Report on Possible Water Pollution from the Use of Two-Stroke Carbureted Marine Engines

Prepared for the
Vermont Water Resources Board

Prepared by the
Vermont Agency of Natural Resources
Department of Environmental Conservation
Water Quality Division
Waterbury, Vermont

January 19, 1999

In 1996, the U.S. Environmental Protection Agency (U.S. EPA) issued regulations to produce cleaner technology for gasoline spark-ignition marine engines. Most spark-ignition outboard engines are two-stroke carbureted engines but also include the new generation of fuel efficient and low emission fuel injected and direct-injected two-stroke, and carbureted and fuel injected four-stroke engines.

The market is currently dominated by carbureted two-stroke engines that are available between 2 and 300 horsepower. Four-stroke engines are available with ratings between 2 and 130 horsepower and are a growing segment of the market. Direct fuel injection two-stroke engines are recent introductions in the higher horsepower range, including 90, 115, 135, 150, 175, 200 and 225 horsepower. Direct fuel injection is also being considered by manufacturers for much lower horsepower engines because of its improved fuel economy and lower emissions . The U.S. EPA regulations encompass outboard engines and gasoline marine engines produced for personal watercraft and jet boats. By the year 2025, the U.S. EPA expects a 75% reduction in hydrocarbon emissions resulting from these regulations (U.S. EPA, 1996a). The goals of these regulations will be reached by a flexible 8 year phase-in schedule beginning in 1998 (U.S. EPA, 1996b).

Due to California's serious air quality situation and mild climate, encouraging greater boating activity than most other states, a more proactive approach was needed to address immediate problems. The California Air Resources Board (CARB) has done extensive research on this issue. In order for California to reach their health-based air quality standards, they instituted a three tier program on December 10, 1998. Under this program a typical marine engine would become 70% cleaner by 2001 and 90% cleaner by 2008. In addition to California's immediate air pollution concerns, they were also prompted by finding constituents of gasoline additives used to promote greater fuel efficiency in water supplies (CARB, 1998).

Agencies such as the East Bay Municipal Utility District, the Tahoe Regional Planning Agency, and the Santa Clara Valley Water District determined that one way to mitigate the levels of gasoline constituents found in water supplies is to restrict or ban the use of gasoline spark-ignition marine engines.

Water and Air Quality Concerns

[Excerpt from CARB,1998] Little is known of the environmental fate of many exhaust, gasoline, and lubricating oil components. An analysis of the impacts of marine engine exhaust, including unburned gasoline, on the aquatic environment is difficult due to the highly variable physical and chemical natures of the exhaust components and the variety of gasoline formulations and additives. Evaporation, deposition, and degradation rates of each of these components, as well as other environmental conditions, would influence each compound's fate, transport and toxicity. Both in-situ and in-tank studies have been conducted on marine engine exhausts while the degree of impact on the aquatic environment is still under investigation.

It is estimated that gasoline spark-ignition marine engines discharge an unburned fuel/oil mixture at levels approaching 20% to 30% of the fuel/oil mixture consumed. This unburned gasoline may include but is not limited to the following constituents: methyl tertiary-butyl ether (MTBE), poly-aromatic hydrocarbons (PAHs), xylenes, ethyl benzene, toluene and benzene (CARB, 1998).

Gasoline marine engines are one of the largest non-road contributors of hydrocarbon emissions, preceded only by garden and lawn equipment. Non-road sources on the average contribute approximately 10% to the average hydrocarbon inventories. Hydrocarbon contributes to ground level ozone which is known to cause irritation to the respiratory system (U.S. EPA, 1996a).

Approximately 30% of all gasoline in the U.S. is reformulated, and almost all gasoline contains fuel oxygenates that are used to promote complete combustion and reduce exhaust emissions of carbon monoxide and reactive organic compounds (U.S. EPA, 1998a). MTBE is used by most refiners to produce reformulated gasoline required in 27 states and the District of Columbia (McCarthy *et al*. 1998). MTBE is the most commonly used chemical compound for blending with gasoline due to its high octane rating, ease of mixing with gasoline, and dilution of undesirable components such as sulfur, benzene, and aromatics (CA EPA, 1998).

MTBE has a concentration of 11% by volume in California gasoline. While this has helped air quality in states with smog problems because it helps fuel burn cleaner in the more efficient automobile engine; MTBE is being released in the unburned fuel emitted by the two-stroke engine. MTBE, listed on the Drinking Water Contaminant Candidate List by U.S. EPA (1998b), is highly soluble in water, does not attach readily to sediments, and does not biodegrade readily. MTBE has been discovered in groundwater, lakes and reservoirs used for drinking water supplies (CA EPA, 1998).

One study, conducted at Donner Lake in the California Sierra mountains, attributed recreational boating as the most important source of MTBE, approximately 86% during sampling. Neither highway runoff nor atmospheric deposition contributed significantly. During the week of July 1-7, 1997 the loading of MTBE to the water column through the direct exhaust of unburned fuel was estimated. It was estimated that the 386 boats on Donner Lake during this time period had passed approximately two gallons of uncombusted fuel each into the water to reach these levels. MTBE concentrations ranged between $<0.1 \mu g \cdot L^{-1}$ to 12 $\mu g \cdot L^{-1}$ (Reuter *et al*. 1998). Though these values were below the U.S. EPA drinking water advisory of 20-40 $\mu g \cdot L^{-1}$, the ability to taste and smell MTBE can occur at levels as low as $2.5 \mu g \cdot L^{-1}$ (CA EPA, 1998).

Typically, most gasoline has MTBE added, though not at levels required for reformulated gasoline. Reformulated gasoline containing oxygenates such as MTBE are not required in Vermont, though it may be present in gasoline delivered to southern Vermont due to the close proximity of Massachusetts and southern New Hampshire where it has been mandated. It is possible that Vermont may be getting the remaining part of a shipment from these states in order for companies to be cost efficient (Moye, VT DEC 1998, pers. comm.).

Benzene, a clear colorless aromatic hydrocarbon, is present in gasoline at levels approaching 1.5%. Benzene is present in both gasoline fuel and is also formed during the incomplete combustion of gasoline. Emissions of benzene in outboards result in the release of volatile organic compounds. The International Agency for Research on Cancer has classified benzene as a Group 1 carcinogen, an agent that is carcinogenic to humans. Follow-up studies have suggested a relationship between exposure to benzene and the occurrence of leukemia, genetic changes in humans, and harmful effects to bone marrow (U.S. EPA, 1996c). Benzene has been classified as slightly persistent in water with a half-life of 2 to 20 days. Approximately 99.5% will volatilize into the air (U.S. EPA, Jan. 1988).

1,3-Butadiene, formaldehyde, and acetaldehyde are all volatile organic compounds which are present in exhaust emissions. All three have been classified as probable carcinogens and/or mutagens by the U.S. EPA. (U.S. EPA, 1996c). Formaldehyde is slightly persistent in water (half-life of 2 to 20 days) with 99% ending up in the air (U.S. EPA, May 1989a). Acetaldehyde is moderately persistent with the same half-life of formaldehyde, though 27% will remain in the water (U.S. EPA, Feb. 1989). 1,3-Butadiene is non-persistent lasting only a few days in the water before it almost completely volatilizes (U.S. EPA, July 1986).

Toluene is a colorless liquid with a sweet pungent odor that may cause mutations. Exposure may cause irritation to the eyes, throat and nose. Repeated exposure can damage bone marrow, liver and kidneys. Toluene has moderate acute toxicity to aquatic life, though it is non-persistent in water with all but 0.5% entering the air (U.S. EPA, Nov. 1986).

Ethyl Benzene is a component of fuel which causes eye, nose and throat irritations and has a high acute and chronic toxicity to aquatic life. It is also non-persistent in water (99.5% volatilizing) (U.S. EPA, July 1988).

Xylenes are a group of similar chemicals used as a solvent in making gasoline. They can irritate nose, eyes and the throat and may damage a developing fetus. Xylenes are similar to toluene in toxicity to aquatic life and persistence in water (U.S. EPA, May 1989b)

Carbon monoxide, a by-product of combustion, is a gas that gives no sign of its presence. U.S. EPA regulations (1996b) does not specifically target carbon monoxide emissions from marine engines since very little is known about its health effects. However other research shows that carbon monoxide is a serious health threat. Carbon monoxide at certain levels has been shown to negatively impact the central nervous system and according to the U.S. EPA is of special concern to the elderly, pregnant women, small children and people with anemia or chronic heart disease (U.S. EPA, 1996c).

A benefit from the implementation of the U.S. EPA and CARB regulations will be reduced exposure to toxic air contaminants found in gasoline and gasoline-powered engine exhaust. This is the result of improved technologies being implemented with increased fuel efficiency. Emissions from combusted and unburned lubricating oil will be reduced as a result of the use of more oil efficient technologies (CARB, 1998).

Outboard Engine Technology

(Partial excerpt from California Air Resources Board staff report, 1998, used with permission, with clarifications in brackets).

Over the last decade, four-stroke engines have enjoyed an increasing market share in low and mid-horsepower outboard engines (under 130 hp). While the four-stroke engines typically cost more to purchase, they are quieter, have less vibration, and use about 30 percent less fuel compared to carbureted two-stroke engines. They also do not produce the objectionable smoke or odor associated with carbureted two-strokes. These advantages have caused continued growth in the four-stroke market segment.

Despite the advantages of four-stroke outboards, a market continues to exist for two-strokes in engines requiring lower initial cost (low horsepower engines) or high horsepower with minimum weight (high horsepower engines). This has caused the development and marketing of lower-emission two-stroke engines using special fuel injection systems. These "direct-injection" engines are currently being marketed as premium high horsepower engines. The direct-injection two-stroke engines are primarily those engines over 130 hp (the 90 hp and 120 hp OMC [Outboard Marine Corporation] engines are also direct injection). Manufacturers have product introductions planned for lower horsepower applications in the future. The current versions of direct-injection two-stroke engines enjoy fuel economy approaching four-stroke engines, reduced smoke and odor, and good performance. They do not currently match the emissions capability of optimized four-stroke engines.

1. Conventional Two-Stroke Engines

All internal combustion piston engines, whether they be used in lawnmowers, automobiles, or watercraft, produce power by burning a fuel which heats the gases in the engine's cylinder causing them to "push" on the piston in the cylinder. This linear motion of the moving piston is converted to rotary motion through a connecting rod and crankshaft, just as any hand-operated crank converts reciprocating motion of a person's arm to rotational motion. The major variations in basic engine design relate to the process used to get a combustible mixture into the cylinder in the first place, igniting it, and expelling the products of combustion to make room for the next charge of combustible mixture. These processes are described as engine cycles. For example, a two-stroke cycle engine is one which completes the processes of charging, combusting fuel, and exhausting waste products in one upward and one downward piston stroke (one rotation of the crankshaft). By the same logic, a four-stroke cycle engine requires two upward and two downward strokes (two rotations of the crankshaft) to do the same process.

Figure 10 provides a cutaway rendition of a two-stroke engine. The piston is located at its lowermost position, where the process of exhausting spent combustion products and inducting fresh fuel and air happen simultaneously through openings in the cylinder called ports. One can further visualize that as the crankshaft rotates, the piston will move upwards, the ports will be sealed, and the fresh fuel/air mixture compressed. When the piston reaches the top, a spark plug ignites the mixture, creating the pressure in the cylinder which forces the piston down, creating power. As the piston approaches the bottom of the cylinder, the ports are again uncovered, and cycle starts over.

The advantages of conventional two-stroke engines are simplicity, light weight, and good power. The disadvantages are poor efficiency (resulting in high fuel consumption), high emissions, and the need to use an oiling system where lubricating oil is used once, then expelled as part of the exhaust. The low efficiency and high emissions result from the charging and exhausting processes occurring simultaneously. As Figure 10 shows, fresh fuel and air coming into the cylinder is able to escape with the exhaust. In typical carbureted two-stroke engines, up to one third of the fuel being delivered to the engine goes straight through the engine without being burned. This unburned fuel results in very high HC [hydrocarbon] emissions.

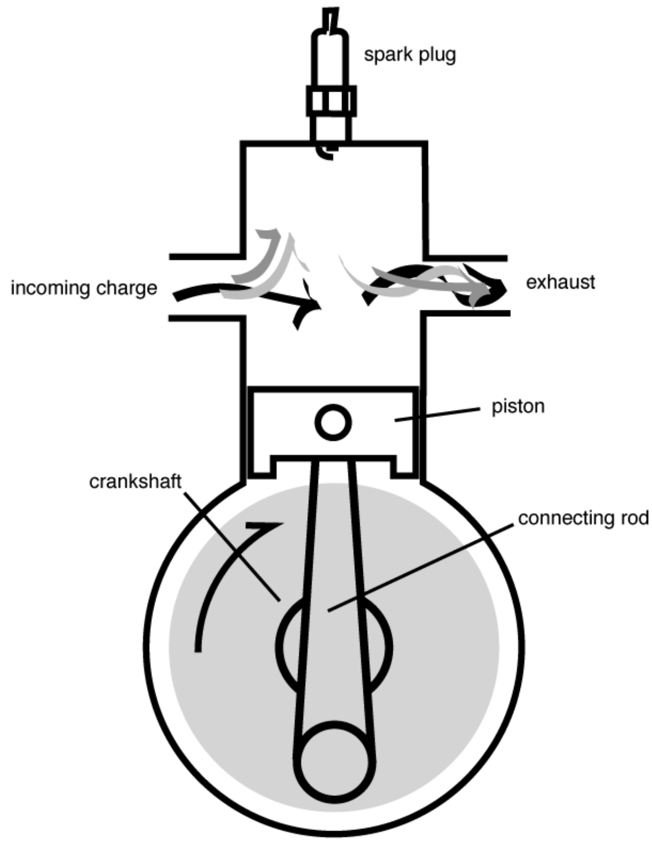

Figure 10. Two stroke engine
Source: CARB, J. Swanton, 10/98

One method of capturing more of the fuel/air in a carbureted two-stroke engine is by using a special exhaust system (called an expansion chamber) which reflects a pressure pulse caused by the exhaust port opening back to the port at the precise time when fuel is starting to escape. This pressure pulse bounces the fuel/air back into the engine increasing horsepower and efficiency. This type of system typically works well in a narrow speed range where the returning pulse arrives at exactly the right time. Efforts to broaden the speed range typically reduce the power gains.

2. Direct-Injection Two-Stroke Engines

The basic problem which causes the short circuiting of fuel through a conventional two-stroke engine is that the fuel and air are premixed into a combustible mixture outside of the engine in a carburetor. If fuel introduction could be delayed until after the piston moves up to cover the ports, all of the fuel would be available for combustion in the engine. This could be done by inducting air instead of fuel/air mixture then injecting the fuel later. Two-stroke direct-injection engines are configured like the engine shown in Figure 10, except that a fuel injector is placed next to the spark plug.

Several manufacturers are using direct-injection two-stroke technology for their more powerful outboards to lower exhaust emissions and improve fuel economy. Also, conversion to direct fuel injection is relatively straight forward for existing two-stroke engine designs, involving a new cylinder head for the injectors, removal of the carburetors, providing a high pressure fuel pump, and providing a computer to manage the fuel system. Currently there are two major manufacturers of direct fuel injection systems, Ficht by OMC and Orbital by Mercury Marine. Both systems inject fuel at very high pressures at rates of up to 100 to 150 times per second. This is done in different ways for each system. The Orbital system uses compressed air, whereas the Ficht system uses an electromechanically controlled piston.

This technology is generally considered new to the marine industry. Data from federally certified engines show that emissions are about 85 percent lower with the direct injection technology than carbureted two-stroke outboard engines.

Through precise delivery of oil as needed, oil consumption during idle and low throttle operation is very low. At higher throttle operation, oil consumption of a two-stroke direct-injection engine is much closer to that of carbureted two-strokes, resulting in emissions associated with oil consumption. Overall, however, two-stroke direct-injection engines consume approximately 50 percent less oil during operation compared to carbureted two-stroke engines.

Although the number of model introductions with direct fuel injection has been limited thus far (only two marine engine manufacturers produce them)...other engine manufacturers have plans to introduce additional models using direct fuel injection in 1999. Industry has stated that more than $500 million has already been invested in application of direct fuel injection technology to outboards and personal watercraft.

3. Four-Stroke Engines

While the direct-injection two-stroke engine represents a large improvement in emissions performance compared to conventional two-stroke engines, the four-stroke engine is typically even cleaner. This is because the process of exhausting and charging the direct-injection two-stroke is very time constrained, since it must occur while the piston passes through the lower part of the cylinder. Efficient exhausting and charging would suggest that the ports should be large and high to provide time for these processes to occur, but high ports would cause the power stroke to be shorter, wasting energy which could instead be put to work pushing the piston. These tradeoffs are major design constraints.

The four-stroke engine devotes separate complete strokes to the exhaust and charging functions. As shown in Figure 11, the charging and exhaust functions are controlled by mechanically activated valves

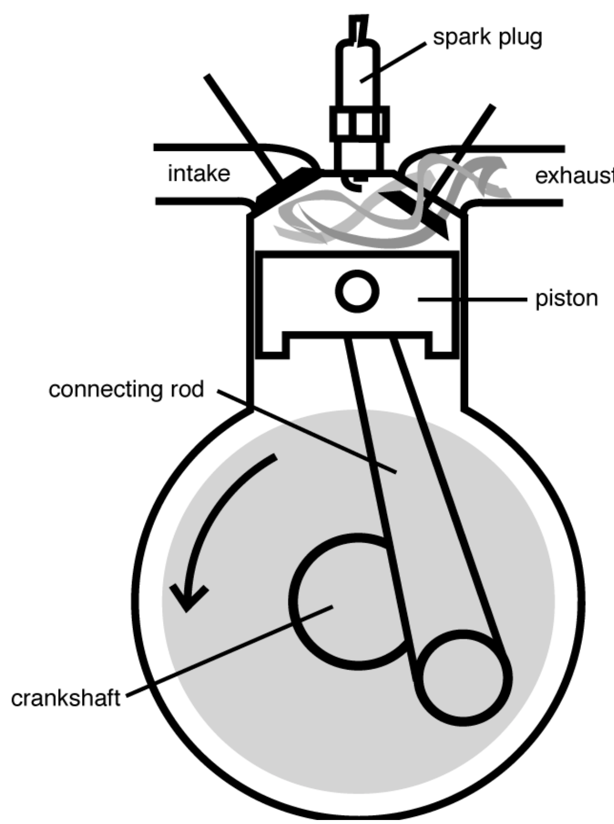

Figure 11. Four stroke engine
Source: CARB, J. Swanton, 10/98

at the top of the cylinder. The timing of the opening and closing of these valves can be optimized for proper charging and exhausting (exhaust stroke shown in Figure 11) and the intake and exhaust valves do not need to be open at the same time preventing short circuiting.

Because of the good mixture control provided by four-stroke engines they typically produce lower emissions than direct-injection two-stroke engines. Compared to conventional carbureted two-stroke engines, the emissions difference is dramatic, typically 75 to 90 percent lower.

Additionally, four-stroke engines do not consume oil as part of the combustion cycle, thus reducing introduction of combusted and unburned oil products to the air and water. Although most outboard engine manufacturers do not manufacture their product lines exclusively with four-stroke technology there has been an increase in its application since the U.S. EPA implemented the national regulation in 1998. Emissions data collected by the U.S. EPA have shown that existing four-stroke engines can easily comply with the proposed California Tier 1, and Tier 2 standards and many currently comply with the proposed Tier 3 standards. The cleanest four-stroke outboard engines, the Honda 115 hp and 130 hp, are almost 95 percent cleaner than a comparably rated carbureted two-stroke engine. These outboard engines are based on one of Honda's popular automobile engines and use advanced multi-port fuel injection.

Engine manufacturers have expressed concern about four-stroke engines, including their larger size, heavier weight, and increased cost. However, this has not been found to be the case for most outboard engines with power output less than or equal to 75 kilowatts (100 hp). Most engines in this class require little equipment repackaging, offer similar power-to-weight ratios, and consume less fuel and oil thereby offsetting increased purchase costs. Manufacturers have indicated that they plan to introduce more four-stroke models under 100 hp.

Currently no four-stroke outboard engines are produced for sale above 130 hp. Trade journals have stated that at least one manufacturer is working on a 200+ hp four-stroke outboard and it is likely that other engine manufacturers will eventually focus on this power range. Note that sterndrive inboard engines are available at power levels exceeding 400 hp that utilize automotive type four-stroke technology, so high horsepower outboards are not the only means of attaining a high horsepower pleasurecraft.

4. Exhaust Aftertreatment

One of the largest breakthroughs in automotive emission control was the introduction of catalytic converters in 1975. These devices are simply a porous ceramic or metal substrate coated with precious metals which cause the chemicals in exhaust to react. They have no moving parts and (automotive catalysts) range in size from a small pet food can to larger than a large coffee can. Catalysts in automobiles are used to reduce NOx [Nitrogen Oxide] and combust HC and CO [Carbon Monoxide] simultaneously eliminating these emissions at efficiencies exceeding 90 percent. Catalysts were such a significant development because they freed engine designers to focus on performance and efficiency while depending on the catalyst to perform much of the emission control. Modern automotive catalysts reduce emissions by orders of magnitude compared to controlling emissions in the engine itself.

The application of catalysts to outboard engines is different from automotive applications for several reasons. First, two-stroke engine exhaust contains oil which could contaminate the catalyst reducing efficiency. Second, water could damage a catalyst by causing a thermal shock which would mechanically damage the substrate, and third, catalysts only perform properly at elevated temperatures (this is a concern because marine engines typically cool the exhaust as much as possible for safety reasons and because the direct-injection two-strokes have relatively low exhaust temperatures).

Despite these potential problems, U.S. EPA in its analysis supporting the national emissions standards, cited catalysts as a potential control technology for two-stroke marine engines in their Regulatory Impact Analysis report. It should be noted that catalysts are being used on other production and demonstration two-stroke engine applications with success....

In addition to these production applications, [CARB] staff believes that catalysts are feasible for marine two-stroke engines. Isolating the catalyst from water contaminants would be accomplished by mounting the catalyst(s) close to the engine above the waterline which would also maximize the operating temperatures or by placing a one-way valve in the exhaust stream to prevent water from entering. Note that engine damage can occur if water enters the engine itself, so the same approaches used to protect engines would need to be applied to the catalyst. Catalyst temperatures would need to be controlled through insulation and/or water cooling to maintain a proper operating environment for good conversion efficiency. Thermal management is required for all catalyst systems; methods of managing temperatures are already well known.

Outboard engine manufacturers cite excessively low (below 400° C) exhaust temperatures as a potential problem for catalysts applied to direct-injection two-stroke engines. However, this problem is not insurmountable. Catalysts are available with operating temperatures extending down to 175° to 250° C....

With respect to oil contamination, the successful use of catalysts on other types of two-stroke engines has shown that this problem can be managed. An approach called open washcoat structure can prevent the ash produced from oil combustion from interfering with catalyst activity.

In summary, [CARB] staff recognizes that there are potential challenges with catalyst application to two-stroke outboards, but the existence of potential technical solutions suggests that catalysts can be applied....

5. Technology Summary

Table 9 summarizes the discussion of available technology. At the bottom of the Table, "typical" emissions required by the [CARB] staff proposal are cited for each tier, [or percentage of the U.S. EPA 2006 standards]. For comparison, baseline carbureted two-stroke engines are shown. A 50 percent efficient catalyst applied to an uncontrolled two-stroke engine could reduce these emissions by half, but the emissions would still exceed all 3 tiers of the staff proposal. Higher catalyst efficiencies are feasible, but the concerns regarding contamination and thermal management become more severe as efficiency is increased. The direct-injection two-stroke is capable of meeting the first [U.S. EPA 2006 standards] and second tiers [80% of the U.S. EPA 2006 standards] of the standards, but compliance with the third tier [35% of the U.S. EPA 2006 standards] would likely require addition of a catalyst.... Some of the current four-strokes use fuel injection which further lowers emissions. Most current fuel injected four-stroke engines would comply with all three tiers of standards. Finally, if a 50 % efficient catalyst was used on the cleanest four-strokes, emissions would drop well below Tier 3 standards. While all of the options shown are feasible and may be used because of the flexibility provided by the averaging provisions of the [CARB] proposed regulations, manufacturers are expected to focus on direct-injection two-strokes, direct-injection two-strokes with catalysts, and four-strokes.

Table 9

Summary of Technology

Technology	Typical Emissions g/kW-hr*	Complexity/level of Development
Carbureted 2-stroke	100 - 600	Simple/low cost/developed
Carbureted 2-stroke with catalyst	50 - 100	Modest/not yet on the market
Direct-injection 2-st	24 - 45	Modest/Developed - current introduction
Direct-injection 2-st with catalyst	10 - 13	Modest/Not developed yet
Carbureted 4-st	15 - 35	On the market/Developed
Fuel Injected 4-st	8 - 25	On the market/Developed
Fuel Injected 4-st with catalyst	4 - 12	Developed for other applications

* Average Emission Level for Tier 1 - 48 g/kW-hr [U.S. EPA 2006 standard]
Tier 2 - 38 g/kW-hr [80% of the U.S. EPA 2006 standard]
Tier 3 - 17 g/kW-hr [35% of the U.S. EPA 2006 standard]

It is also noteworthy that outboard engines are not the only choice for marine propulsion. In particular, sterndrives are very popular. They combine an automotive engine with emission capabilities of the four-stroke engines, shown in Table 9, with the bottom portion of an outboard. Thus, the engine is mounted inside the boat, and power is transmitted through a shaft and gears to outside the hull to an outboard drive unit which mounts to the propeller. Sterndrives are more fuel efficient than carbureted two-stroke outboards and are available at power levels exceeding the most powerful outboard. Both Mercury and OMC are major sterndrive manufacturers. Sterndrives are also potentially less expensive than high-horsepower direct-injection outboards....

However, based upon Honda's introduction of 115 and 130 horsepower outboards which use fuel injected four-stroke automotive engine designs, [CARB] projects that these types of engines may grow in popularity in the 100-150 horsepower range. In fact, [CARB] staff may be underestimating the potential for automotive based engines because automotive engines are produced in much greater quantities than marine two-stroke outboards. Production economies of scale could make these engines cost-competitive with the marine engines despite their complexity. For example, a 115 horsepower Honda automobile engine without accessories, currently retails for approximately $2,500 at the dealership. An OMC 115 horsepower two-stroke direct-injection replacement engine similarly equipped retails for $7,800. Given that the two-stroke engines would still require catalysts one can see the potential for over 100 horsepower auto-derived four-stroke outboards.

Personal Watercraft

Personal watercraft differ from outboards in a number of key areas. First, personal watercraft have the engine and drive unit inside of the hull. Outboards are specifically designed to be mounted outside of the hull as a single unit which includes the engine, transmission, and drive (propeller). The whole engine is turned to maneuver the boat for outboards, while personal watercraft are maneuvered by changing the direction of the nozzle which ejects water to provide thrust. Outboards provide thrust to move a boat through a propeller which turns freely in the water, while personal watercraft suck water from under the hull and pump it through a nozzle to provide thrust. The power unit for a personal watercraft is an engine connected directly to a water pump. This type of jet propulsion has been used for decades in larger boats equipped with automotive engines as a low-cost drive system which is safe because no moving parts are outside of the boat hull. Jet drive units, whether they are used in full sized boats or personal watercraft, typically have poor fuel economy because of water friction inside the drive and because pulling water from under the hull tends to "suck" it into more firm contact with the water, which increases hull drag. When these drive unit characteristics are combined with a carbureted two-stroke engine which wastes up to 30 percent of its fuel, fuel economy is very poor and hydrocarbon and oil emissions are very high. [California currently estimates that personal watercraft are being used on an average of 41 hours per craft per year on lakes and rivers and fuel consumption is estimated at 5 to 10 gallons per hour (CARB, 1998)].

The two-stroke engines used in personal watercraft are typically purpose-designed and were derived primarily from early snowmobile engines. Their basic design is similar to two-stroke outboards, but they are optimized for the power absorption characteristics of the jet pump rather than a propeller. Propellers require a broad power band for acceptable low- and mid-speed performance while the power absorption of a jet drive is very low at low and mid-engine speeds, then becomes very high near maximum speed. This allows for personal watercraft engine designs to use larger/higher ports which increase peak power at the expense of low- and mid-range power.

The major personal watercraft manufacturers have now developed direct-injection two-stroke engines. Polaris and Tigershark have both announced 1999 models using OMC's Ficht direct-injection two-stroke technology. Initial emission test results have shown that just installing direct fuel injection on personal watercraft engines may not produce the same emission reductions expected for outboards. Some of this may be because the personal watercraft manufacturers are purchasing this technology and are about a year behind in its application....

Summary and Conclusions

Two-stroke carbureted marine engines are used in most outboards and in almost all personal watercraft. Inboard and sterndrive marine engines found in larger boats are based on automobile engines that have lower emissions. Unlike automobile emissions, which are exhausted to air, marine engines exhaust directly into the water, enhancing pollutant transfer. Two-stroke carbureted marine engines are highly inefficient in their use of gasoline and oil, and are the second largest non-road contributor of hydrocarbons. Current use of carbureted two-stroke technology results in the discharge of enormous quantities of gasoline into the environment. It is estimated that these engines discharge an unburned fuel/oil mixture at levels approaching 20% to 30% of the fuel/oil mixture consumed. Considering this, as much as 50 to 60 gallons of fuel per year is discharged into the environment from one average personal watercraft operated for 41 hours per year. It has also been estimated that the operation of a 100 horsepower personal watercraft for 7 hours results in more ozone precursor emissions (hydrocarbons & oxides of nitrogen) than the operation of a 1998 passenger car driven over 100,000 miles.

Pollution of the Vermont environment is occurring (though not easily documented) due to the incomplete burning of the fuel/oil mixture by conventional two-stroke outboard and personal watercraft engines. Of 38,000 registered boats in Vermont, 29,000 are equipped with outboard engines (Giguere, 1998, pers. comm.). Nationally, approximately 95% of all outboards are two-stroke carbureted engines (Moye, VT DEC 1998, pers. comm.). Assuming Vermont follows the national average, there are approximately 27,550 two-stroke outboards in VT.

Quantities of pollution caused by two-stroke outboards can be estimated using figures from The Vermont Lake and Pond Recreational Survey, conducted in1996 which contacted 873 individuals. The questions on the survey included the number of boats per household, type of boat, fuel usage, and propulsion type. Estimated fuel usage averaged 92 gallons per year per boat (Macro International, 1996). Based on the 20-30% estimated release of unburned fuel between 507,000 and 760,000 gallons of fuel/oil mixture is being released into Vermont lakes annually. It is important to note that boats registered out of state which are used on Vermont waters were not included in the above calculation, and therefore this estimate is conservative.

Technology in the form of the four-stroke and direct injection two-stroke marine engines has been developed to improve the combustion of fuel. Conversion to technologies that do not cause the release of unburned fuel would have ozone precursor reduction benefits as well. Though this technology comes at a higher price than the conventional two-stroke engine, the greatly improved gas mileage, decreased oil usage, reduced emissions of hydrocarbons, and quieter performance offset the increased cost. (CARB, 1998).

Regulations adopted by U.S. EPA will help reduce emissions from spark-ignition two-stroke engines by 75% by the year 2025. California has set in place guidelines to achieve these goals by 2008. Further research into the impacts on the aquatic environment, explorations of options for addressing this concern, and outreach efforts to inform and educate the Vermont boating public would be appropriate.

References

California Air Resources Board. 1998. Public hearing to consider adoption of emission standards and test procedures for new 2001 and later model year spark-ignition marine engines. Staff report.

California Environmental Protection Agency. 1998. MTBE (methyl tertiary butyl ether). Briefing paper.

Giguere, D. 1998. Vermont Department of Motor Vehicles. pers. comm.

Macro International Inc. May 1996. Vermont Lake and Pond Recreational Survey. Market Research and Consulting Division.

McCarthy, J.E. and M. Tiemann. March 1998. CRS Report of Congress. MTBE in gasoline: clean air and drinking water issues. Congressional Research Service. The Library of Congress.

Moye, T. 1998. Vermont Department of Environmental Conservation, Air Pollution Division. pers. comm.

Reuter, J.E., B.C. Allen, R.C. Richards, J.F Pankow, C.R. Goldman, R.L. Scholl and J. S. Seyfried. 1998. Concentrations, sources and fate of the gasoline oxygenate methyl tert-butyl ether (MTBE) in a multiple-use lake. Environ. Sci. Technol. 32:3666-3672.

United States Environmental Protection Agency. July 1986. 1,3-Butadiene. Chemical Abstract Service. Fact Sheet 106-99-0.

United States Environmental Protection Agency. November 1986. Toluene. Chemical Abstract Service. Fact Sheet 108-88-3.

United States Environmental Protection Agency. January 1988. Benzene. Chemical Abstract Service. Fact Sheet 71-43-2.

United States Environmental Protection Agency. July 1988. Ethyl Benzene. Chemical Abstract Service. Fact Sheet 100-41-4.

United States Environmental Protection Agency. February 1989. Acetadehyde. Chemical Abstract Service. Fact Sheet 75-07-0.

United States Environmental Protection Agency. May 1989a. Formaldehyde. Chemical Abstract Service. Fact Sheet 50-00-0.

United States Environmental Protection Agency. May 1989b. Xylenes. Chemical Abstract Service. Fact Sheet 1330-20-7.

United States Environmental Protection Agency. 1996a. Emission standards for new gasoline marine engines. Office of Mobile Sources. EPA Fact sheet EPA420-F-96-012.

United States Environmental Protection Agency. October 1996b. Federal Register. Control of air pollution; gasoline spark-ignition marine engines; new nonroad compression-ignition and spark-ignition engines, exemptions; rule. 40 CFR Parts 89, 90 and 91.

United States Environmental Protection Agency. June 1996c. Regulatory Impact Analysis Control of Air Pollution Emission Standards for New Nonroad Spark-Ignition Marine Engines. Office of Air and Radiation. Washington, DC.

United States Environmental Protection Agency. January 1998a. MTBE Fact Sheet #3. Office of Solid Waste and Emergency Response. EPA 510-F-97-016.

United States Environmental Protection Agency. March 1998b. Federal Register. Announcement of the Drinking Water Contaminant Candidate List. EPA W-97-11; FRL-5972-5