in 1996 and 1997, the OSLTF was used for two small craft spills in the Los Angeles/Long Beach area. Both were commercial fishing vessels; one sank and the other ran aground. The fund expended over $412 thousand in Coast Guard and contractor costs. In 1997 $388 thousand, or 93% of that year's total OSLTF cleanup costs for California pleasure craft and commercial fishing vessels, were incurred because of groundings (NPFC, 1998b). These reports highlight the importance of regular vessel maintenance, prompt attention to abandoned vessels, and safety in vessel handling.

Data from another state can provide perspectives. For example, the Texas General Land Office estimated that in 1996 and 1997, the state spent about $113 thousand to clean up 37,296 gallons of spilled waste oil and about $58 thousand to clean up 47,712 gallons of spilled diesel fuel (Smith et al., *in press*). Since 1992, almost $2 million has been spent by joint state and federal operations on oil spill cleanup in Texas, not including thousands of dollars of associated costs, such as internal agency costs. (Smith, 1998) Texas coastal pleasure craft accounted for only 0.1% - 0.2% of the total gallons of oil reported spilled in 1996 and 1997. Commercial fishing vessels contributed 2% in 1996, but 67% in 1997, of the total volume spilled. (See Table 6.)

Context, Sources and Incidence of Pleasure Craft Oil Spills

On a global scale, tar balls that foul beaches, affecting recreation and tourism, are the primary impact of oil spills. Petroleum hydrocarbons in the water column and sediments and refined oils, that accumulate in sheltered areas after large spills, affect the quality of life and damage living resources on a local basis. (GESAMP, 1990). Reported pleasure craft oil spills primarily occur in and near marinas, that are often near storm drain openings (SDUPD, 1992), and historically, sewage outfalls drained to bays (Mearns, et al., 1991). Thus, it is difficult to assess accurately pleasure craft contributions to petroleum contamination of the water column and sediments.

Although they are under-reported, United States Coast Guard reports provide an estimate of pleasure craft oil and fuel spills. The Coast Guard is the primary investigating agency for oil spills in coastal waters. The most current, national data are for "marina" and "recreational" spills in 1993. Table 1. shows that "recreational" and "marina" sources spilled about 17,000 gallons of oil, less than one percent of the total spilled in 1993. Average spill sizes for these two sources are probably influenced by large maximum spill sizes. Median spills of three gallons for "recreational" and five gallons for "marina" better estimate typical spills. (USCG, 1998a)

The fact that oil spilled by pleasure craft is a small part of the reported total should not be taken to indicate that it is an insignificant problem. Numerous conversations with Coast Guard and other personnel have indicated that many small spills go unreported, so the total oil spilled by pleasure craft is likely to be much higher than published data suggest. In addition, pleasure craft oil and fuel spills are a chronic occurrence in confined marina and harbor waters, where tidal flushing is often poor (Hollin et al., 1998), increasing residence time and exposure of marine organisms to refined, petroleum materials. Refined oil used by pleasure craft is generally more toxic than crude oil spilled by tankers; dispersion in the water, which propeller and hull movements may promote, increases its availability to marine life (Van Gelder-Ottway, 1976).

Table 1. Total National Recreational and Marina Spill Statistics for 1993 (USCG, 1998a)

Detailed Source	Recreational	Marina
Volume of Spills (gal.)	7,375	9,666
% of Spills by Volume	0.4%	0.5%
Number of Spills	520	65
% of Spills by Number	5.8%	0.7%
Average Spill Size (gal.)	14	149
Maximum Spill Size (gal.)	900	5,000
Median Spill Size (gal.)	3	5

National data on causes of spills by vessels is aggregated across all vessel types, so it does not show contributions from specific pleasure craft operations. However, such data is available in statistics developed by the US Coast Guard Marine Safety Office in San Diego for San Diego Bay, Mission Bay and Oceanside Harbor (USCG, 1998c).

Table 2. Percent of Gallons of Oil Reported Spilled by Pleasure Craft Operations in San Diego Area Marinas in 1996 (selected), 1997 and 1998 (through October 15) (USCG, 1998c) (Percentages may not sum to 100% due to rounding.)

Spill Source	1996	1997	1998 (through Oct. 15)
Bilge Pumping	32%	41%	34%
Fueling	18%	38%	23%
Sinking	Not Available	2%	17%
Unknown	Not Available	20%	26%
Total Volume Spilled	205 gallons	374 gallons	408 gallons

Spill profiles vary each year, according to Olsson (1994). This observation is supported by San Diego area data in Table 2., showing that 205 gallons were reported spilled in marinas during 1996, and 374 gallons were spilled marinas during 1997, whereas 408 gallons had already been spilled in San Diego area marinas by October 15, 1998. Relative contributions of different causes also varied annually in San Diego. Thus, it would be important to examine annual variations and trends before designing an oil spill intervention program.

Data on causes of pleasure craft and commercial fishing vessel spills were also available for August 1989 - July 1992 for Washington coastal waters (Puget Sound, Strait of Juan de Fuca, and Pacific Coast) (Table 3.). There, sinking was a far more important cause of oil spills, than in San Diego. Bilge pumping was also an important spill source for pleasure craft, whereas fueling and internal transfers were important causes of commercial fishing vessel spills. (Olsson, 1994)

Table 3. Percent of Gallons of Oil Reported Spilled by Selected Pleasure Craft and Fishing Vessel Operations in Washington Coastal Waters in 1989-1992 (Olsson, 1994)

Spill Source	**Pleasure Craft**	**Commercial Fishing Vessels**
Bilge Pumping	14%	9%
Fueling	4%	11%
Sinking	69%	53%
Other Vessel Casualty	2%	1%
Non-Specific	7%	10%
Internal Transfers	3%	7%
Vessel Maintenance	0%	7%
Total Volume Spilled	663 gallons	5,319 gallons

A different approach to determining spill contributions by pleasure craft operations was taken by Nevin et al. (1998), who surveyed California pleasure craft owners on their perceptions of causes for oil leaks. They found that 39% believed leaks occurred during automatic bilge pumping, 31% by leaks in the engine, 27% by insufficient space under the crankcase and 22% by oil spilling from a container when transferred. Three-fourths of the survey respondents changed their own oil. Half fueled their boats while they were in the water and three-fourths fueled their boats, themselves. Of these, 90% fueled slowly, 81% did not top off their fuel tanks, and 68% used an absorbent pad or rag to wipe up fuel spills, practices known to reduce spills during vessel fueling. The authors suggested that survey results may be overly optimistic, "due to the tendency to under-report behaviors that may be looked upon negatively by others" (Nevin, et al. 1998;19).

Interviews with numerous Coast Guard staff, who regularly investigate reported spills, indicate that important causes of small craft spills include: automatic bilge pump discharges, inattention to engine room maintenance, overflows that occur during fueling because many small craft fueling systems provide no automatic shutoff or warning that the tank is nearly full, neglect of regular maintenance, and failure to remove abandoned vessels promptly.

As noted above in national Coast Guard data, reported pleasure craft oil spills are often a small proportion of total spills in a harbor. Data from the Los Angeles/Long Beach and San Diego areas, Washington state and Texas also show minor contributions by pleasure craft to total volume of reported spills. There were interesting regional and annual variations in proportions of spills contributed by facilities and vessel types.

The US Coast Guard Marine Safety Office/Group in Los Angeles/Long Beach investigates oil spills along the Southern California coast from Morro Bay to Dana Point. They reported spills by vessel type, but not by operation within vessel types. Table 4. shows total gallons spilled in the Los Angeles/Long Beach area and percentages reported in 1996 and 1997 for fixed platforms, freight ships and barges, unknown sources, fishing boats, facilities and pleasure craft. Other sources were pipelines; public, passenger, and unclassified vessels; tow and tug boats; tank ships and barges; motor vehicle; and artificial island. Annually, total volume spilled and relative contributions of sources varied considerably. However, the reported total that could be attributed to pleasure craft related sources was in the range of 200-250 gallons both years. (USCG, 1998b)

Table 4. Percent of Gallons of Oil Reported Spilled by Vessel Types and Facilities in the Los Angeles/Long Beach Area in 1996 and 1997 (USCG, 1998b)

Spill Source	**1996**	**1997**
Fixed Platform	39%	Not Reported
Fishing Boat	2%	21%
Freight Ships and Barges	7%	33%
Facilities	48%	12%
Unknown Source	Not Reported	29%
Pleasure Craft	(209 gallons) 1%	(242 gallons) 2%
Other	3%	3%
Total Volume Spilled	27,365 gallons	12,316 gallons

Table 5. Percent of Gallons of Oil Reported Spilled by Vessel Types and Facilities in the San Diego Area in 1996, 1997 and 1998 (through November 4) (USCG, 1998c)

Spill Source	**1996**	**1997**	**1998 (through Nov. 4)**
Navy	80%	61%	86%
Unknown Source	13%	28%	2%
Fishing Boat	2%	1%	3%
Pleasure Craft	(205 gallons) 2%	(290 gallons) 5%	(521 gallons) 4%
Facilities	3%	5%	5%
Total Volume Spilled	13,644 gallons	5,732 gallons	12,204 gallons

Table 5. shows contributions of vessel types in the San Diego area varied annually, but the Navy

was the primary source of spills. Pleasure craft spills varied more than in the Los Angeles/Long Beach area, in the range of 200 - 500 gallons per year and comprised 2% - 5% of total reports.

As in Southern California, contributions by different vessel types on the Texas coast varied annually. Commercial fishing vessels spilled about 21,000 gallons in 1997, or 67% of the total. In 1996 commercial fishing vessels spilled only 4,830 gallons, or 2% of total Texas coastal spills. Other vessels included tankers, tugboats, tank barges, cargo vessels, container and roll on/roll off ships, offshore service, public, and recreational vessels. Pleasure craft contributed from 0.1% to 0.2 % of reported oil spills in 1996 and 1997. (Smith et al., *in press*)

Table 6. Percent of Gallons of Oil Reported Spilled by Vessels on the Texas Coast in 1996 and 1997 (Texas General Land Office, 1998) Percentages do not sum to 100% due to rounding.

Spill Source	**1996**	**1997**
Tank barge, tugboat, tanker	98%	30%
Commercial fishing vessels	2%	67%
Recreational vessels	0.1%	0.2%
Other	0.3%	3%
Total gallons spilled	310,729	32,302

Olsson (1994) reported that commercial fishing vessels spilled more oil than any other vessel type in Washington coastal waters during 1989-1992, although they did not dominate spill volumes to the extent they did in Texas. Of 22,108 gallons reported spilled in Washington coastal waters, shore facilities contributed 44%, commercial fishing vessels spilled 24%, freight ships spilled 13%, tank barges spilled 9%, and tug boats and pleasure craft each spilled 3%.

Types of Oil and Fuel Spilled

Coast Guard reports from the Los Angeles and Long Beach area for 1996 and 1997 and from the San Diego area for 1995 through November 4, 1998 indicated types of oil and fuel spilled by pleasure craft. Tables 7. and 8. show that fuels comprised from 88% to 93%, whereas lubricating and waste oils contributed only 6% to 10% of total reported pleasure craft spills in those areas. This “snapshot” of the types of oil and fuel products likely to be spilled from these boats, can help to focus an assessment of the likely environmental impacts of pleasure craft oil spills and provide further insights for developing spill prevention programs.

Although fuels contributed most of the volume of reported pleasure craft spills, it is important to consider the conditions under which a spill is likely to be reported when interpreting the data. Fueling spills occur at a limited number of busy sites (fuel docks), whereas bilge pumping and other maintenance activities occur on thousands of individual boats with much less likelihood of public scrutiny. Nevin et al. (1998), for example, found that boaters believed that 39% of their oil leaks occurred during automatic bilge pumping and 22% occurred by oil spilling from a container when transferred. As noted above, there are also some disincentives for reporting spills by boats at marinas. Thus, the data likely underestimate the importance of bilge pumping, poor engine maintenance, and oil changes as sources of petroleum pollution in marinas and harbors.

Numerous conversations with vessel owners, Coast Guard personnel and fuel dock staff have indicated that design of the fueling system of vessels is a culprit in fueling spills. As reported by Nevin (1998), cramped space under the crankcase may contribute to the possibility of engine room spills to the bilge space. This suggests the importance of encouraging vessel redesign with an eye to spill prevention.

Table 7. Types and Volumes of Oil Spilled by Pleasure Craft in Los Angeles and Long Beach Area During 1996 and 1997 (USCG, 1998b)

Product Type Spilled	**Gallons**	**(%)**
Diesel Oil	236	58%
Fuel Oil No. 2-D	61	15%
Gasoline	58	14%
Lubricating Oil	31	8%
Waste Oil, Lubricants, Possible Contaminant	15	4%
Other	4	1%
Total	405	100%

Table 8. Types and Volumes of Oil Spilled by Pleasure Craft in San Diego Area During 1995 Through November 4, 1998 (USCG, 1998c) (Percentages do not sum to 100% due to rounding.)

Product Type Spilled	**Gallons**	**(%)**
Diesel Oil	808	73%
Gasoline	224	20%
Lubricating Oil	42	4%
Waste Oil	27	2%
Total	1,101	99%

Implications of Pleasure Craft Spill Statistics for Prevention Programs

Olsson analyzed several cases of vessel oil spills and identified human error as their primary cause. He also implicated human error as a component of equipment failure. Reluctance of marina managers and boat owners to report spills, because of stiff fines, or because small spills and slicks are considered normal, hinder cleanup efforts and collection of data that could provide insights on causes of spills. Podlich and Pereira (1998) found that boaters were more receptive to pollution prevention when they were told it could help the environment and help them avoid potential fines. Their finding that boater education on oil spill prevention needed to be tailored to local areas is supported by Coast Guard data showing regional differences in spill profiles.

This suggests that enforcement, alone, cannot reduce pleasure craft oil spills. However, combining regionally based education to promote environmental stewardship and provide information on best management practices with enforcement as a "backbone" could be a critical methodology for reducing oil spills from vessels. Marina staff also have an important role to play. Podlich and Pereira (1998) recommended training and educating marina personnel as a means for influencing boater behavior; Johnson (1996) found that most boaters who attended pollution prevention seminars had been encouraged to participate by their marina managers.

Thus, in all areas, educating fishing vessel and pleasure craft owners on operational safety, locations of shoals, the need for regular maintenance, bilge oil management and fueling procedures should be effective in reducing the volume of small craft spills. Working with shore facility operators, commercial fishing vessel owners and freight companies would have the greatest potential to reduce spill volumes in Washington state. Working with the Navy in the Port of San Diego and with freight companies, fixed platforms and other facilities in the Ports of Los Angeles and Long Beach would have the greatest potential to reduce the total volume of spills in those areas. Raising awareness of the importance of replacing two-stroke outboard motors with four-stroke models could reduce emissions of oil and fuel from this source.

In all regions, educating boaters on environmental impacts of small, chronic spills of oil in marinas and harbors could foster a commitment to environmental stewardship that would promote voluntary efforts to reduce spills. This author found in a series of interviews conducted in 1996, that boaters and marina staff valued a clean and aesthetically pleasing boating environment. As Bill Dysart, past Commodore of the San Diego Association of Yacht Clubs has commented, it is important to avoid "preaching" to boaters and that the message is best received from within the boating community. Thus, providing information on environmental impacts and pollution prevention in a positive and informative style and working to develop leadership in educational efforts on the part of boating groups have great potential to promote oil spill prevention.

Technical interventions also can be effective in reducing oil spills and improving environmental quality of coastal waters. The Texas General Land Office and the Port Isabel-San Benito Navigation District have succeeded in getting commercial fishing vessels in Port Isabel to use their demonstration facility for oily bilge water collection and processing. In 21 months the facility extracted 22,000 gallons of used engine oil from 100,000 gallons of oily bilge water from commercial fishing vessels and was able to discharge the filtered water to the harbor. Removing waste oil and diesel from bilge water has the potential to improve water quality and to reduce costs borne by state and federal agencies and responsible parties. They are working to establish similar facilities at other Texas ports (Smith, et al., *in press*).

Chemical Composition of Compounds Found in Petroleum Products and Their Environmental Significance

Petroleum products contain thousands of different organic compounds, each with a carbon backbone and attached hydrogen atoms. They range in structure from the simple aliphatic compound, methane, that has a single carbon atom surrounded by four hydrogen atoms, to highly complex compounds with up to 50 carbon atoms. The carbon atoms of larger compounds may be arranged in straight chains, branched chains and rings. Different petroleum products contain different mixtures of these compounds. (Olsen et al., 1982) Petroleum products may also contain other elements, such as nitrogen, oxygen, sulfur, vanadium and nickel (NRC, 1985).

Aromatic hydrocarbons are made of six-carbon rings, called "aromatic" or "benzene" rings, often depicted as having a hexagonal shape. Examples of aromatic compounds with a single, benzene ring are benzene, toluene, pyridine (also contains nitrogen), and phenol (also contains oxygen). Note that some cyclic hydrocarbons found in petroleum are not aromatic compounds, for example cyclohexane, cyclopentane, and hopane. (NRC, 1985)

The polycyclic aromatic hydrocarbons, or PAHs, have multiple, six-carbon rings, that differ in number and arrangement, as if a child had assembled hexagonal building-blocks. Examples include naphthalene (two rings side by side), phenanthrene (three rings in a curved row), pyrene (four rings, stacked one-two-one) and benzanthracene (four rings, with three-in-a-row and the fourth set at an angle). Dibenzothiophene is a PAH that contains sulfur, quinoline contains nitrogen, and fluorenone contains oxygen. (NRC, 1985) PAHs with a bent or angular structure are also referred to as having a "bay region." PAHs may be grouped into low molecular weight (LMW) compounds, such as naphthalene, biphenyl, acenaphthene, 1-methyl naphthalene, and high molecular weight (HMW) compounds, such as fluoranthene, pyrene, benzo(a)pyrene, and perylene. (Mearns et al., 1991)

PAHs occur in crude and refined petroleum products, and are also produced by combustion of organic matter, as well as naturally by living organisms. They may occur in domestic and industrial waste waters, sewage, urban runoff, and atmospheric discharges from combustion of fossil fuels or other, heated, decomposition of organic matter. The highest concentrations of PAHs in marine sediments occur near urban areas. (Connell and Miller, 1984) The high molecular weight PAHs fluoranthene and pyrene are produced by combustion (Mearns et al., 1991), so their presence in sediments may suggest, for example, that engine exhaust was the source of contamination.

Toxic effects of petroleum products are usually due to aromatic compounds, according to Connell and Miller (1984), who reported that PAH concentrations from 0.1-0.5 ppm are usually toxic to aquatic organisms. They noted that many petroleum compounds that contain oxygen, nitrogen or sulfur are also toxic, but that less was known about their toxicity in marine areas.

The lighter molecular weight PAHs, naphthalene and phenanthrene, are the major PAHs found in water when crude or refined oils are released. Naphthalene and phenanthrene react with water to form more toxic, methylated compounds. PAHs generally are metabolized in higher organisms to form reactive, water-soluble epoxides, that are often more toxic than the original compounds. These metabolites may damage essential proteins, enzymes, and DNA. Parent PAH compounds with a "bay region" (angular structure) are more likely to form biologically damaging epoxides. (Mearns et al., 1991)

In the Southern California Bight (ocean and coastal areas from Point Conception in California to Cabo Colnett and Bahia de San Quintin in Baja California) treated sewage, stormwater runoff, and oil spills have been documented as PAH sources. Atmospheric sources, refinery and drilling wastes, and natural oil and hydrothermal seeps are suspected, but less well-documented sources of PAHs in this region. (Mearns et al., 1991)

PAHs, especially those of higher molecular weight, become adsorbed to particulate matter in marine waters and sediments. Microbes can degrade PAHs, but they degrade high molecular weight forms slowly. High molecular weight PAHs are less reactive, tend to bioaccumulate to a greater extent, and are retained in body tissues longer than low molecular weight forms. Sessile bivalve mollusks, such as mussels (*Mytilus* sp.) metabolize PAHs slowly, so they are good indicators of PAH contamination. (Mearns et al., 1991)

Connell and Miller (1984) also noted that concentrations of 1-100 μg/ml of soluble aromatic derivatives (SAD) are generally lethal to adult organisms after several hours to 48 hours; whereas concentrations of 0.1-1 μg/ml are generally toxic to larval stages. However, concentrations in the environment are relatively low and sublethal effects are usually more important. Sublethal concentrations range from less than 10 ppb to over 1000 ppb of SAD, with larvae and juveniles most sensitive to concentrations under 1000 ppb. Sublethal effects include behavioral changes, physiological effects, toxicity to embryos, disruption of ionic regulation, reductions in rates of growth, development, and feeding, development of cancers, and mutations. Carcinogenic PAHs generally have four, five, or six benzene rings and an angular structure.

Meador et al. (1995) reviewed literature on bioavailability, uptake and elimination of PAHs in invertebrates and fish in marine ecosystems. These processes determine accumulation and retention of PAH in tissues. They reported that PAHs tend to accumulate most readily in invertebrates, such as mollusks, whose enzymes don't transform them rapidly. On the other hand, fish are well able to metabolize PAHs, but the products of these metabolic transformations do accumulate in their bile. Polychaete worms and crustaceans generally have an intermediate ability to metabolize PAHs. Steady-state body burden is generally reached in days for low molecular weight PAHs and in a few weeks for high molecular weight PAHs. Fish can eliminate half of their steady-state body burden in a few days and invertebrates take one or two weeks to do so, depending on the metabolic rate of the species. This suggests that in areas with constant inputs of petroleum hydrocarbons, marine organisms may maintain elevated body burdens of PAHs, which could be expected to increase the likelihood of toxic effects.

Fish can metabolize PAHs rapidly, so exposure and toxic effects may not be reflected in tissue levels. For example, Meador et al. (1995) reviewed a study in the Elizabeth River, Virginia estuary that found fish living along an increasing gradient of PAH-contaminated sediments had increased numbers of cataracts, less biomass and were fewer in number, even though they did not have noticeable tissue concentrations of these contaminants. Because the ability of fish to metabolize PAHs rapidly makes it difficult to determine the total accumulation of PAH in fish tissues directly, metabolic products of PAH are measured to determine PAH exposure.

Meador et al. (1995) also reported that most studies indicate PAH concentrations are not likely to biomagnify, except perhaps in species at lower trophic levels, that cannot metabolize them effectively. For example, one study found that grass shrimp (*Palaemonetes pugio*) had 15-24 times as much dimethylnaphthalene than the brine shrimp (*Artemia* sp.) on which they had been feeding. Because vertebrates can actively biotransform PAHs, they are not likely to show high levels. However, studies of winter flounder (*Pseudopleuronectes americanus*) have found that carcinogenic metabolites of PAHs, such as benzo[a]pyrene, were bioaccumulated from prey species.

Large, Crude Oil Spills Versus Small, Chronic, Refined Oil Spills

The majority of research on environmental impacts of oil discharged into the marine environment has addressed large spills of crude oil. Many of the more dramatic effects of these "disastrous" spills are due to the physical effects of large amounts of heavy oil on the sea, shoreline and marine life, especially birds and intertidal organisms. For example, smothering by a blanket of crude oil commonly kills intertidal invertebrates when crude oil slicks come ashore. The weight of oil clinging to seaweed causes fronds to break away. Gray and harbor seals have been killed by coating with oil. Oil clogs the feathers of seabirds, destroying their ability insulate the bird and allow it to maintain body temperature. Oil also destroys the feathers' ability to repel water, causing the birds to sink and drown. (NRC, 1985)

Small discharges of lubricating oil, for example oily bilge water, have neither the weight nor the volume of the large, crude oil spills. Although more diesel and gasoline may be spilled at one time during fueling operations, they, too, are small compared to spills from tankers and facilities that have received most of the research attention. Diesel and gasoline are far more volatile than crude oil; lighter petroleum hydrocarbons quickly evaporate under normal atmospheric conditions (Dodd, 1974). Sunken vessels may discharge much larger amounts of fuel, but can generally be effectively remediated in a small, local area by containment and removal. As a result, pleasure craft fuel spills contribute to air pollution, but much of their volume is usually removed from marina and harbor waters within a short time. Note that dispersants and emulsifiers that have been used to remediate oil spills are, themselves, toxic (Baker and Crapp, 1974) and serve to move petroleum spills into the water column, where they become more available to marine species. Spill remediation professionals are generally aware of concerns regarding the use of dispersants. Anecdotal accounts by marina and Coast Guard personnel indicate that some pleasure craft owners consider it standard practice to disperse oil and fuel with soap. This point should be addressed in educational programs.

Thus, the extreme physical effects observed in large spills of crude oil are not pertinent to pleasure craft discharges. Instead, research on chronic discharges of refined oil has focused on sediment accumulation and on toxicity. Much of this research has concerned petroleum products carried to harbors by upland runoff or has focused on No. 2 fuel oil, which is not typically used in pleasure craft. However, results of this research can help to illustrate the general types of effects that may be expected from pleasure craft oil and fuel spills in marinas.

Oil Toxicity Studies and Their Applicability to Pleasure Craft Oil Spills

The repeated, small discharges of lighter weight petroleum products that characterize small craft oil and fuel spills do not create the blanketing or smothering effect that large, crude oil spills impose on seabirds and shorelines. Thus, toxicity is the primary environmental concern to be considered. Most academic research on environmental impacts of oil spills has focused on crude oil, whereas pleasure craft use refined oil products. These studies may provide insights on the impacts of pleasure craft oil, if product weights, relative amounts spilled and relative toxicities are considered.

Van Gelder-Ottway (1976) compared toxicities of crude oils, refined oils and oil emulsions to intertidal molluscs common on British rocky shores that are similar to some species occurring in California. She evaluated percent mortality of *Littorina littoralis*, *L. saxatilis*, *L. neritoides*, *Gibbula umbilicalis* and *Mytilus edulis* (a mussel which is also an aquacultural species) when exposed for one hour and mortality of *L. littorea* and *Nucella lapillus* when exposed for six hours to Kuwait crude oil; seven different fuel, household and medicinal oils; and 20/50 weight motor oil. Exposures were followed by a five-day recovery period in seawater. Full-strength products were used in these tests, whereas exposures in small craft harbors are more likely to come from diluted and dispersed materials. However, they are useful as comparisons among crude and refined petroleum products.

Species varied in sensitivity, but overall, leaded gasoline was by far the most toxic (possibly due to the lead additive) followed by kerosene and crude oil. Heavy, black 3500 fuel oil was nearly non-toxic and medicinal oil was non-toxic to all species. The other fractions were relatively less toxic than kerosene and crude oil. Howe and Ottway (1971) and Crapp (1971) found a similar order of toxicity of oil fractions to prawns and gastropod molluscs.

The 20/50 weight motor oil test is most pertinent to pleasure craft. A six-hour exposure killed ten percent of *L. littorea* and a one-hour exposure killed ten percent of *M. edulis*. A one-hour exposure killed no *L. littoralis*, no *L. saxatilis,* 2 percent of *L. neritoides*, and thirty-two percent of *G. umbilicalis*. Results were not reported for *N. lapillus*.

Refined oil toxicities to marine life, such as the hydrozoan *Tubularia crocea*, the toadfish *Opsanus tau* (L.), and the oyster *Crassostrea virginica* were also reported by Chipman and Galtsoff (1949). In general, oil products with low boiling points (the lighter weight fractions) were much more toxic than heavy fuel and bunker oils; crude oils had intermediate toxicity for marine life.

When spilled on water, diesel oil quickly spreads to form a thin film. About 1,000 gallons can cover a square nautical mile. Diesel is lighter than water, so it will float, but it can be physically mixed into the water column, forming fine drops that are kept in suspension by currents. It is completely degraded by microbes in one to two months time. Diesel is considered to be one of the most acutely toxic oils to fish, invertebrates and seaweeds in the water column, although small spills in open water are rapidly diluted and no fish kills have been reported. Crabs and bivalves may be tainted from small diesel spills in nearshore areas; they may bioaccumulate the oil, but will also depurate (purge) it in several weeks. Small diesel spills may potentially affect birds but few have been reported to be directly affected . However, small spills that ground by nesting colonies or sheens that move into dense rafting groups could seriously affect them. (NOAA, undated)

In contrast, Allen (1971) found that embryos of the purple sea urchin *Strongylocentrotus purpuratus* were very sensitive to 16 different petroleum fractions, but especially to the heavier crude and bunker oils. Van Gelder-Ottway suggests that the explanation may lie in Kűhnhold's (1969) report that emulsified, heavier petroleum fractions were more toxic than lighter ones to herring eggs and larvae. Fine dispersions of oil in seawater, up to 1.0 ppm, can persist for several weeks (Parker, et al., 1971), suggesting that significant amounts of emulsified oil could remain dispersed for extended periods in harbors, where the water is frequently agitated by the activity of vessels. Spooner (1968a) found that crude oil droplets passed undigested through the gut of mussels (*M. edulis*) and were then digested by ciliates Spooner (1968b).

Toxicity of oil-water emulsions to intertidal gastropods (*L. littorea*, *L. littoralis* and *Patella vulgata*) were evaluated by Van Gelder-Ottway (1976) for concentrations ranging from 0.625 - 20.0 ppt emulsion of crude oil in sea water after 6 and 24 hours exposure plus a five-day recovery period. *L. littorea* and *L. littoralis* mortalities were negligible after 6 hours of exposure to all concentrations of oil-water emulsion and low (8% and 16%) after 24 hours of exposure at the highest concentrations. However, after only 6 hours of exposure, *P. vulgata* suffered mortalities ranging from 10% at a concentration of 0.625 ppt to 58% at 20.0 ppt. For comparison, 6 hours of exposure to undiluted crude oil killed 28% of *L. littorea*, 64% of *L. littoralis*, and 100% of *P. vulgata*, whereas mortality in seawater was negligible for all species.

The effect on toxicity of mixing oil and fuel with water may be pertinent to harbors where vessel activity may cause sheens and slicks of oily bilge water, waste oil, and fuel to mix with water. To apply the above reports to pleasure craft discharges, and to aid comparison to more recent studies, it is important to understand their terminology. The USEPA (1993) has defined "dispersion" as spreading of oil on the water's surface and to some degree into the water column, "emulsion" as a fine dispersion of oil droplets in water, and "mousse" as a thick, foamy oil and water mixture formed when petroleum is mixed with water by wind and waves. Van Gelder-Ottway created brown, foamy emulsions, that she described as a dispersion of fine oil droplets in water, but sound like the current definition of an oil and water mousse. However, several of the above authors appeared to use the term emulsion to mean "fine dispersion" of oil droplets in water, in the sense of USEPA's definition. Thus, Van Gelder-Ottway's mixture was probably heavier than and the other authors' mixtures were probably more like emulsified, pleasure craft discharges.

Physical persistence of refined oils in the marine environment may also cause biological damage. Persistent oils include creosote and crude, residual fuel, tar and lubricating oils. Non-persistent oils include other distilled hydrocarbon oils, such as motor spirit, kerosene, gas, animal and vegetable oils. Persistent oils cause biological damage for a longer period of time, whereas non-persistent oils cause damage via their toxicity, but for a shorter period of time. After an oil spill at sea, non-persistent oils evaporate fairly rapidly, but persistent oils undergo a weathering process. Asphaltene content, wax melting point, viscosity and specific gravity increase; sulphur content decreases. Lubricating oils are persistent, but tend to be thin, in contrast to thick, heavy, weathered, crude and fuel oils. Weathered lumps of crude and fuel oils attach to algae and animals, adding weight and pulling them from their attachments. Persistent oils adhere to birds' feathers, destroying their insulating properties. (Van Gelder-Ottway, 1976) Thus, bilge oil and waste oils are persistent oils; diesel and gasoline are not. However, diesel persists somewhat longer than gasoline, according to comments by Coast Guard personnel.

Van Gelder-Ottway (1976) studied oil and dispersant mixtures and found that they were more toxic to limpets than were crude oil or dispersant, alone. This confirmed Spooner's (1968a) finding that dispersant and oil mixtures were more toxic to barnacle larvae and young adult mussels than straight crude oil. Van Gelder-Ottway also suggested that mixtures of oil and dispersants on the open sea would rapidly disperse and degrade. However, severe environmental impacts would occur when dispersants were applied to nearshore spills, because the mixture becomes dispersed in the water column, instead of remaining on the surface. For example, Smith (1968) found barren tidepools following treatment with dispersant after the *Torrey Canyon* spill. Mortalities of limpets and rock pool algae were particularly evident.

G.J. Miller was a leader in research on ecotoxicology of petroleum hydrocarbons in the marine environment during the peak of interest in the 1970s and 1980s. His 1982 review paper in the *Journal of Applied Toxicology* presents a broad picture of this subject. He first described how petroleum hydrocarbons are transported and transformed in the marine environment. Transport occurs by dispersion, volatilization, dissolution, emulsification, sorption, sedimentation and bioaccumulation. They are transformed by chemical processes, such as photolysis, polymerization, and oxidation/reduction and by biological processes, such as microbial degradation and metabolism within organisms. Photochemical and microbiological processes are the most important.

Photochemical transformations of crude and fuel oils produce reactive radicals, potentially toxic intermediate peroxides and hydroperoxides, carboxylic acids, esters, oxygenated aromatic compounds, carbonyl compounds and carbon dioxide. Bacteria can oxidize aromatic hydrocarbons from single-ring compounds, such as benzene, to multi-ring or polycyclic aromatic hydrocarbon (PAH) compounds, such as benzo[a]pyrene. Some bacteria can oxidize PAHs, such as naphthalene, into metabolic products, like salicyclic acids, naphthoic acids and naphthyl alcohols. Experimental evidence indicates that many marine and estuarine microbes can quickly break down certain constituents of petroleum hydrocarbon mixtures, but the degradation of PAHs can be very slow. It is thus difficult to predict the breakdown or persistence of various petroleum compounds by marine microorganisms. (Miller, 1982)

Miller also evaluated lethal and sub-lethal toxicities of petroleum hydrocarbons to marine organisms, noting several, basic features:
"i. The impact of oil, even in chronic amounts, affects a wide diversity of marine organisms, from plants through to invertebrates and vertebrates. However, considerable variation in tolerances and sensitivities are observed amongst species and between life stages.
ii. The impact of oil on marine organisms, generally, tends to increase according to the following habitat classifications: Pelagic > Sub-tidal > Intertidal. One notable exception is the high

mortality of seabirds, such as auks and sea ducks, in pelagic regions as a result of chronic oil exposure.
iii. Sublethal studies indicate significant physiological and behavioral sensitivities amongst many invertebrates, e.g., crustaceans, larval and juvenile forms of fish. Embryotoxicity and disruption of ionic regulation has been observed amongst seabirds." (Miller, 1982; 92)

Studies of lethal toxicities of crude and fuel oil mixtures with water found that refined (No. 2 fuel) oil was generally more toxic than crude oils and that fish and decapod crustaceans were the most sensitive to both. Intertidal species were more tolerant than others, which Miller attributes to their ability to insulate themselves from short (96 hours) exposures. Brown shrimp larvae and molting stages of other decapods were more sensitive than adults. There was no clear pattern regarding sensitivity of eggs. (Miller, 1982)

Miller (1982) also reported that experiments on sub-lethal responses of marine species determined that some ecologically important species were sensitive to and others were tolerant of low, persistent concentrations of soluble, petroleum hydrocarbons. He noted that photosynthesis, filter feeding, survival and fecundity were affected in some species. Low concentrations in seawater and sediments can cause tainting of edible species; this has been reported for fish, crustaceans and molluscs. Sub-lethal concentrations range from 10 ppb to over 1000 ppb and larvae and juveniles are the life stages that are most sensitive to concentrations under 1000 ppb of soluble aromatic hydrocarbons.

Miller concluded that data were too non-specific or otherwise inadequate to draw conclusions about environmental levels of soluble aromatic hydrocarbons in different marine habitats. He suggested it may be in the range of <10 - 100 ppb for seawater and intertidal water and reported that levels near 100 ppb are common in polluted estuarine and coastal waters. If this is correct, the predicted effects on marine organisms exposed for a long period of time are: bioaccumulation of hydrocarbons in body tissues, tainting of edible tissues, accumulation in brains of vertebrates, behavioral changes, metabolic stimulation or depression, reduced reproductive success, and mortality of sensitive larvae and juveniles. Lethal and sub-lethal effects vary among classes of marine organisms, making it difficult to predict safe exposure levels.

He noted that there were insufficient studies at that time to fully determine the lethal toxicities of marine species to soluble, aromatic hydrocarbons. However, he noted that polycyclic aromatic hydrocarbons (PAHs) may be the most significant human health risk from consuming contaminated seafood, because they are well-documented as carcinogens. Many of the compounds of oxygen, nitrogen and sulfur that occur in petroleum are toxic or otherwise detrimental, but their effects in the marine environment are poorly understood.

Miller (1982) reported two general characteristics of ecosystem responses to petroleum contamination, gleaned from his critical review of the literature:
i. Simplification of ecosystem structure and reversion of succession by at least one stage following acute exposures;
ii. Gradual modifications of community structure, such as diversity and increase of opportunistic species, and of basic processes, such as nutrient flux and production, in the case of chronic

exposures.
He noted that recovery times appeared to be relatively short for plankton, but longer for other communities.

In contrast to Miller's inconclusive findings about fish eggs, Pearson et al. (1985) found that seawater contaminated by crude oil did affect reproduction of Pacific herring (*Clupea harengus pallasi*). The highest concentration of total hydrocarbons in these mixtures was 28 ppm and the highest exposure to monoaromatic hydrocarbons was 4.7 ppm. No effect was observed after two hours of exposure of eggs or sperm; hatching success of attached eggs exposed for 24 hours in the first 29 hours after fertilization was not affected. However, a significantly higher percentage of larval fish hatching from exposed eggs had abnormalities and those in which a large amount of oil was present as droplets on the eggs showed the most severe effects. Thus, fresh oil dispersed into the water column, where it can attach to eggs, is most likely to affect fish larvae.

Recently, Heintz et al. (*in press*) determined that embryos of pink salmon *(Oncorhynchus gorbuscha)* were sensitive to polycyclic aromatic hydrocarbons in weathered oil. Mortality of embryos exposed to a total PAH concentration of only 1 ppb were significantly higher than controls. This suggests that fish eggs may be more sensitive to very low levels of PAH than previous research had indicated. Further Heintz et al. (*in prep*) observed increased mortality in eggs spawned in 1989 by two-year old salmon which had been exposed to oiled streams as eggs and larvae. In comparison, eggs spawned by the next year class of adult fish showed increased mortality only if they were released in zones that were still contaminated. This suggests that the 1989 year class of spawners acquired sublethal damage during their exposure as eggs and larvae.

Petroleum Hydrocarbon Accumulation in Marina Sediments and Its Environmental Significance

Because of the massive contribution of urban runoff to petroleum hydrocarbons in harbor sediments, it is difficult to determine the portion that may be attributed to pleasure craft discharges. For example, McMahon (1989) found elevated petroleum hydrocarbons in sediments of enclosed marinas that contained fuel docks and received upland drainage. Even the elevated levels in his samples (106-187 mg/kg wet weight) were lower than those reported by other scientists (280-366 mg/kg wet weight and over 1000 mg/kg wet weight) for polluted sediments. Thus, he did not consider his samples to be indicative of significant water pollution.

Voudrias (1981) conducted an intensive study of three estuarine creeks in Eastern Virginia to determine the effects of marinas on levels and types of petroleum compounds found in their sediments. Two of the creeks experienced activity by marinas, boat repair yards, and commercial fishing operations. The third was surrounded by marsh and woodland and seldom used by boats.

He found that sediments from the creeks with marinas contained significantly higher levels of hydrocarbons that indicated oil pollution, compared to the third creek. The creek with the largest number of marinas had the highest levels of hydrocarbons, whereas the creek with very little boating activity contained the lowest levels. Total aliphatic hydrocarbon concentration in the sediment was 16 µg/g in the creek without marinas and 87-93 µg/g in the two creeks with marinas. Total aromatic hydrocarbon concentration was 2 μg/g in the creek without marinas, 27 μg/g in the creek with most marinas and 9 μg/g in the creek with fewer marinas.

Voudrias also found that hydrocarbons associated with marina activities included aliphatic compounds, such as phytane and some hopanes, and combinations of polycyclic aromatic compounds, such as napththalenes, phenanthrenes and anthracenes that were indicative of petroleum contamination. All three creeks contained pyrogenic, polycyclic aromatic hydrocarbons, that were indicative of inputs from runoff.

It can be difficult to distinguish the effects on benthic (bottom-dwelling) communities of sediment contamination by chronic, low-level, local discharges of petroleum hydrocarbons, such as those produced in marinas, from the effects of polluted runoff. Olsen et al. (1982) reported on two studies that demonstrated the impacts of such localized discharges. One study monitored North Sea benthic communities exposed to chronic, low-level petroleum discharges from an undersea storage tank and two oil production platforms for four years after production began. Sediment concentrations of aromatic hydrocarbons increased from 10 to 25 ppm near the storage tank and one platform. There was no significant difference in the total density of benthic fauna after one year, total densities were somewhat reduced after two years, and both total densities and number of species were much reduced after four years. This study was unusual, because results were not influenced by the presence of urban runoff. Another study followed benthic communities after a waste water treatment plant in Finland began removing 90-95% of hydrocarbons from the discharges of an oil refinery. Two years after treatment began, mean annual hydrocarbon levels in sediments had declined from 920 ppm to 530 ppm. After three years, the number of macrobenthic species had increased from four to nine and the total biomass had increased from 27.6 to 282.5 grams wet weight per square meter.

Studies Pertinent to the Coast of Southern California

The Southern California Bight extends from Point Conception in California to Cabo Colnett and Bahia de San Quintin in Baja California. There, the Southern California Gyre, a current that traps warm water, has allowed specific, regional populations of marine life to develop, and serves as a reservoir of materials flowing from the land, air and sea. Runoff from land and sewage outfalls are the primary sources of petroleum hydrocarbon contamination of the sea and harbors in the region. Large vessel and facility spills are important, too. The Gyre exacerbates the potential for contaminant loading and resultant environmental effects of the large, urban, coastal population. (Mearns, et al., 1991)

Woodward-Clyde Consultants (1996) cited U.S. Coast Guard data on oil spills into San Diego Bay, indicating an annual average of 2,500 gallons per year during 1985-1989. They estimated that this volume would contribute 500 kg per year of PAHs, considering that PAHs were 6% by weight of diesel fuel, the major type of fuel spilled in the Bay. They concluded that fuel spills from vessels were a major source of PAH loadings to San Diego Bay. PAH loading from reported pleasure craft spills can be estimated from the above ratio of 0.2 kg PAH per gallon of oil. Thus, for 1996 and 1997 the annual average of 226 gallons of oil reported spilled by Los Angeles/Long Beach area pleasure craft (Table 4.) contributed 45 kg of PAH to harbors in that area and the annual average of 248 gallons reported spilled by San Diego area pleasure craft

(Table 5.) contributed 50 kg PAH to harbors in that area.

A study of natural oil seeps in the Santa Barbara Channel provided further insights on effects of chronic, low level oil emissions on communities of Southern California mussels (*Mytilus californianus*) (Straughan, 1981). Mussel communities exposed to natural seeps were compared to unexposed communities. Petroleum was highly correlated with changes in community composition. However, the quantity of trapped sediment was more important to changes in community composition and was more closely related to individual species distributions than was petroleum.

Kanter et al. (1983) investigated the toxicity of oil to selected California sport and commercial fish and shellfish: California halibut (*Paralichthys californicus*); northern anchovy *(Engraulis mordax*); and California mussel (*Mytilus californianus*). Embryos, larvae and adults of these species were exposed to the water soluble fraction of Santa Barbara crude oil at concentrations of 5 ppb, 50 ppb and 500 ppb. In general, all species showed some accumulation of petroleum hydrocarbons in their tissues and reduced survival, proportional to concentrations of petroleum to which they were exposed. Halibut larvae had more deformities and those exposed at 500 ppb were significantly smaller than controls. Some damage to adult halibut gill and liver tissues was observed. Growth of anchovy larvae was depressed. At 50 ppb or more, anchovy larvae had deformities that interfered with feeding and growth. Adult anchovies were able to purge their tissues of petroleum hydrocarbons up to a threshold level, beyond which the compounds accumulated. Their gill tissues were damaged at 500 ppb. Exposed mussel larvae grew more slowly than controls and growth rates were inversely proportional to concentration. Like anchovies, there appeared to be a threshold above which adult mussels accumulated petroleum hydrocarbons in their tissues.

Although these experiments dealt with crude oil, they did examine low concentrations and they can provide insights on the likely effects of low level, refined petroleum compounds on economically important Southern California species. Based on Van Gelder-Ottway's (1976) finding that refined petroleum is often more toxic than crude oil, effects observed by Kanter would be expected to occur at lower concentrations of refined petroleum.

Mearns et al. (*in press*) evaluated national "Mussel Watch" program data. Mussels (and oysters) feed by filtering large volumes of water, so they tend to accumulate contaminants from the water column. Because they metabolize PAHs slowly, they are good indicators of the presence of PAHs in the water column. Tissues of mussels at eight sites in California had the lowest levels of PAHs, most of which were on the open coast, including a site at Point La Jolla in the San Diego area (98 ppb dry weight) and one in Santa Monica Bay in the Los Angeles area (131 ppb dry weight). However, three California sites were among the 25 sites with the most PAH contamination in mussels. These were at Coronado Bridge (6,912 ppb dry weight) and Harbor Island (4,589 ppb dry weight) in San Diego Bay and at a fishing pier in San Pedro Harbor (3,906 ppb dry weight) in the Los Angeles area. The authors proposed that runoff and wastewater discharges from major urban areas were probably the primary factors influencing PAH levels in mussels. This finding suggests that Southern California harbors have elevated PAH levels, but the open coast does not.

Fairey et al. (1996) reported on the toxicity of sediments in San Diego Bay and their effects on benthic communities. They classified numerous sites as having benthic communities that were undegraded, transitional, or degraded. The benthic community index used in this study was based on characteristics of the community, such as presence of specific indicator species, pollution indicator species, species richness, etc. This simple approach was chosen, because San Diego Bay has a variety of habitats, that may need to be evaluated by specific index variables.

This study appeared to offer an opportunity to determine whether marinas with storm drains had elevated levels of PAH in their sediments and whether the facilities, themselves, or the level of PAH in their sediments was clearly associated with degraded benthic communities. Major marina basins in San Diego Bay are located in north San Diego Bay at Shelter Island and Harbor Island; in mid San Diego Bay at Glorietta Bay, the Naval Amphibious Base, and the Convention Center; and in south San Diego Bay at the Coronado Cays and Chula Vista. These marina basins generally receive storm drain discharges.

Sediment concentrations of PAH were evaluated with respect to:
Threshold Effects Level (TEL)
   311.70 ppb for total low molecular weight (Total LMW) PAHs
   655.340 ppb for total high molecular weight (Total HMW) PAHs
Probable Effects Level (PEL)
   1442.00 ppb for total low molecular weight (Total LMW) PAHs
   6676.14 ppb for total high molecular weight (Total HMW) PAHs
These levels are defined mathematically with regard to statistical analysis of the data. However, TEL generally means that PAH levels below TEL are not toxic and PAH levels above PEL generally cause toxic effects. Toxic effects would be expected to occur occasionally when PAH levels fall between TEL and PEL.

Note that for low molecular weight PAH (LMW):
Below TEL (generally not toxic) = 0 - 311.7 ppb
Below PEL (occasionally toxic) = 311.7 - 1442 ppb
and for high molecular weight PAH (HMW):
Below TEL (generally not toxic) = 0 - 655.34 ppb
Below PEL (occasionally toxic) = 0 - 655.34 ppb

Fairey et al.'s (1996) results are presented in Table 9.. Basins with most or all stations below TEL (generally not toxic) were considered to have a low level of PAH. Basins with most or all stations below PEL (occasionally toxic) were considered to have a moderate level of PAH.

Table 9. Level of PAH Concentrations and Status of Benthic Communities for Marina Basins in San Diego Bay (Fairey et al., 1996)

Location of Marina Basin	Low Molecular Weight PAH Concentrations	High Molecular Weight PAH Concentrations	Benthic Community Status

Shelter Island	Low: 10 stations below TEL	Moderate: 10 stations below PEL	Not Analyzed
Harbor Island	Low: 12 stations below TEL 1 station below PEL	Moderate: 13 stations below PEL	6 Sites Undegraded
Convention Center	Low: 4 stations below TEL	Moderate: 4 stations below PEL	3 Sites Transitional
Glorietta Bay	Low: 4 stations below TEL	Moderate: 4 stations below PEL	2 Sites Undegraded 1 Site Transitional
Naval Amphibious Base	Low: 7 stations below TEL	Moderate: 2 stations below TEL 5 stations below PEL	3 Sites Undegraded
Coronado Cays	Low: 7 stations below TEL	Low: 6 stations below TEL 1 station below PEL	2 Sites Undegraded 1 Site Degraded
Chula Vista	Low: 3 stations below TEL	Low: 3 stations below TEL	3 Sites Degraded

Based on McMahon's (1989) study of Australian marinas, one would expect undegraded sites to occur in the absence of marina activities and storm drains. Because all of the basins have marinas and some storm drain influence, but some have undegraded benthic communities, this prediction was not supported by the data.

Based on toxicity studies, one would predict differences in levels of PAH to correspond to differences in benthic community status. Because all marina basins had low levels of low molecular weight PAH, LMW levels would not be helpful in explaining differences in benthic community status. On the other hand, five basins had moderate levels of high molecular weight PAH and two basins (Coronado Cays and Chula Vista) had low levels of high molecular weight PAH. However, differences in HMW PAH levels do not appear to correspond to differences in benthic community status. The five basins with moderate levels of HMW PAH have sites with degraded, transitional and undegraded benthic communities. The two basins with low levels of HMW PAH have degraded and transitional benthic community sites. Therefore, this prediction, too, was not supported by the data.

Two reasons may explain the lack of correspondence between benthic community status and status of PAH levels or presence of marinas and storm drains. First, the authors reported that classification of benthic communities was based on a limited data set without site comparison to an existing known reference. Second, factors such as other contaminants, sewage and nutrient enrichment, water circulation or differing combinations of such factors likely have a greater influence on benthic communities than PAH levels, alone.

In general, the inputs and impacts of pleasure craft oil and fuel spills on the environment of coastal marinas in Southern California have not been clearly determined. Focused studies would be helpful in sorting out the contribution of pleasure craft and the fate and effects of their oil and fuel spills in confined marina waters.

Other Issues Related to Pleasure Craft Petroleum Discharges

Two-stroke engines used in outboard motors and personal watercraft discharge oil and fuel to marine and inland waters. Older models discharge unburned oil and fuel that drain into the crankcase to prevent hydraulic lock and engine damage; up to 56% may be discharged as exhaust (Jackivicz and Kuzminski, 1973). These engines have raised public concern in lakes frequented by water-skiers, sport fishers and personal water craft users. A recent study (Oris et al., 1998) assessed water collected from Lake Tahoe in areas with high and low levels of boating activity. Elevated PAH levels (5-70 ng total PAH/L) corresponded to peak boating activity. Fish larvae grew 46% less in water from areas of high boating activity. There was a dose response relationship between PAH levels, mortality and reproductive ability of zooplankton.

These engines are thus likely to elevate PAH concentrations in coastal harbors with high levels of activity by personal watercraft, water ski boats, and other outboard motor-powered vessels. Newer, more expensive, four-stroke engines emit 97% less pollution than older two-stroke engines, and 90% less pollution than newer two-stroke engines (Long, 1997). Working with dealers, event promoters and clubs to educate current and prospective vessel owners on the value of shifting to newer technology would help to resolve this problem.

A more recent concern is the emission of methyl-*tert*-butyl ether (MTBE), an oxygenated additive that replaces smog-producing agents in gasoline. MTBE is much more soluble than other, volatile components of gasoline, is not readily biodegradable and is not degraded by exposure to ultraviolet light. (Tahoe Research Group, 1997) It also migrates with groundwater and is suspected of causing cancer in rodents, but human data is not available. MTBE is primarily a concern for drinking water supply. For example the City of Santa Monica lost about half of its water supply when nine drinking water wells were closed because of MTBE contamination. (McClurg, 1998) A USEPA blue-ribbon panel has been established to consider how to ensure public health, while continuing to improve air and water quality (USEPA, 1998).

Marine engines also contribute to atmospheric pollution by discharging PAH and other products of fuel and oil combustion (*personal communication*, Jack Anderson, Columbia Analytical Services, Inc.). PAHs attached to particulate matter are washed by rainfall to marine waters or onto land, where they may become a constituent of urban runoff (*personal communication*, Richard Smith, San Diego County Air Pollution Control District). Atmospheric discharges and precipitation to watersheds were not the focus of this report, but they would merit attention in understanding the broader environmental impacts of small craft petroleum discharges.

Conclusions and Recommendations

Sinkings, groundings and chronic, small spills of fuel, oily bilge water, and waste oil by small craft have the potential to affect marine life in poorly flushed Southern California marinas and harbors. Many commercial fishing vessels are similar in size to Southern California recreational boats, so these conclusions and recommendations also generally apply to them.

Obtaining accurate estimates of the volumes of small craft fuel and oil spills and efforts to remediate them are hampered by under-reporting. This situation appears to be influenced by disincentives, such as potential fines, reluctance to report a friend, and the risk that diligent reporting may cause a facility to appear to have an unusually high spill rate. Lack of awareness by boat owners of the impacts of accumulated spills of oily bilge water, fuel and waste oil also probably contributes to under-reporting and to the continued occurrence of these discharges.

Small craft spills are among many sources of refined, petroleum hydrocarbon contamination of water and sediments in marinas and harbors. Storm drains and other land-based sources of contamination are major contributors of these pollutants, although exact amounts, relative amounts, and impacts of contributions by small craft and land-based sources have not been definitely determined. Current interest in the incidence and the social, environmental and economic impacts of small craft spills, coupled with the scarcity of data, suggests that focused studies could provide timely guidance for decision makers and educators.

There are no firm answers to the question, "What are the environmental impacts of pleasure craft oil and fuel spills?" However, available data strongly suggest that these chronic, low level discharges of refined petroleum products contribute to degradation of habitats and marine life in poorly flushed coastal marinas and harbors of Southern California through bioaccumulation, sediment accumulation, toxicity to some life stages, and associated behavioral, developmental, reproductive and physiological effects. Polycyclic aromatic hydrocarbons (PAHs) are the primary, toxic constituents of concern. Large discharges of oil-fuel mixtures and the fuel additive, methyl *tert*-butyl ether (MTBE), is of concern with regard to 2-stroke engines used in some personal watercraft and outboard motors. Atmospheric discharges from marine engines are further sources of concern. These effects contrast with the blanketing or smothering effects of large, crude oil spills on seabirds and shorelines.

The Precautionary Principle, adopted at the Second International Conference on the Protection of the North Sea in 1987, "argues that every effort should be made to relieve the potential burdens on the environment resulting from the input of foreign substances," or, "Prevention is better than cure," (GESAMP, 1990:104). This leads to the question, "Are the actions for the protection of the environment, taken on the basis of our present knowledge, sufficient, or do we have to assume that the future holds risks which are beyond our knowledge and therefore need to be taken into account in our current pollution prevention strategies?" (GESAMP, 1990:105).

Answering this question definitively with regard to small craft oil and fuel spills would require considerable research. Available data suggest the likely answer is that more efforts are needed to protect the environment from the effects of chronic, low level discharges of oil and fuel by small craft in coastal marinas and harbors. This is partly because the confined waters in which they occur are generally poorly flushed, partly because they are almost certainly greater than they are reported to be, and partly because they add to the total volume of petroleum hydrocarbon discharges from storm drains and other sources to harbors. Several, cost-effective and relatively simple measures could significantly reduce discharges if adopted by small craft owners, maintenance workers and small craft facility managers. Agencies, scientists, and educators also have roles to play.

In general, it is important to prevent sinkings and groundings through regular vessel maintenance, knowledge of harbor geography (shoals) and Rules of the Road (rights of way), and by safe boat handling practices. Leaks and spills can be prevented by "good boat-keeping," that is, by regular engine maintenance, bilge oil management, careful fueling procedures, and careful handling, collection and recycling of used oil. Re-engineering vessel fueling systems and engine room spaces can further reduce the possibility of fuel and oil spills.

The following recommendations are provided to assist pleasure craft and commercial fishing vessel owners, maintenance workers, marina and harbor managers, port authorities, government agencies, educators, and scientists in reducing the incidence of small craft oil and fuel spills. They are based on discussions with boaters, boating business personnel, Coast Guard active duty and auxiliary personnel, Sea Grant staff and other environmental educators, staff of regulatory agencies, port and harbor districts, harbor patrol and lifeguard service personnel, and the author's experiences in conducting consensus building and educational programs on preventing pollution from marinas and recreational boating.

1. Work with the boating community to develop sustainable leadership in encouraging and educating boaters and boating businesses to improve small craft pollution prevention.

2. Work with the boating community to advise boat owners, maintenance workers, marina and harbor managers and product vendors on how oil and fuel spills affect the boating environment and to encourage an ethic of environmental stewardship.

3. Educate boat owners, maintenance workers, and marina and harbor managers on sound methods and technologies for preventing and remediating spills of small craft oil and fuel.

4. Work with vessel manufacturers to encourage redesign of vessel fueling systems and engine spaces to minimize possibilities for oil and fuel spills

5. Educate and encourage boat owners to inspect their vessels and conduct maintenance regularly to prevent leaks and sinkings or to hire a contractor to perform these services regularly.

6. Educate boat owners on safe boat operations, rules of the road, and local harbor geography to reduce incidence of collisions, groundings, and sinkings that may lead to leaks and spills.

7. Establish convenient, affordable systems for collecting, handling, and recycling used oil. Educate boat owners, maintenance workers and marina and harbor managers on the availability of these systems and on the importance of proper handling and recycling of used oil.

8. Encourage the boating community to participate actively in watershed management programs to reduce land-based pollution of coastal marinas and harbors.

9. Encourage increased and more rapid reporting of small craft oil and fuel spills, including sheens and slicks, to facilitate cleanup efforts and understanding of spill sources and causes.

10. Encourage local, state and federal agencies to consider developing an incentive or amnesty system that would encourage members of the boating community to report spills, when conscientious reporting may result in legal action against the reporting party or a friend and cause a facility to appear to have a high rate of spills.

11. Encourage the United States Coast Guard to:
a. Develop a uniform system of data recording on causes of pleasure craft and commercial fishing vessel fuel and oil spills by local Marine Safety Offices, nationwide, to complement their existing records on volumes of spills from various vessel types; and
b. Make recent annual data summaries on volumes and causes of spills by various types of small craft and related facilities readily available from each Marine Safety Office to assist decision makers and educators in identifying trends and current priority problems in each local region.

12. Consider installing bilge water pumpout and oil recovery stations in harbors where small craft bilge water is a significant source of petroleum hydrocarbon discharges.

13. Encourage focused studies to determine more accurately the amounts, the social, economic and environmental impacts, and the relative contributions of petroleum hydrocarbons by small craft and land-based sources to coastal marinas and harbors in Southern California.

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