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Emissions Testing of Two Recreational Marine Engines with Water Contact in the Exhaust Stream

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Thesis submitted to the
College of Engineering and Mineral Resources
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2000

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Abstract

Emissions Testing of Two Recreational Marine Engines with Water Contact in
the Exhaust Stream

Brian E. Mace

Recreational marine engine operation effects water quality as well as air quality. Significant quantities of hydrocarbons are discharged into the rivers, lakes, and estuaries used as recreational boating waters. In order to investigate the impact of recreational marine engine operation on water quality, a MerCruiser 3.0LX four-cylinder four-stroke inboard engine and a Mercury 650 two-cylinder two-stroke outboard engine were tested using EPA required certification procedures. Both engines were tested with exhaust gas/cooling water mixing (scrubbing) in the exhaust stream using both freshwater and saltwater. Additionally, the inboard engine was tested without exhaust scrubbing. Gaseous emissions (HC, NO_X, CO, and CO_2) from the engines were continuously measured using a constant volume sampling system. Both exhaust gas and cooling water samples were collected and speciated for hydrocarbon species present. In addition, carbonyl compounds were collected by diverting a portion of the exhaust stream through 2,4-dinitrophenylhydrazine (DNPH) charged cartridges. Chromatography methods were used for species identification. Detailed descriptions of the testing apparatus, equipment, and analysis procedures used are included. Results for gaseous emissions, carbonyl compounds, and aqueous samples are reported. The mass ratios of hydrocarbons to carbon dioxide gaseous emission for the MerCruiser and Mercury engines were approximately 0.0046 and 0.55 respectively. These results show that concerns over gaseous hydrocarbon emissions from these sources are warranted. Additionally, high levels of acetone were detected in gaseous emissions from the MerCruiser engine while operated with exhaust scrubbing.

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Nomenclature

Abbreviations

AQIRP	Auto/Oil Air Improvement Research Program
BTDC	before top dead center
CFR	Code of Federal Regulations
CO	carbon monoxide
CVS	constant volume sampling
DNPH	2,4-Dinitrophenylhydrazine
DNR	Department of Natural Resources
EPA	Environmental Protection Agency
GC	gas chromatography
gpm	gallons per minute
HC	hydrocarbon
IB/SD	inboard/stern-drive
IC	internal combustion
ICOMIA	International Council of Marine Industry Associations
ISO	International Standards Organization
lpm	liters per minute
NMMA	National Marine Manufacturers' Association
NO$_X$	oxides of nitrogen
OB	outboard
ppm	parts per million
ppt	parts per thousand
PSR	primary supply reservoir
PWC	personal watercraft
RMC	recreational marine craft
RME	recreational marine engine
RPM	revolutions per minute
RW	river water
SAE	Society of Automotive Engineers
scfm	standard cubic feet per minute
SRW	salinated river water
SSR	secondary supply reservoir
STW	salinated tap water
SWRI	Southwest Research Institute
TDC	top dead center
TW	tap water
WOT	wide open throttle
WVU	West Virginia University
WVWRRI	West Virginia Water Resources Research Institute

Definitions

lean test............................A test performed with jets more restrictive than specified by the manufacturer installed in the carburetor. The causes the engine to run a leaner than specified air:fuel ratio

carbonyl ....Organic compounds that contain a carbon atom double bonded to an oxygen atom.

TDC test..........................A test performed with the engine ignition timing retarded to top dead center

brake specific emissions ...Emissions (usually on a mass basis) produced by an engine divided by the amount of work energy produced during a test.

oxygenates........................Organic compounds containing oxygen atoms.

quenching ....Rapid cooling of exhaust products in the exhaust manifold of a marine engine caused by direct contact with cooling water.

exhaust scrubbing.............Synonym for quenching

dry test ....A test performed with cooling water directed away from the exhaust manifold in order to avoid exhaust gas quenching.

wet test............................A test performed with cooling water directed to the exhaust manifold according to manufacturer specification.

regulated gasses................Engine exhaust emissions gasses regulated by the Environmental Protection Agency. The number of regulated gasses can vary depending on which EPA regulation a particular engine must satisfy. Hydrocarbons and oxides of nitrogen are regulated for recreational marine engines.

unregulated gasses............Engine exhaust emissions gasses not regulated by the Environmental Protection Agency. Carbon monoxide is commonly regulated by the EPA, but is not regulated for recreational marine engines.

standard test.....................A test performed with the engine tuned to manufacturer specifications.

maladjustment test............A test performed with a tunable engine parameter purposefully adjusted out of compliance with manufacturer specifications. Engine timing and carburetor jetting were the two parameters adjusted.

1. Introduction

In recent years, interest in internal combustion (IC) engine emissions has broadened to include off-road sources. The U.S. Environmental Protection Agency (EPA) has started inventorying the emissions from these sources and is in the process of implementing certification requirements that pertain to many of them. Industrial, commercial, and recreational sources of off-road IC engine emissions are all under scrutiny, and in some cases certification requirements are already in place.

Emissions from recreational marine crafts (RMCs) have been under the watchful eye of the EPA since the early 1970's. Starting with the 1998 model year, the EPA implemented a hydrocarbon (HC) plus oxides of nitrogen (NO_X) emissions standard for outboard (OB) engines. Manufacturers of outboard engines are required to demonstrate that their products meet EPA emissions standards in order certify them for sale in the United States. The regulations are aimed at a 75 percent overall reduction in current recreational marine engine (RME) HC emissions, while allowing for a slight increase in NO_X emissions. In order to allow manufacturers time to develop the technology necessary to meet the reduction requirements, the EPA will phase in emissions standards over a period of nine years (1998 – 2006 model years). Also, manufacturers will be allowed to average between engine families in order to give them the flexibility to focus on small segments of their product line at different times during the phase in period [1].

For the 1999 model year, manufacturers of personal watercraft (PWC) engines (those used in jet skis, wave runners, etc.) are required to meet the same regulations. However, no emissions requirements are planned for inboard/stern-drive (IB/SD) engines [1]. Outboard and PWC engines are targeted by the EPA because the majorities are of two-stroke design. These engines tend to have poor fuel efficiencies because the fuel delivery and combustion chamber designs have been antiquated by those used in today's highly regulated automotive engines. Poor fuel efficiency leads to comparatively large amounts of unburned and partially burnt fuel being released into boating waters and the atmosphere during operation. Although IB/SD engines lack many of the pollution control devices found on today's on-road engines; the majority are four-stroke engines based heavily on current automotive technology. Therefore, these engines tend to be more efficient and produce fewer pollutants than comparable two-stroke engines. Hence, the EPA has neglected to regulate them for now.

RMEs are significantly different from their land-based counterparts. The engine compartments of most RMCs and PWCs are totally enclosed and poorly ventilated in order to protect passengers from the engine and to protect the engine from water damage. Even outboard engines are fitted with protective covers for this reason. Poor ventilation can cause evaporative emissions to build up and reach explosive concentrations around the engine. In order to reduce the possibility of explosion, marine engines are fitted with intake flame arrestors, sealed electronic circuitry, and water jacketed exhaust systems: features that are seldom found on land-based engines.

The cooling systems used on RMEs are also considerably different than those found on most land-based engines. RMEs sink waste heat energy to the reservoir on which they are operated instead of to the atmosphere. Most systems draw cooling water from the reservoir, pump it through the engine block and exhaust manifold water jackets, mix it with hot exhaust gases and then discharge the mixture back to the reservoir. Some RMEs have recirculatory cooling systems that dump waste heat energy to the reservoir through a water/water heat exchanger. Regardless of the type of system used, the result is the same. Hot exhaust gases are mixed with engine cooling water and the mixture is dumped back to the reservoir. This process is known as exhaust scrubbing, and is implemented to reduce exhaust system surface temperatures and noise.

The mixing of hot exhaust gases (200C – 650C) with relatively cool water (approximately 80C) influences engine emissions in two ways. First, soluble, condensable and particulate pollutants from the exhaust stream are transferred to the cooling water. Second, the rapid cooling (quenching) of the exhaust gases by direct contact with cooling water alters the chemical reactions that normally occur when gases are allowed to slowly cool in the atmosphere. These two factors could potentially have profound effects on the overall pollutants emitted by RMEs. However, EPA testing procedures for RMEs do not require manufacturers to scrub exhaust gases with cooling water during certification testing, as would occur under normal boating operation. Therefore, only gaseous emissions are regulated and no attempt is made to quantify pollutants transferred to the aqueous environment.

As EPA emissions standards are phased in, outboard and PWC engines will have to become more fuel-efficient in order to meet certification requirements. Increased fuel efficiency will result in higher combustion and exhaust temperatures. This will lead to improvements in air quality, but the possibility exists that quenching of exhaust gases at higher temperatures could increase production of compounds that are toxic to the aquatic

environment. Therefore, as more efficient OB and PWC engines gradually replace existing engines air quality will improve, but water quality could be adversely affected.

In a joint effort between the Departments of Chemistry and Mechanical and Aerospace Engineering at West Virginia University (WVU), a research team was assembled to investigate the effects of exhaust scrubbing on both air and water quality. Funding was obtained from the State of Maryland Department of Natural Resources (DNR), West Virginia Water Resources Research Institute (WVWRRI), Maryland Soy Board and West Virginia University Research Corporation. The project commenced in March of 1996 and three engines were tested: a 1989 four cylinder, four-stroke MerCruiser 3.0LX stern-drive; a 1968 four cylinder, two-stroke Mercury 650 outboard; and a 1972 four cylinder, four-stroke Westerbeke 40 inboard diesel.

Although there were many facets to this research, this thesis will focus on apparatus design and gaseous emissions data collected by the Department of Mechanical and Aerospace Engineering on the MerCruiser and Mercury test engines. A summary of the findings of the WVU Department of Chemistry pertaining to the same engines will also be included. Detailed information pertaining to the procedures and findings of the WVU Department of Chemistry is available in the thesis of T.J. Vanyo [2]. Additional information is available through a Society of Automotive Engineers (SAE) Technical Paper [3] and through final reports presented to the funding agencies [4, 5, 6].

2. Literature Review

Background

Since the early 1950's, several studies have been conducted to assess the impact of marine engine operation on the aquatic environment. The majority of these studies focused on quantifying hydrocarbon (HC) pollutants found in recreational boating waters and reservoir sediments, and finding links between their existence and recreational boat usage [7, 8, 9, 10, 11]. All of these studies either found no link between aquatic HC pollutants and recreational boat use, or were unable to directly pinpoint recreational crafts as the culprit.

During the early 1970's, the U.S. Environmental Protection Agency (EPA) along with the National Marine Manufacturer's Association (NMMA) studied the effects of outboard (OB) motor usage on water quality in both warm and cold water lakes [12]. Small lakes in Florida and Michigan were subjected to engine operation described as "three times greater than saturation boating." Impact on aquatic biota was monitored for a period of three years.

The EPA/NMMA study also attempted to quantify the various HC species transferred to recreational boating waters by OB engines. Engines were coupled to a dynamometer and operated under steady state conditions. Raw emissions samples were drawn upstream of scrubbing water introduction. Condensable HC species in the exhaust stream were collected by passing the sample through a cold trap. Carbon monoxide (CO), carbon dioxide (CO_2), oxides of nitrogen (NO_X) and the remaining hydrocarbons were quantified using gas analyzers. The total condensable exhaust fraction was calculated by subtracting detected hydrocarbon levels from tests run with the cold trap from levels detected during tests run without the cold trap. Chromatography techniques were used to separate the condensable fraction into aromatics, olefins, phenols, carbonyls and paraffins.

The investigators concluded that HC emissions produced by two-cycle engines are vastly different than those produced by four-cycles. Two-cycle HC emissions species fractions were found to closely resembled the chemical makeup of the fuel. This was linked to lower in-cylinder combustion temperatures and direct fuel transfer to the exhaust by the scavenging process common to two-cycle engines. This led to the conclusion that two-cycle engines produce a much larger condensable HC fraction than do four-cycles. However, no significant damage to water quality, plant or animal life in the test lakes was reported.

In 1971, EPA contracted with Southwest Research Institute (SWRI) to quantify emissions from various stationary and mobile sources, including OB marine engines. The purpose of the study was to expand the National

Emissions Inventory, as required by the U.S. Air Quality Act of 1967. SWRI's findings were published in 1973 as Part Two of a final report submitted to EPA [13]. A portion of the research was also published as a Society of Automotive Engineers (SAE) Technical Paper in 1974 [14].

Although the main focus of the SWRI study was to quantify the effects of OB motor usage on air quality, some effort was made to investigate effects on water quality. Four two-cycle OB engines were coupled to a dynamometer and operated under steady state conditions. Similar to the EPA/NMMA study, a raw exhaust sample was drawn from the exhaust manifold upstream of cooling water introduction. A bubble column was used in place of EPA/NMMA's cold trap. A small propeller was used to create turbulence in the bubble column. HC, CO, CO_2 and NO_X emissions were quantified using gas analysis equipment. Light HC's and aldehydes in the raw exhaust sample were also quantified using gas chromatography and wet chemistry respectively. Total HC emissions transferred to the water were calculated by subtracting detected HC's in bubbled samples from detected HC's in raw samples. The investigators incorporated water sample collection capabilities into their bubble column, but no attempt was made to identify or quantify HC species transferred to the test water.

The EPA/NMMA and SWRI studies estimated the quantities of HC emissions lost in the exhaust scrubbing process to be between 20 and 50 percent by mass for two-cycle OB engines. Both studies produced some data regarding HC species transferred to the marine environment, but it cannot be assumed that the quantified species actually locate in the water column due to uncertainties introduced by the test procedures. Exhaust scrubbing in the EPA/NMMA test engines likely cooled exhaust gases more rapidly than the cold trap. Also, gases cooled in the trap were not introduced to the excess water present in the exhaust manifold due to scrubbing. It is highly likely that the trapped species would have undergone some degree of chemical restructuring under actual operating conditions. Although exhaust scrubbing was simulated in the SWRI study, the quantities of HC species lost during the scrubbing process were calculated from raw gas measurements and not from water sample analysis. Therefore, HC's transferred to the bubble column test water were likely chemically altered as well.

Duty Cycle Development

In 1988, the International Council of Marine Industry Associations (ICOMIA) published a five-mode steady state duty cycle that it hoped would be adopted internationally for evaluation of recreational marine engines. The cycle was designated as ICOMIA Standard 36-88, and was later adopted by the International Standards

Organization (ISO) as the ISO E4 Recreational Marine Duty Cycle. A 1990 SAE Technical Paper summarizes E4 cycle development [15].

During the 1971-1972 boating season, Outboard Marine Corporation (OMC) conducted a usage study on eleven boats powered by their engines. Engine speed was recorded and operators noted specific information about the craft and boating activities. Approximately 200 hours of usage data was obtained. The NMMA began expanding the study in 1973 to include a wider variety of engines and geographic areas. An additional 33 boats produced 160 hours usage data. The data was analyzed and reduced at the University of Wisconsin.

The data was broken up into five categories based on engine type (inboard or outboard) and rated power. Each category was further divided into 10 percent increments of rated maximum engine speed. The amount of time spent in each speed range was averaged for all boats and organized into the described matrix. Thus organized, the data showed the average amount of time spent in each engine speed range for boats in five categories.

The NMMA decided not to develop a transient test cycle, and opted for a steady state cycle for three reasons. First, most boats are fitted with friction throttles because adjustments are made much less frequently than in on-road vehicles. Secondly, transients have a much shorter duration in boats than in on-road vehicles due to the characteristics of the propulsion system. Finally, the ISO was exhibiting a trend towards adopting steady state duty cycles for off-road engine evaluation.

In order to define the individual modes of the cycle, it was first necessary to understand the speed vs. torque relationship of marine engines. Data collected by the NMMA showed that a simple power law could be used to describe the speed/torque relationship. The data showed that the exponent varied between 1.15 and 2.1, depending primarily on hull design. An average value of 1.5 was adopted. Therefore, it was decided that the modes would be defined by torque being proportional to engine speed to the 1.5 power ($RPM^{1.5}$). The cycle was then divided into 4 modes based on rated engine speed and one idle mode. Increments of 40, 60 and 80 percent of rated speed were adopted. The 20 percent rage was excluded because most OB engines idle at between 10 and 15 percent of rated speed. Also, usage data showed only a small portion of operating time was spent in the 20 percent range.

Time weighting factors for each mode of the cycle were determined from the usage data obtained by NMMA. The power factor for the cycle, which is defined as the sum of the power multiplied by the time weighting

factor for each mode, was found to be 20.7 percent. This was felt to be on the low side by some industry observers, but power factors calculated from other usage data were comparable. The ISO E4 Duty Cycle is shown in Table 2-1.

Table 2-1: ISO E4 Recreational Marine Duty Cycle

Mode	Engine Speed as Fraction of Rated Speed	Engine Torque as Fraction of Maximum Torque at Rated Speed	Time Weighting Factor as Fraction of Total Test Time	Modal Power Factor
1	Idle	0	0.40	0
2	0.40	0.253	0.25	0.0253
3	0.60	0.465	0.15	0.0418
4	0.80	0.716	0.14	0.0801
5	1.00	1.000	0.06	0.0600
			Power Factor	0.2072

Emissions Regulations

In the early 1980's, the United States and several countries in Western Europe were considering implementing emissions regulations on recreational marine engines (RMEs). At that time, no testing standards had been developed for determining the emissions levels emitted by RMEs. Fearing that the lack of standard testing procedures would result in manufacturers having to perform a multitude of emissions tests to certify their products for sale in different countries, ICOMIA began developing an emissions testing standard for recreational marine engines. The standard was published in 1989 as ICOMIA 34-88, and is detailed in an SAE Technical Paper [16].

The ICOMIA standard includes the use of the ISO E4 five mode steady state duty cycle and specifies raw emissions sampling be used to determine concentrations of HC, CO, CO_2 and NO_X in engine exhaust. The sample probe is to be inserted in the exhaust manifold such that no scrubbing water is directly ingested. The equipment and configuration specified is technically equivalent to SAE recommended practice for small utility engine exhaust analysis [17]. No mechanism for measuring exhaust pollutants transferred to the marine environment is included. ICOMIA justified this by citing that several studies, including two that were organized by the EPA, found that little or no damage to marine life or water quality can be attributed to marine engine operation.

On December 3, 1996 the EPA published emissions regulations for new gasoline spark ignited marine engines [1]. The regulations are aimed at a 75 percent overall reduction in then current recreational marine engine HC emissions by the year 2025, while allowing for a slight increase in NO_X emissions. In order to allow manufacturers time to develop the technology necessary to meet the reduction requirements, EPA will phase in emissions standards over a period of nine years (1998 – 2006 model years). Manufacturers are permitted to average between engine families, but must meet the standard on a corporate average basis. Personal watercraft (PWC) and

OB marine engines are regulated. Inboard/stern-drive (IB/SD) engines are excluded. OB and PWC engines are targeted by the EPA because the majority are of two-stroke design. EPA feels that the 75 percent reduction can be attained without regulating IB/SD engines.

Compliance with the regulation is determined by comparing measured brake specific $HC+NO_X$ emissions for an engine family ($[HC+NO_X]_{meas}$) to the regulated value calculated in the following equations:

Equation 2-1

$$HC_{base} = \left(151 + \frac{557}{P^{0.9}}\right) \text{ or } 300 \frac{g}{kW\text{-}hr}, \text{ whichever is lower}$$

Equation 2-2

$$[HC + NO_X]_{reg} = [A \times HC_{base} + B] \text{ or C, whichever is lower}$$

where P is the rated power of the engine family in kilowatts and values A, B and C are found in Table 2-2. $[HC+NO_X]_{meas}$ must be less than or equal to $[HC+NO_X]_{reg}$ in order to comply.

Table 2-2: Calculation Factors for Outboard and Personal Watercraft $HC+NO_X$ Emissions Standards

Model Year	A	B	C
1998	0.917	2.44	278
1999	0.833	2.89	253
2000	0.750	3.33	228
2001	0.667	3.78	204
2002	0.583	4.22	179
2003	0.500	4.67	155
2004	0.333	5.56	105
2005	0.250	6.00	81

The new EPA regulations include most of the content found in the ICOMIA 34-88 standard, including the use of the ISO E4 duty cycle. However, EPA does not require that raw emissions sampling be used for exhaust gas measurement. Constant volume sampling is permitted. Exhaust gas scrubbing is permitted, but not required. No regulations regarding the quantification of pollutants transferred to the marine environment are included.

3. Objectives

The primary objective of this research was to quantify the influence that exhaust scrubbing in RMEs has on air and water quality. Determining effects of exhaust scrubbing on gaseous emissions and identifying the HC species introduced into the water column were of particular interest.

Three primary factors that were suspected to have the greatest influence on air and water quality were identified: engine type, engine tuning and water properties. In order to narrow the research objective and help give the project some focus, the following guidelines based on those factors were established: Both two and four-stroke gasoline engines should be tested with and without exhaust scrubbing. At least one of the test engines should be tested in various states of maladjustment. Finally, since RMCs are operated on all types of waterways, each engine should be tested using both fresh and salt water.

Having thus narrowed the objective, the following tasks necessary for project completion were identified:

1. The type of water to be used for testing needed to be determined. In addition, the necessary equipment and procedures required for its transport, storage, and preparation needed to be developed.

2. Criteria for determining the effects of engine operation on air and water quality needed to be identified. Equipment needed for sample analysis had to be acquired and/or prepared for use. Collection procedures needed to be developed for both gaseous and aqueous samples.

3. Test engines needed to be selected, procured, mounted, instrumented, tuned and otherwise readied for testing. Methods for maladjustment of at least one engine also needed to be developed.

4. A suitable dynamometer needed to be obtained and readied for testing.

5. Cooling and sampling systems for each engine needed to be designed and constructed for operation both with and without exhaust scrubbing. Procedures for proper use of these systems needed to be developed.

6. Each test engine needed to be tested, samples and test data collected, and analysis completed.

4. Experimental Approach

Test Water

In order to reproduce actual engine operating conditions as closely as possible, original plans called for the use of local river or lake water to be used as engine cooling water during testing. However, transporting the large volumes of water needed for testing to the laboratory proved to be too time consuming and costly. Therefore, two identical tests were performed; one using river water and the other using ordinary tap water. Test results showed only negligible differences. Therefore, tap water was used for the remainder of the tests. The results of these tests are discussed in Chapter Five.

The State of Maryland Department of Natural Resources requested that saline solutions be created using Instant Ocean® synthetic sea salt at a salinity level of 17 parts per thousand (ppt). Ordinary seawater has a salinity of approximately 34-ppt. The State of Maryland DNR's primary interest in this project was to determine if RMCs are contributing to declining water quality in the Chesapeake Bay. The Chesapeake Bay has a salinity approximately half that of normal seawater, or 17-ppt.

Test water was obtained from a normal tap water service outlet. Since water was supplied to the laboratory through an underground pipeline, variations in initial test water temperature were small.

Saline solutions were prepared by pouring the synthetic sea salt into the test water and stirring until it dissolved. The mixture was tested for proper concentration using a hydrometer supplied by Aquarium Systems, manufacturer of Instant Ocean®.

For convenience, some nomenclature was developed pertaining to the different types of sample water. Since the only two types of water used were locally obtained river water and tap water, they were referred to as "RW" and "TW" respectively. Additionally, an "S" was added to the beginning of the abbreviations if the sample water was salinated. Therefore, the four possibilities were RW, TW, SRW, and STW. Since only one test was completed using unsalinated river water, the SRW designation was never actually used.

Procedure for Determination of Air and Water Quality

<u>Air Quality</u>

The effects of engine operation on air quality were determined in three ways. First, concentrations of regulated HC and NO_X and unregulated CO and CO_2 gases were continuously monitored during all tests. Second, a

composite exhaust gas sample was collected for each test and speciated for HC species present. Third, a portion of the exhaust stream was directed through 2,4-dinitrophenylhydrazine (DNPH) charged cartridges in order to trap and identify oxygenated HC species.

In order to track changes in the concentrations of regulated (HC and NO_X) and unregulated (CO and CO_2) gases in the exhaust stream during testing, continuous sampling of exhaust gases concentrations were recorded using a constant volume sampling (CVS) system. The CVS system was part of an emissions testing laboratory located at the West Virginia University Engine Research Center. Raw engine exhaust gases and background air (referred to as dilution air) were drawn into a full-scale dilution tunnel by a large blower. A mixing orifice located near the mouth of the dilution tunnel forced thorough mixing of the exhaust gases and as they entered the tunnel. Flow through the tunnel was controlled by critical flow venturies. Portions of the diluted exhaust mixture were drawn from the tunnel through a series of probes located near the tunnel exit and fed to a bank of Rosemont gas analyzers. During testing, concentrations of HC, NO_X, CO, and CO_2 were continuously monitored and recorded using Rosemont model 402, 955, and 868 analyzers respectively. All guidelines listed in Title 40, Part 91 of the CFR regarding testing equipment and exhaust gas sampling procedures were followed [1]. Data collection and analysis for continuous sampling of exhaust gas emissions was handled by the WVU Department of Mechanical and Aerospace Engineering.

In order to determine the effects of exhaust scrubbing on the individual HC species present in the exhaust stream, composite samples of dilute exhaust gases and background air were collected and speciated for HC species present using gas chromatography. A Varian 3600 Gas Chromatograph (GC) was used for sample analysis. The analysis methods used were developed by the Auto/Oil Air Quality Improvement Research Program (AQIRP) [18, 19]. Sample collection and analysis for exhaust gas HC speciation was handled by the WVU Department of Mechanical and Aerospace Engineering.

Although the GC results provided a good indication of the effects that exhaust scrubbing has on a large number of HC species, it was not very helpful in tracking changes in oxygenated HC species in the exhaust stream. The research team felt that it was important to track oxygenates because they are soluble in water and would likely see increased production when exhaust gases were quenched by cooling water. Therefore, a portion of the exhaust stream was directed through 2,4-dinitrophenylhydrazine (DNPH) charged cartridges during each test. Carbonyl compounds (compounds that have a carbon atom double bonded to an oxygen atom) react with DNPH to form

hydrazine derivatives, which are soluble in water. Analysis and identification of the original carbonyl containing compounds was accomplished by reducing the hydrazine derivatives into aqueous solution and analyzing them by high performance liquid chromatography (HPLC). Three target carbonyl compounds were identified: Formaldehyde, Acetaldehyde and Acetone. Analysis of the DNPH charged cartridges was preformed by the WVU Department of Chemistry. More specific details regarding the procedures and equipment used are available in the Thesis by Vanyo [2].

<u>Water Quality</u>

Effects of engine operation on water quality was determined by analyzing samples of engine cooling water for target HC species. In order to determine where in the water column these HC compounds were locating, a 30-gallon sample of engine cooling water was allowed to settle for ten minutes after each test. 250-milliliter samples of cooling water were then drawn from the surface, middle, and bottom of the container. A 250-milliliter sample of pre-test cooling water was also collected so that species present in the water prior to testing could be accounted for. Sample analysis was performed by the WVU Department of Chemistry using liquid chromatography. Details pertaining to the procedures and equipment used are available in the Thesis by Vanyo [2].

Engine Selection and Preparation

The research team decided that only two gasoline engines would be tested due to time and financial constraints. It was decided that engine selection would be based on perceived EPA standings regarding acceptable emissions output. The EPA estimates that the average age of current recreational marine engines is around 25 years [1]. Therefore, a pre-1998 two-cycle outboard (preferably one of average age) would represent the class of engines that the EPA is attempting to regulate. Likewise, a late model four-cycle inboard or stern-drive engine would represent the class of engines that the EPA feels produce acceptable emissions levels. Comparison based on results obtained from both engines would lead to conclusions about the effects of exhaust scrubbing on water quality and whether or not the current EPA regulations will benefit or degrade the marine environment.

A 1989 MerCruiser 3.0LX four cylinder four-cycle stern-drive engine and a 1968 Mercury Marine 650 four cylinder two-cycle outboard engine were obtained for testing. Although the engines were used, they were both found to be in good mechanical condition and were for sale to the boating public when obtained. Once installed, both were tuned to manufacturer specifications before testing was initiated.

The research team decided that maladjustment tests would only be performed on the MerCruiser engine. Engine timing and the fuel delivery system were targeted as the most likely parameters to be changed by boat owners. Therefore, it was decided that the engine would be tested with the engine timing retarded to top dead center (TDC) and with more restrictive jets installed in the carburetor. The manufacturer specified engine timing for the MerCruiser engine was 8 degrees before TDC (BTDC). The manufacturer specified carburetor jets had a cross sectional area of 0.00255 square inches.

It was not possible to obtain carburetor jets with smaller cross sectional areas from either the manufacturer or after-market vendors. Therefore, the jets were manufactured in-house by filling the manufacturer specified jets with solder and drilling them out to a smaller diameter. Two sets were made; one set each with cross sectional areas of 0.00238 and 0.00212 square inches. These represented 7 and 17-percent decreases in cross sectional area respectively. However, the diffuser cones of the manufactured jets were partially filled and no longer conical in shape. Therefore, it was not possible to calculate the effective change in cross sectional area and resulting change in air fuel ratio. Changes in the air-fuel ratio were calculated using continuous exhaust gas data instead.

For convenience, some nomenclature was developed regarding the different engine conditions used during testing. Tests run with the engine adjusted to manufacturer specifications were referred to as "Standard" tests. All tests run with the engine timing retarded to TDC were referred to as "TDC" tests. All tests run with leaner carburetor jets installed were referred to as "Lean" tests. As a group, the TDC and Lean tests were referred to as "Maladjustment" tests. Maladjustment tests were only performed on the MerCruiser engine.

Dynamometer Setup

A 300 series Mustang eddy current power absorber was used to apply load to the engines during testing. The power absorber was controlled by a Dyne Systems Co. Dyne Loc IV dynamometer control unit. The Dyne Loc IV is a speed-locking device that required both engine speed and load inputs. An encoding speed sensor and a load cell rated at 500 lb_f were used to provide input to the dynamometer controller.

Engine Cooling Systems Design and Construction

Engine cooling systems that would allow the engines to be tested both with and without exhaust scrubbing were required. Additionally, since EPA guidelines called for a five-mode steady state test cycle, provisions were

needed for keeping exhaust gases from contacting engine cooling water during warm-up and transient operation. Provisions for sample water collection were also needed.

For convenience, some nomenclature was developed regarding the different test conditions used. Tests performed without exhaust scrubbing were referred to as "Dry" tests. Results obtained from Dry tests represented the type of results manufacturers would likely produce during EPA certification testing. Tests performed with exhaust scrubbing were referred to as "Wet" tests. Results obtained from Wet tests represented the expected emissions output during normal engine operation.

Cooling Systems for MerCruiser Engine

The MerCruiser 3.0LX engine was placed on support stands and coupled directly to the power absorber using the stock drive coupling. The engine had a water-jacketed exhaust manifold and riser intended to reduce bilge temperatures and muffle engine noise during normal boating operation. Cooling water was normally drawn through an inlet in the drive unit and fed to the engine by a gear driven pump. Water pumped from the drive unit was split into two streams. One stream passed through the thermostat housing where it was regulated and pumped through the engine cooling passages by a belt driven water pump. This water was then expelled into the exhaust manifold water jacket. The other stream passed directly into the exhaust manifold water jacket. Water then passed through the exhaust manifold and riser water jacket and into the exhaust stream, where it mixed with the hot exhaust gases. The exhaust/cooling water mixture then flowed back into the drive unit where it was expelled below the water surface around the propeller hub.

Setup for Dry Testing

In order to perform baseline emissions testing on the MerCruiser engine, it was first necessary to devise a method of keeping the cooling water from mixing with the exhaust gases upon exiting the exhaust riser. This was accomplished by brazing a two-inch diameter, 90 degree steel elbow into the exhaust port of the riser. A piece of five-inch diameter steel tubing was then cut and fitted to the riser in such a way that the elbow passed through the side of the tubing. The tubing was then welded back together around the elbow and attached to the riser with a steel band clamp. A J-type thermocouple was installed in the elbow just outside of the steel tubing. This system made it possible to fully separate the cooling water and exhaust gases, and to monitor the temperature of the exhaust gases during testing. A diagram of the exhaust gas separator is shown in Figure 4-1.

Figure 4-1: Exhaust Gas Separator Shown Attached to the Exhaust Riser
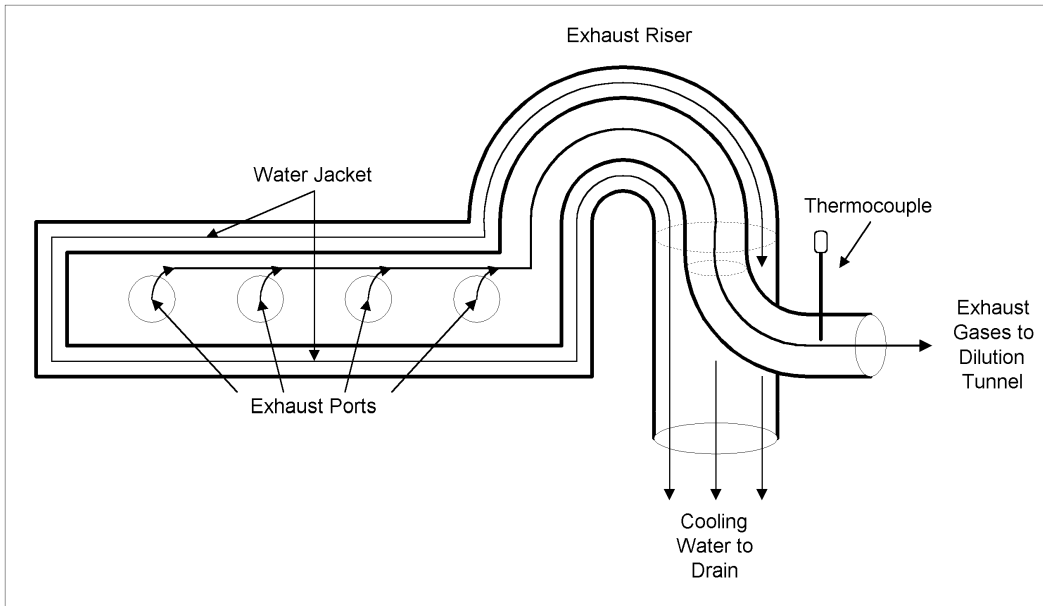
During testing, cooling water was supplied to the engine via a standard tap water service outlet. Flow to the engine was monitored and controlled using a Blue White 41000 flow meter and a one-inch diameter bronze globe valve. Water discharged from the engine was routed to a floor drain by a five-inch diameter collapsible hose.

Setup for Wet Testing

In order to mimic original operating conditions as closely as possible, a single reservoir of cooling water was recirculated through the engine during testing. This reservoir was designated the primary supply reservoir (PSR). Two criteria dictated the volume of water required. First, it had to be large enough to allow for adequate cooling of the engine. Second, it had to be small enough to ensure that detectable concentrations of HC species would be present upon test completion.

The first criterion represented the lower limit of the PSR volume. It was necessary to have a large enough volume of water to prevent the cooling water temperature from approaching the engine cooling water operating temperature of 77 Celsius. Since all engine cooling water would be obtained from a standard tap water service outlet, it was assumed that initial cooling water temperature would be at or below standard temperature (25C). It was decided that a temperature differential of at least 25 Celsius between the maximum cooling water temperature and the engine cooling water operating temperature should be maintained. Therefore, the allowable temperature

differential was 25 Celsius (ΔT=50C–25C=25C). The specific heat of water was used to determine the mass of cooling water required to maintain this temperature differential, as shown in Equation 4-1.

Equation 4-1

$$\Delta U_{CW} = (mC\Delta T)_{CW}$$
$$\Delta U = \text{change in internal energy of cooling water}$$
$$m = \text{mass of cooling water}$$
$$C = \text{specific heat of cooling water}$$
$$\ddot{A}T = \text{temperature differential of cooling water}$$

It was assumed that the engine would be around 30 percent efficient, meaning that 30 percent of the total energy extracted from the fuel would be transferred to work energy and the other 70 percent would be lost as heat. Since the exhaust manifolds of both engines were water-jacketed, a worst-case scenario where all of the lost heat energy from the engine would be transferred to the cooling water was assumed. Using the ISO E4 cycle data for the MerCruiser engine, it was determined that the engine would produce approximately 10,000 kJ of work energy during a ten minute test. The amount of heat energy produced along with this work energy is found in Equation 4-2.

Equation 4-2

$$E_{fuel} = (Q - W)_{eng}$$
$$Q_{eng} = -0.7E_{fuel}$$
$$W_{eng} = 0.3E_{fuel}$$
$$Q_{eng} = -0.7\left(\frac{W_{eng}}{0.3}\right) = -2.33W_{eng} = -2.33 \times 10000KJ = -23300KJ$$
$$E_{fuel} = \text{available energy from the fuel}$$
$$Q_{eng} = \text{heat input to engine}$$
$$W_{eng} = \text{work output from engine}$$

If all the heat energy produced by the engine is assumed to be transferred to the cooling water, ΔU_{CW} in Equation 4-1 is equals $-Q_{eng}$ in Equation 4-2. The minimum required volume of the PSR can then be calculated as shown in Equation 4-3.

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Equation 4-3

$$m_{CW} = \left(\frac{-Q_{eng}}{C_{CW} \ddot{A} T_{CW}} \right)$$

$$V_{CW} = (mv)_{CW}$$

$$V_{CW} = \left(\frac{-(-23300 \text{KJ})}{4.2 \, ^{KJ}\!/_{kg \cdot K} \times 25K} \right) \left(1 \, ^L\!/_{kg} \right) = 222L = 59 \text{ gal.}$$

$$m_{CW} = \text{mass of cooling water}$$

$$V_{CW} = \text{volume of cooling water}$$

$$v_{CW} = \text{specific volume of cooling water}$$

The second criterion represented the upper limit of the PSR volume. The equipment used for aqueous sample analysis was capable of detecting HC concentrations as low as one part per million (ppm). Also, preliminary baseline tests showed that the MerCruiser engine was producing an average of 13.3 grams of gaseous HC's during a ten minute test. The research team estimated that approximately five percent of the total HC's present in the exhaust stream would remain in the water during wet testing. If the hydrogen to carbon ratio of the HC species transferred to the water is assumed to be equal to that of the fuel, the upper limit of the PSR volume is calculated in Equation 4-4.

Equation 4-4

$$y_{HC} = \text{ppm}_{HC} \times 10^{-6} \, \tfrac{\text{mol}_{HC}}{\text{mol}_{sol}}$$

$$y_{HC} = \frac{n_{HC}}{n_{HC} + n_{H_2O}}, \, n_{H_2O} = n_{HC} \frac{(1 - y_{HC})}{y_{HC}} \cong n_{HC} \times 10^6$$

$$m_{H_2O} = m_{HC} \times 10^6 \left(\frac{MW_{HC}}{MW_{H_2O}} \right)$$

$$m_{H_2O} = (0.05 \times 13.3) g \times 10^6 \left(\frac{13.7}{18} \right) = 506 \text{kg}$$

$$V_{CW} = 506 \text{kg} \left(\frac{1L}{1 \text{kg}} \right)_{H_2O} \left(\frac{1 \text{gal}}{3.79L} \right) = 136 \text{gal}$$

$$y = \text{mole fraction}$$

$$\text{ppm} = \text{concentration in parts per million}$$

$$n = \text{number of moles}$$

$$MW = \text{molecular weight}$$

$$V_{CW} = \text{cooling water volume}$$

The volumes found in Equation 4-1 and Equation 4-4 represent rough estimates of the limits of the reservoir volume. An initial reservoir volume of 100-gallons was chosen for a ten minute test. However, it was also decided that the system would be constructed to allow for adjustment in the reservoir volume if it became necessary.

In order to accommodate the 100-gallons of cooling water, the PSR was constructed using two 55-gallon plastic drums. The drums were connected near their bases using four-inch diameter PVC pipe and fittings. The reservoir was placed on the second floor of the testing laboratory, one level (11.5 feet) above the test sled. In order to cool the engine during testing, water was pumped from the base of the PSR to the cooling water inlet on the front of the cylinder head using a positive displacement pump (designated the supply pump). Since the drive unit was not used during testing, the supply pump replaced the inlet water feed pump normally used to supply cooling water to the engine. In order to monitor and control the flow of cooling water to the engine, a Blue White 41000 flow meter and a one-inch diameter bronze globe valve were placed inline downstream of the pump. All connections were made using one-inch diameter PVC pipe, PVC fittings, and polypropylene tubing.

In order to simulate real world operating conditions as closely as possible, a bubble column was constructed to separate the exhaust gases from the cooling water once the mixture was discharged from the engine. A 35-gallon plastic drum was placed on a stand that was permanently affixed to the test rig. The exhaust gas/cooling water mixture was routed to the base of the drum via two-inch diameter PVC pipe and PVC fittings. The exhaust mixture inlet was placed at a depth of 16-inches from the designated water surface level to be used during testing. A sight glass was attached to the outside of the bubble column using two-inch diameter clear PVC pipe and assorted fittings. Two sample collection valves were installed in the column using 0.5-inch diameter bronze gate valves. One valve was placed at the midpoint of the designated water depth and the other in the bottom of the drum. A drain was also installed in the bottom of the drum.

Preliminary testing showed that too much water was being lost from splashing over the sides of the bubble column. Therefore, a splash shield was made from an 18-inch diameter by 24-inch long piece of steel ducting. The shield was riveted to the top of the column. A splash cone was made from steel mesh and riveted into the splash shield.

A large hood was constructed and installed over the bubble column to capture the exhaust gases rising from the water surface. The top of the hood was connected to the dilution tunnel using a five-inch diameter stainless steel

pipe. Due to limited floor space in the laboratory, the test rig was placed in a location that required nearly 50-feet of transfer pipe to reach the dilution tunnel. Therefore, the dilution tunnel air inlet was partially blocked in order to draw dilution air from around the hood. This ensured that none of the exhaust gases were lost and improved flow through the long transfer pipe. A diagram of the complete bubble column and exhaust hood is shown in Figure 4-2.

Figure 4-2: Bubble Column Used for Wet Testing of the MerCruiser Engine.
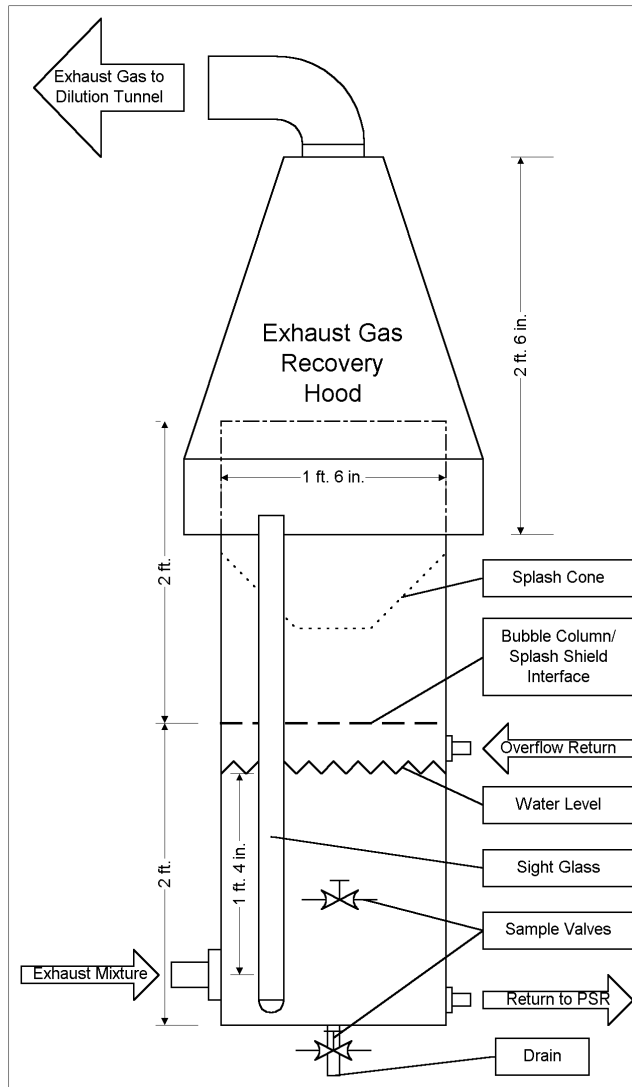
Cooling water was returned from the bubble column to the PSR using a positive displacement pump (designated the return pump). A Blue White 41000 flow meter and a one-inch diameter bronze globe valve were placed inline downstream of the pump in order to monitor and control the flow of water returning to the PSR. All connections were made using one-inch diameter PVC pipe, PVC fittings, and polypropylene tubing.

In order to maintain the appropriate water level in the bubble column during testing, an overflow tube was installed in the PSR. The tube was constructed from one-inch diameter PVC pipe and fittings and was installed near the base of the drum. The tube was L shaped so that it traversed horizontally to the center of the drum and then vertically up the center of the drum. The top of the tube was cut so that it would be flush with the water surface in the PSR once the volume of water required to fill the bubble column was removed. The tube was connected to the bubble column using one-inch diameter polypropylene tubing and PVC fittings. A one-inch bronze ball valve was installed in the connection tube near the base of the PSR.

Proper bubble column water level was maintained by always setting the cooling water flow through the return pump at a higher rate than that of the supply pump. The additional water removed from the bubble column would simply spill into the overflow tube and be returned back to the bubble column. This feature also made it possible to circulate the cooling water between the bubble column and PSR by closing off the bubble column inlet and running the return pump.

Since the prescribed test cycle was comprised of steady state modes, it was necessary to avoid introducing transient emissions into the test samples. This was an easy task for the exhaust gas samples, but preventing transient emissions from entering the recirculatory cooling system designed for the MerCruiser engine proved to be somewhat difficult. The solution was to use a secondary supply reservoir (SSR) and route the exhaust/cooling water mixture discharged from the engine away from the bubble column during transients. This required a switching system that would allow cooling water to be drawn from either the PSR or the SSR and be expelled either to the bubble column or to another location. The SSR was constructed from an additional 55-gallon plastic drum and placed in the same location as the PSR. Inlet water was switched between the PSR and SSR using two one-inch diameter bronze ball valves installed upstream of the supply pump. The discharged mixture was routed either to the bubble column or to a drain outside of the laboratory using two two-inch diameter PVC ball valves. This system made it possible to avoid putting transient emissions into the sample water. A diagram of the entire cooling system is shown in Figure 4-3.

Cooling System for Mercury Engine

Although original plans called for both engines to be tested Dry and Wet, it would have been to difficult to separate the cooling water from the outboard's exhaust manifold without significantly compromising engine exhaust tuning. Therefore, only Wet tests were performed on the Mercury engine.

Figure 4-3: Cooling System Used to Avoid Transient Exhaust Emissions Contamination of Sample Water for MerCruiser Engine
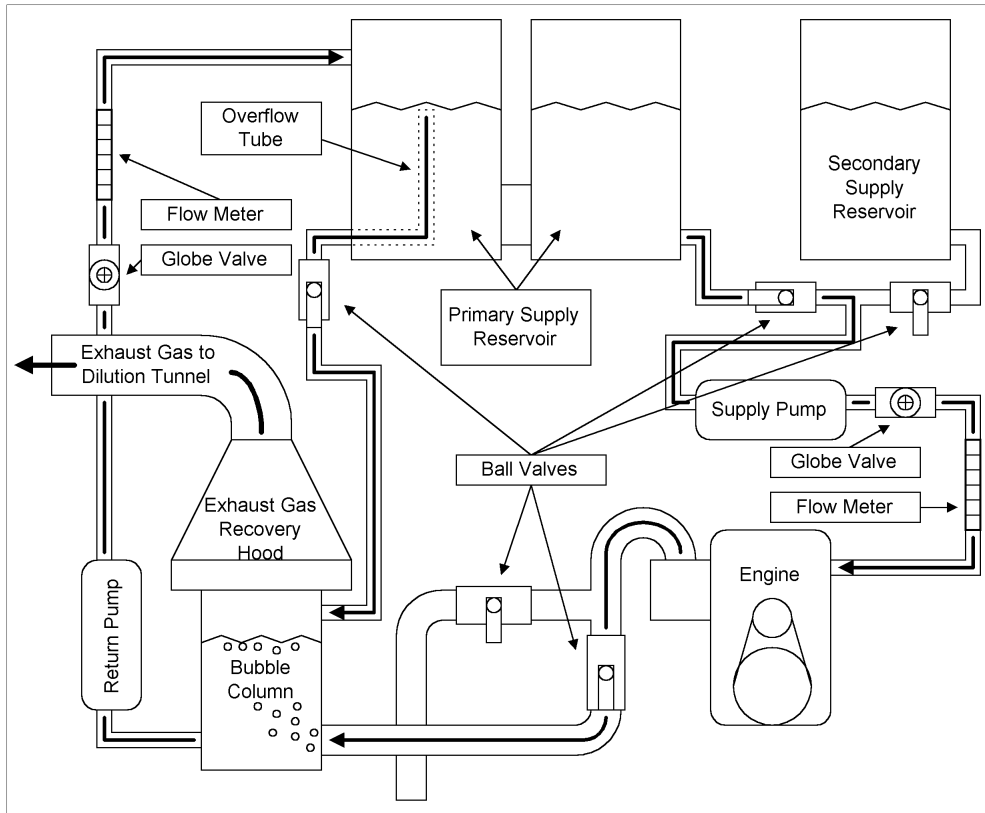
Unlike the MerCruiser engine, the Mercury 650 outboard engine's lower drive unit was not removed for testing. The drive unit provided a 2:1 gear reduction between the engine output shaft and the propeller shaft. Since the speed sensor used with the dynamometer control unit was coupled directly to the power absorber, the control unit's angular velocity readings were exactly half of the actual engine speed. However, the engine was rated by the manufacturer with the drive unit intact. Therefore, rated torque and power were not affected by the gear reduction.

Originally, the outboard engine was to be tested while running in a large reservoir of water. However several potential problems with this setup lead to the development of another approach. First, it would have been difficult to couple the propeller shaft to the power absorber because the connecting shaft would have to pass through the walls of the reservoir. Also, it would have been difficult to find a way to collect all of the exhaust gases rising out of the reservoir around the engine and still provide the engine with a fresh intake charge of air. Therefore, it was decided that cooling water would be fed to the engine from a supply reservoir and the exhaust gas/cooling water mixture would be collected at each point of discharge from the engine.

Concentrations of cooling water contaminants from the Mercury engine were expected to be large enough that a recirculatory cooling system like the one used with the MerCruiser engine would not be needed. Therefore, a single pass cooling system was constructed for testing of the Mercury engine. Performance data for the lower drive unit water pump was unavailable. Therefore, some preliminary tests were done to determine the volume of water needed for testing. It was determined that the 110-gallon primary supply reservoir used with the MerCruiser engine would hold enough water for a five minute test, so it was used to supply cooling water to the engine during testing. Water was pumped to the engine using a positive displacement pump through one-inch diameter polypropylene tubing. A Blue White 41000 flow meter and a one-inch bronze globe valve were placed inline downstream of the pump in order to monitor and control the flow of water to the engine.

Unlike the MerCruiser engine, the exhaust gas/cooling water mixture was not discharged from the Mercury outboard in one convenient location. The majority of the mixture was discharged around the propeller hub. A portion of the mixture was also discharged through three orifices near the engine/drive unit housing interface. One of the orifices was used to verify operation of the drive unit water pump. The other two appeared to be vents for the upper portion of the drive unit. In order to contain all of the mixture, it was necessary to epoxy pieces of 0.5-inch diameter copper tubing into the two vents. This made it possible to route the flow from all three sources to a convenient location using polypropylene tubing.

Collecting the mixture discharged at the propeller hub was accomplished by attaching a four-inch diameter four-way PVC junction to the propeller hub using a rubber coupler and hose clamps. A portion of the lower fin had to be removed in order to allow the rubber coupler to slide up over the hub. A four-inch diameter to two-inch diameter reducer bushing was cemented into the PVC junction opposite the propeller hub. Two rotating shaft oil seals were pressed into the two-inch opening in the bushing. A 1.5-inch diameter drive shaft was installed through the oil seals and over the splines on the propeller shaft in order to connect it to the power absorber. The junction was then oriented so that the remaining two openings (perpendicular to the installed shaft) were angled at approximately 45 degrees to the test sled.

The cooling water was gravity fed from the lower of the two remaining openings in the junction to a sealed collection chamber through four-inch diameter PVC pipe and fittings. The collection chamber was made from a five-gallon plastic bucket. The polypropylene tubes connected to the other three points of discharge were also fed

into the collection chamber. Since the collection chamber acted only as a common collection point and was too small to hold all of the sample water, a small submersible pump was placed in the collection chamber to pump the sample water to another location.

As was the case with the MerCruiser engine, it was necessary to avoid introducing transient emissions into the sample water during testing. This was accomplished by using two one inch diameter bronze ball valves to direct the flow of water pumped from the collection chamber to either the sample collection reservoir or to a floor drain. The 30-gallon plastic drum used as the bubble column for testing of the MerCruiser engine was used as the sample collection reservoir for the outboard system, because the necessary sample collection valves were already in place.

Exhaust gases were directed into the transfer pipe, and eventually the dilution tunnel by an exhaust stack made from four-inch diameter PVC pipe and fittings. The stack was connected to the final opening in the PVC junction and was oriented vertically. In order to reduce the amount of liquid water carried into the dilution tunnel, an expansion chamber was constructed from a five-gallon plastic bucket and installed in the exhaust stack. A diagram of the entire sampling system is shown in Figure 4-4.

Testing Procedures

Once the setup for each testing apparatus was completed, the critical flow venturies were arranged to attain the desired flowrate of air in the dilution tunnel. Propane injections were then performed to verify the integrity of the emissions testing equipment. The results of the injections had to show that the equipment complied with the guidelines stated in Title 40, Part 91 of the CFR before testing would commence [1]. The nominal flowrates used for the two engines are show in Table 4-1. Actual flow varies slightly from these values due to cell air temperature and pressure.

Table 4-1: Dilution Tunnel Flowrates

Engine	Flowrate
MerCruiser 3.0LX	1000 scfm
Mercury 650	2000 scfm

Before testing commenced, all analyzers were properly warmed and calibrated as specified in Title 40, Part 91 of the CFR [1]. The mass flow controllers used to control the flow of dilute exhaust to the sample collection bag and the DNPH cartridges were warmed and calibrated. The 80-liter Tedlar bags used to collect both the dilute exhaust and background air samples were evacuated and readied for sample collection. The three-liter Tedlar bags

used for dilute exhaust and background air sample storage were evacuated and labeled. The DNPH cartridges were labeled and returned to the storage freezer. For wet testing, the 250-ml sample bottles used for sample collection were labeled and organized. Once all of the above procedures were completed, the test engine was warmed to operating temperature.

Figure 4-4: Cooling System Used to Avoid Transient Exhaust Emissions Contamination of Sample Water for Mercury Engine
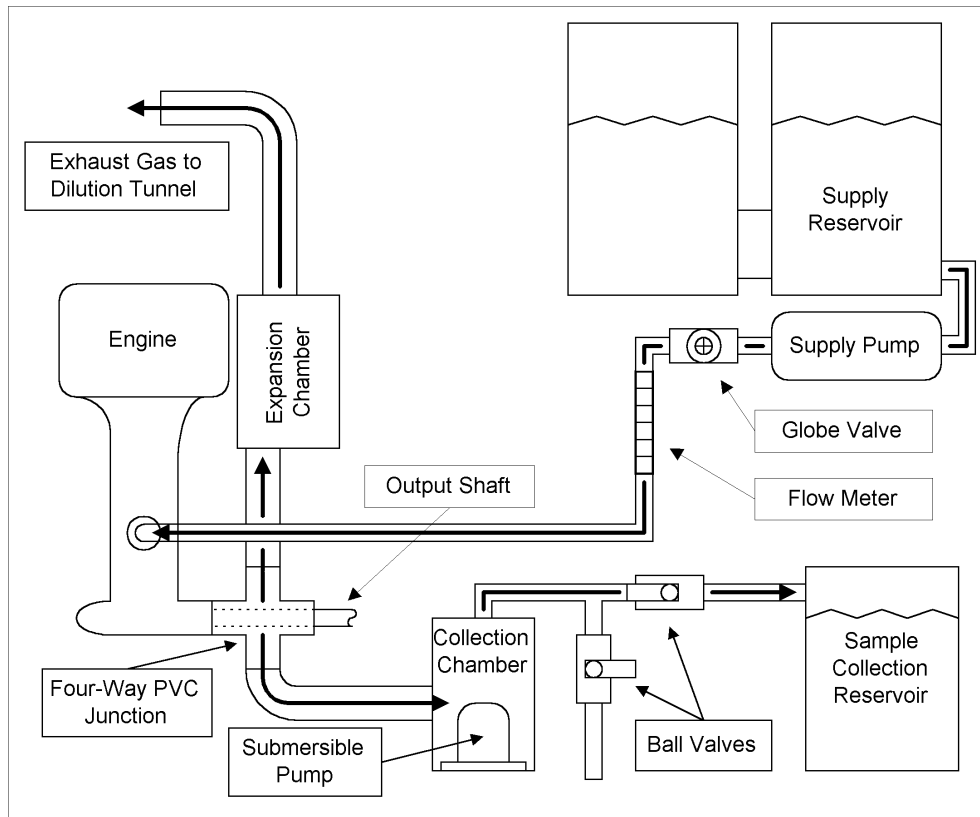
Testing Procedures for the MerCruiser 3.0LX Engine

  Before testing could begin, the set points and cooling water flowrates for each mode of the ISO E4 cycle had to be determined. Since all modal set points for the cycle are functions of wide open throttle (WOT) power at rated speed, the engine was started and run at rated speed and WOT. The power at that setting was recorded and the rest of the set points were calculated. According to MerCruiser, the inlet water feed pump from the drive unit supplied three gallons per minute (gpm) of water to the engine per 1000 revolutions per minute (rpm) of engine speed. This information was used to calculate the proper supply pump flowrates for each mode of the cycle. The test cycle and flowrates for the MerCruiser 3.0LX engine are shown in Table 4-2.

It was decided that Maladjustment testing of the MerCruiser engine would be done using only the third mode of the ISO E4 cycle. Test time would be 360-seconds. Also, Maladjustment tests would only be performed using unsalinated tap water. Test information and flowrates for maladjustment testing of the MerCruiser engine are shown in Table 4-3.

Table 4-2: MerCruiser 3.0LX test cycle and cooling water flow parameters

E4 Mode	Engine Speed	Power	Time	Energy	Cooling Water Flow
(---)	(rpm)	(kW)	(s)	(kW-hr)	(gpm)
1	4200	77.6	36	0.78	12.6
2	3360	44.4	84	1.04	10.1
3	2520	21.6	90	0.54	7.6
4	1680	7.8	150	0.33	5.0
5	Idle (700)	0.4*	240	0.03	2.1
		Totals	600	2.71	

Table 4-3: MerCruiser 3.0LX test parameters used for maladjustment testing

E4 Mode	Engine Speed	Power	Time	Energy	Cooling Water Flow
(---)	(rpm)	(kW)	(s)	(kW-hr)	(gpm)
3	2520	21.6	360	2.16	7.6

Dry Testing Procedures

Testing procedures for Dry testing of the MerCruiser engine were executed in the following sequence:

1. The dilute exhaust and background collection bags were evacuated and connected to the appropriate sample lines. An appropriately labeled DNPH cartridge was removed from the storage freezer and placed in the sample line. The engine was then started and set in the first mode of the ISO E4 cycle. The flow of cooling water supplied to the engine was adjusted to the appropriate rate.

2. The readings from the continuous analyzers (HC, NO_X, CO, and CO_2) were allowed to stabilize. Once they were stable, data collection from the continuous analyzers was started. The dilute exhaust and DNPH sample pumps were turned on at flows of 4.1 and 1.5 liters per minute (lpm) respectively. An average exhaust temperature was recorded for the mode. Once the sample time for the mode had elapsed, data collection was halted and the sample pumps were turned off.

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* Since the engine was coupled directly to the dynamometer, it was not possible to obtain zero torque at idle.

3. The engine was set at the next mode and the cooling water flowrate was adjusted in accordance with Table 4-2. For Maladjustment testing, steps three and four were not applicable.

4. Steps two and three were repeated until all five modes of the cycle had been run.

5. Upon completion of the fifth mode, the engine was shut down and the cooling water supply was turned off.

6. The DNPH cartridge was removed from the sample line and returned to the freezer. Portions of the dilute exhaust and background air samples were then transferred from the 80-liter Tedlar collection bags to appropriately labeled three-liter Tedlar bags and placed in a black plastic bag to protect them from ultraviolet light. The data from the continuous analyzers was then downloaded to disk storage.

Testing procedures concluded with step six. If additional tests were to be run, the sequence would begin again with step one. Once all tests were concluded, all samples were delivered to the appropriate laboratories for analysis.

Wet Testing Procedures
Since the exhaust hood was placed over the bubble column on the wet testing apparatus, exhaust gases were not released into the dilution tunnel until the exhaust gas/cooling water mixture was released into the bubble column. Therefore, the continuous analyzers were not able to stabilize before emissions were introduced into the cooling water. Several preliminary tests were performed to determine how much time was required for the analyzers to stabilize once the exhaust mixture was routed to the bubble column. This was done for each of the five modes of the test cycle. All analyzers stabilized within 60-seconds for all modes. This lead to a decision to start exhaust sample and continuous analyzer data collection exactly 60-seconds after water was routed to the bubble column for each mode. Therefore, the cooling water endured 60-seconds more exposure to the exhaust stream per mode than the exhaust gas samples. This was accounted for in calculating test results.

Testing procedures for Wet testing of the MerCruiser engine were executed in the following sequence:

1. The cooling water supply reservoir and the bubble column were both rinsed with tap water. Both sample collection valves were also rinsed. The PSR and the SSR were filled with 100 and 50-gallons of tap water respectively. For salt water tests, synthetic sea salt was added to both reservoirs until the

appropriate salinity level of 17-ppt was reached. The ball valve connected to the overflow tube was then opened to allow the bubble column to fill to the appropriate level. The return pump was then turned on and set to a flowrate of 10-gpm. The cooling water was then allowed to circulate between the bubble column and the primary reservoir for five minutes. Once the five minutes had passed, a background sample of the cooling water was collected in a 250-ml bottle from the bubble column's upper sample collection valve. The initial cooling water temperature was also measured with a handheld thermocouple reader and recorded.

2. The dilute exhaust and background collection bags were evacuated and connected to the appropriate sample lines. An appropriately labeled DNPH cartridge was removed from the storage freezer and placed in the sample line. The engine was then started and set in the first mode of the ISO E4 cycle. Cooling water was drawn from the SSR and the exhaust mixture was routed to a drain outside of the laboratory. The flow of cooling water was adjusted to the appropriate rate for the first mode of the cycle.

3. The system was then switched to draw cooling water from the PSR and return it to the bubble column. The return pump flowrate was then set to approximately two-gpm greater than that of the supply pump so that the overflow could maintain the proper water level in the bubble column. Data and sample collection was started 60-seconds after the switch in order to allow the continuous analyzers to stabilize. The dilute exhaust and DNPH sample pumps were turned on at flows of 4.1 and 1.5-lpm respectively. An average exhaust mixture temperature was recorded for the mode. Once the sample time for the mode had elapsed, data collection was halted and the sample pumps were turned off. The system was then switched back so that the supply pump was drawing from the SSR and the exhaust mixture was routed away from the bubble column.

4. The engine was set in the next mode and the supply pump flowrate was adjusted in accordance with Table 4-2 above. For Maladjustment testing, steps four and five were not applicable.

5. Steps three and four were repeated until all five modes of the cycle had been run.

6. Upon completion of the fifth mode, the engine was shut down and the cooling water was allowed to circulate between the bubble column and the primary supply reservoir for 10 minutes at 10-gpm. The

DNPH cartridge was removed from the sample line and returned to the freezer. A portion of the dilute exhaust and background air samples were then transferred from the 80-liter Tedlar collection bags to appropriately labeled three-liter Tedlar bags and placed in a black plastic bag to protect them from ultraviolet light. The data from the continuous analyzers was then downloaded to disk storage.

7. Once the sample water had circulated for 10 minutes, the return pump was turned off and the water was allowed to settle for an additional 10 minutes. The temperature of the posttest sample water was measured using a handheld thermocouple reader and recorded. Next, A water sample was collected in a 250-ml sample bottle from the middle of the sample water using the bubble column's upper sample collection valve. A sample was also collected in a 250-ml bottle from the bottom of the column using the lower sample collection valve. The water level in the column was then drained down until the water surface was at the same level as the upper sample collection valve. A final sample of the surface water was collected in a 250-ml bottle. The bubble column and cooling water reservoirs were then drained to complete the test.

Testing procedures concluded with step seven. If additional tests were to be run, the sequence would begin again with step one. Once all tests were concluded, all samples were delivered to the appropriate laboratories for analysis.

Testing Procedures for the Mercury 650 Engine

Before testing could begin, the set points for each mode of the ISO E4 cycle had to be determined. The positive displacement pump located in the drive unit was used to feed cooling water to the engine. Therefore, the flowrates did not need to be controlled externally as they were for the inboard engine. Since all modal set points for the ISO E4 cycle are functions of the rated speed and the wide open throttle (WOT) power at rated speed, the engine was started and run at rated speed and WOT. The power at that setting was recorded and the rest of the set points were calculated.

In order to avoid ratcheting the drive unit gears, the test cycle modes were run in reverse order for the OB engine, with the exception of the idle mode, which was still run last. The test cycle for the Mercury 650 engine is shown in Table 4-4.

Table 4-4: Mercury 650 Test Cycle Parameters

E4 Mode	Engine Speed	Power	Time	Energy
	(rpm)	(kW)	(s)	(kW-hr)
1	2000	3.6	75	0.07
2	3000	9.9	45	0.12
3	4000	20.3	42	0.24
4	5000	35.5	18	0.18
5	Idle (700)	0.0	120	0
		Total Time	300	0.61

Testing procedures for Wet testing of the Mercury engine were executed in the following sequence:

1. The cooling water supply and sample collection reservoirs were both rinsed with tap water. Both sample collection valves were also rinsed. The supply reservoir was then filled with 100-gallons of tap water. For salt water tests, synthetic sea salt was added to both reservoirs until the appropriate salinity level of 17-ppt was reached. A background water sample was collected in a 250-ml bottle from the supply reservoir. Also, the initial cooling water temperature was measured with a handheld thermocouple reader and recorded.

2. The dilute exhaust and background collection bags were evacuated and connected to the appropriate sample lines. An appropriately labeled DNPH cartridge was removed from the storage freezer and placed in the sample line. The engine was then started and set in the first mode of the ISO E4 cycle. Sample water was routed to a floor drain.

3. The continuous analyzer readings were allowed to stabilize. Once they had stabilized, the continuous analyzers were turned on. The dilute exhaust and DNPH sample pumps were turned on at flows of 4.1 and 1.5-lpm respectively. Also, a portion of the sample water flow was directed into the sample collection reservoir. When the sample time for the mode had elapsed, data collection was halted and the sample pumps were turned off. All sample water was then routed to a floor drain.

4. The engine was set at the next mode of the test cycle shown in Table 4-4.

5. Steps three and four were repeated until all five modes of the cycle had been run. Upon completion of the fifth mode, the engine was shut down and the cooling water supply was turned off. The DNPH cartridge was removed from the sample line and returned to the freezer. The temperature of the sample

water was measured using a handheld thermocouple reader and recorded. A portion of the dilute exhaust and background air samples were then transferred from the 80-liter Tedlar collection bags to appropriately labeled three-liter Tedlar bags and placed in a black plastic bag to protect them from ultraviolet light. The data from the continuous analyzers was then downloaded to disk storage.

6. The sample water was allowed to settle for 10 minutes upon test completion. Once that time had elapsed, the water samples were collected. A water sample was collected in a 250-ml sample bottle from the middle of the sample water using the bubble column's upper sample collection valve. A sample was also collected in a 250-ml bottle from the bottom of the column using the lower sample collection valve. The water level in the reservoir was then drained down until the water surface was at the same level as the upper sample collection valve. A final sample of the surface water was collected in a 250-ml bottle. The cooling water supply and the sample collection reservoirs were then drained to complete the test.

Testing procedures concluded with step six. If additional tests were to be run, the sequence would begin again with step one. Once all tests were concluded, all samples were delivered to the appropriate laboratories for analysis.

Test Matrix

In order to ensure good repeatability and provide a base for statistical analysis, it was decided that five tests would be run on each engine for all desired test condition combinations. Determinations of repeatability were based on continuous gaseous emissions data. Additional tests were completed if at least three of the five did not show good repeatability. However, testing proved to be very burdensome. Each Wet test required at least three technicians and took over an hour to complete. Therefore, the number of tests was dropped from five to three for Maladjustment testing of the MerCruiser engine. Again, additional tests were performed if repeatability was poor. Table 4-5 summarizes the proposed project test matrix.

Table 4-5: Proposed Test Matrix for Both Engines

Engine	Test Type	Engine Condition	Test Condition	Number
MerCruiser	Standard	Normal	Dry	5
MerCruiser	Standard	Normal	Wet, TW	5
MerCruiser	Standard	Normal	Wet, STW	5
MerCruiser	Maladjustment	Normal	Dry	3
MerCruiser	Maladjustment	TDC	Dry	3
MerCruiser	Maladjustment	Lean	Dry	3
MerCruiser	Maladjustment	Normal	Wet, TW	3
MerCruiser	Maladjustment	TDC	Wet, TW	3
MerCruiser	Maladjustment	Lean	Wet, TW	3
Mercury	Standard	Normal	Wet, TW	5
Mercury	Standard	Normal	Wet, STW	5
			Total	43

In order to keep all test data organized, each test run was assigned a number corresponding to the date the test was run and the test number (starting with 1) for that day. For example, the fourth test run on January 15, 1997 was assigned the number 1/15/97/4. A logbook was maintained that included the test numbers, test type, engine tested, engine condition, test condition, water type, and other pertinent information for each test.

5. Results

General Information

In all, 63 tests were performed on the MerCruiser engine and eight on the Mercury. Although only 33 tests were scheduled for the MerCruiser engine, 30 additional tests were run for two reasons. First, the MerCruiser engine was the first engine tested. Many of the initial tests were completed while the testing apparatus and sample analysis procedures were still being refined. Hence, some of the early data was lost or was incorrect. Second, the MerCruiser engine developed a carburetor float problem and a head gasket leak during testing. Both problems were repaired, but some tests had to be repeated. Only eight of the ten tests scheduled for the Mercury engine were completed because of a drive-line failure during the ninth test. However, at least three tests showing good repeatability were completed for both test conditions, so no attempt was made to repair the engine and continue testing.

Results for Continuous Exhaust Gas Sampling

EPA guidelines in Title 40, Part 89 of the CFR require that gaseous emissions data be reported on a brake specific (mass per unit energy) basis summed over all five modes of the test cycle [1]. Figures 5-1, 5-2, and 5-3 show gaseous emissions sampling results presented in this way for Standard tests run on both engines. Figure 5-4 shows gaseous emissions sampling results for Maladjustment tests run on the MerCruiser engine. The data shown in Figures 5-1 through 5-4 are also shown in tabular form along with individual mode data in Appendices A, B and D.

Figures 5-1 and 5-2 show brake specific emissions of regulated (HC and NO_X) and unregulated (CO and CO_2) gases for Standard tests run on the MerCruiser engine. Dry runs are shown in Figure 5-1 and Wet runs in Figure 5-2. Runs made using river water (RW) and salinated tap water (STW) are identified in Figure 5-2. Comparatively high CO and HC values for the 9/12/96 runs in Figure 5-1 are a result of the carburetor float problem. To a lesser extent, comparatively high CO and HC values for the 10/15/96 and 10/16/96 runs in Figure 5-1 and the 10/22/96 and 10/29/96 runs in Figure 5-2 are likely a result of the head leak. A noticeable decrease in CO emissions was noted upon repair of the head leak between the 10/29/96 and 12/5/96 runs. As a result of these problems, only data from the 12/12/96, 1/15/97, 1/27/97, and 1/28/97 tests were used for comparisons.

Figure 5-1: Brake Specific Emissions for Standard Dry Tests Run on MerCruiser 3.0LX Engine
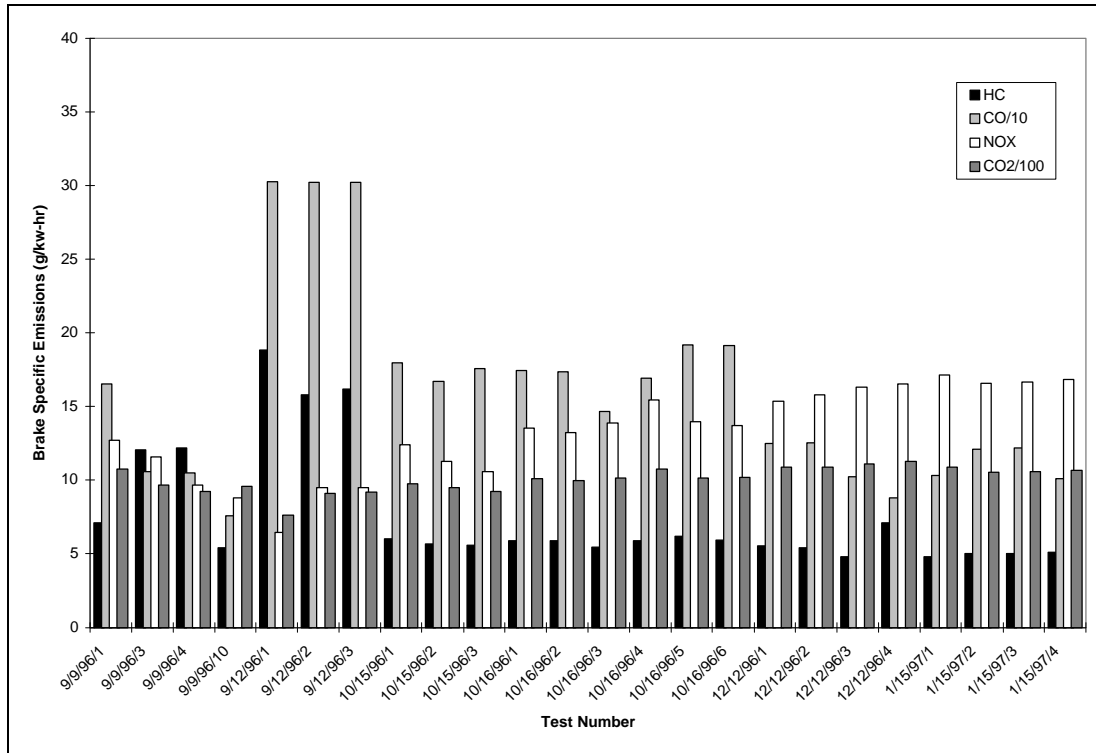
Figure 5-2: Brake Specific Emissions for Standard Wet Tests Run on MerCruiser 3.0LX Engine
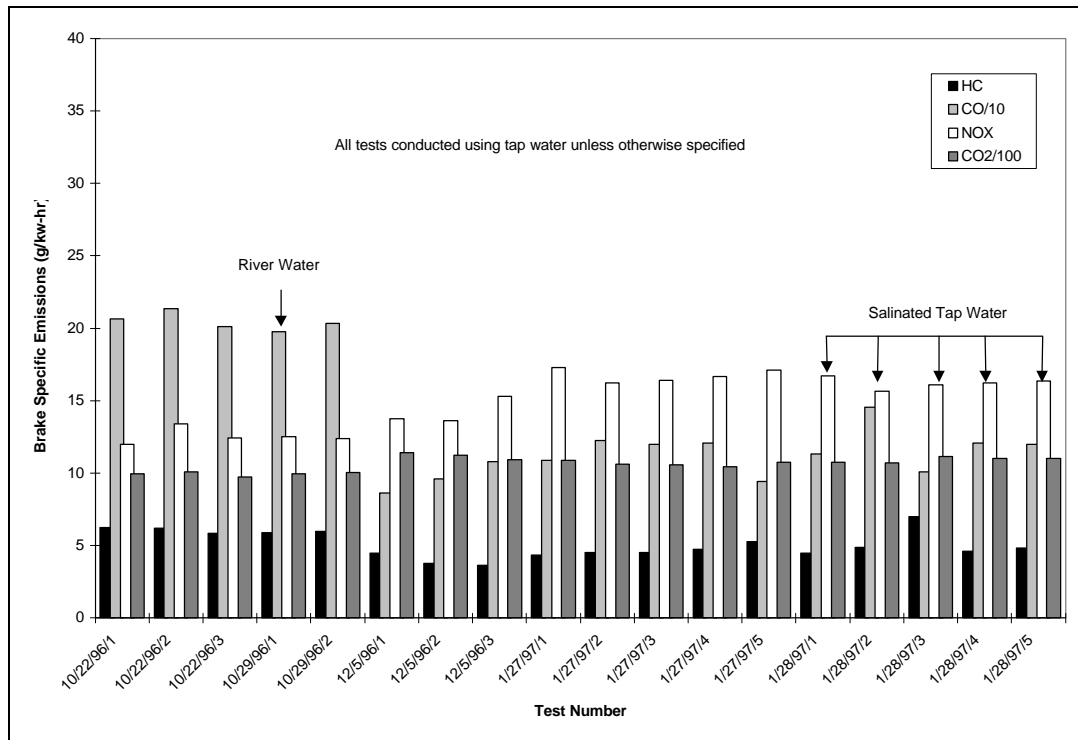
Figure 5-3: Brake Specific Emissions for Standard Wet Tests Run on Mercury 650 Engine
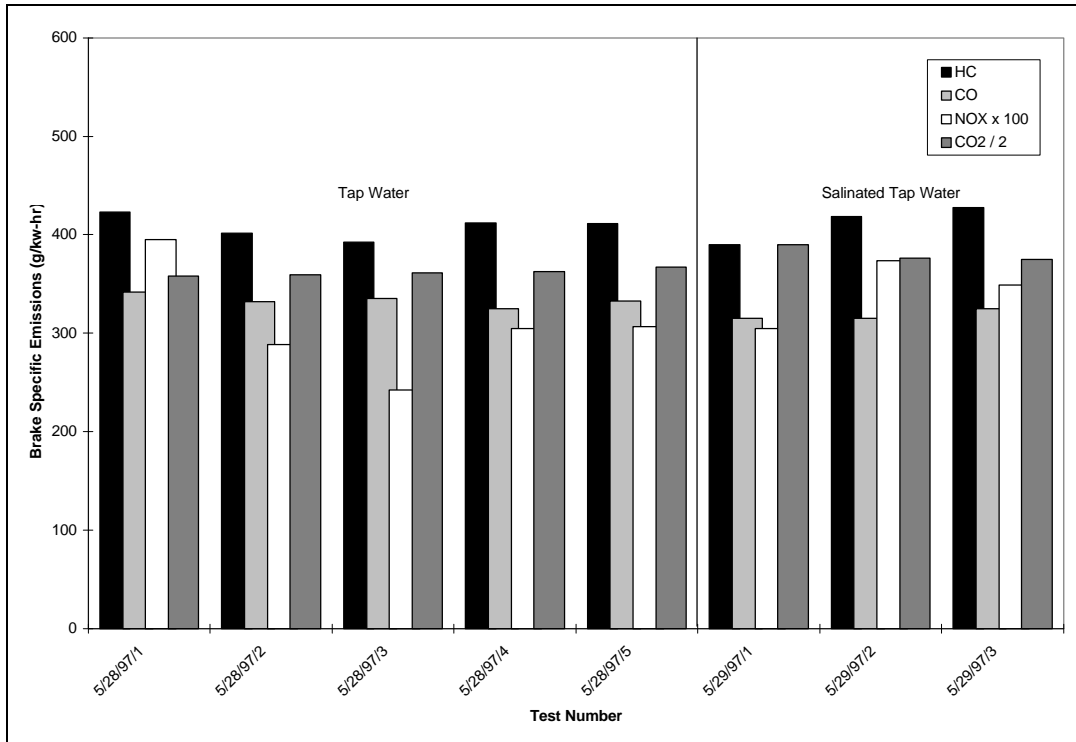
Figure 5-4: Brake Specific Emissions for Maladjustment Tests Run on MerCruiser 3.0LX Engine
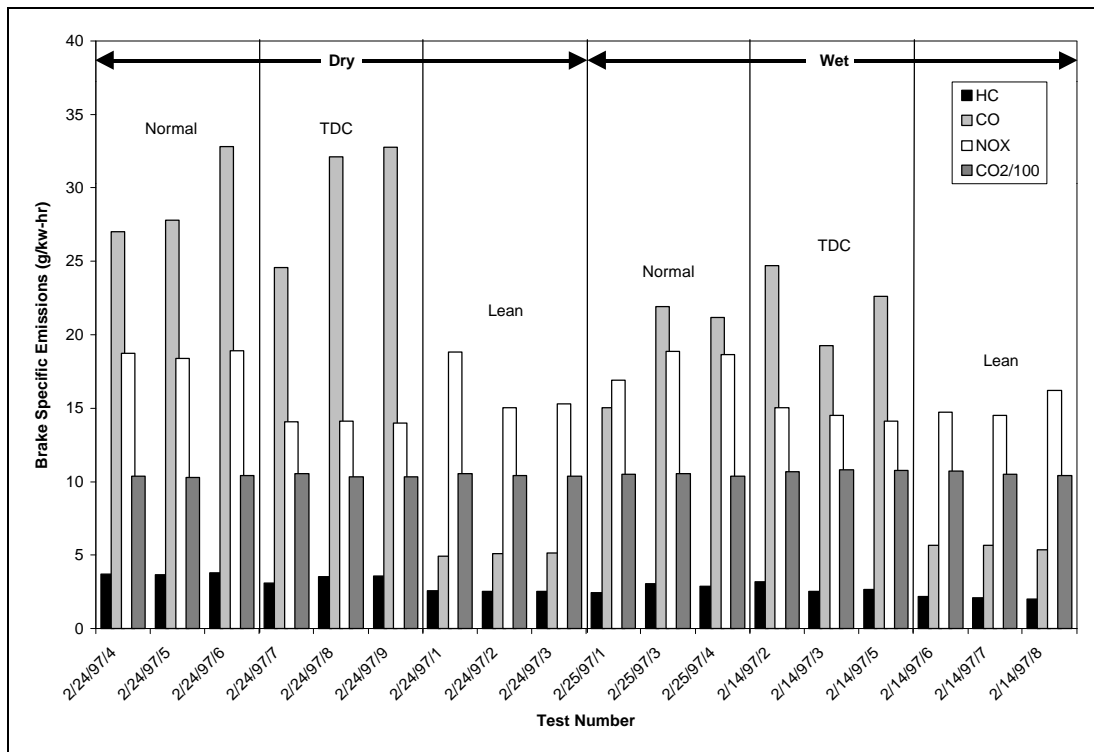
Figure 5-3 shows brake specific emissions of regulated and unregulated gases for all tests run on the Mercury engine. Tests run using TW and STW are separated by a dividing line. Only three tests were performed on the Mercury engine using STW because of the driveshaft failure. All eight runs were used for comparisons.

Figure 5-4 shows brake specific emissions of regulated and unregulated gases for the Maladjustment tests run on the MerCruiser engine. Figure 5-4 is broken into six columns of three tests each. The first three columns contain all Dry tests and the second three contain all Wet tests. No tests were run using saltwater. Each column of three tests is labeled according to the engine condition used for those tests. All tests were used for Maladjustment comparisons. Only mode 3 of the ISO E4 cycle was used for these tests. Therefore, direct comparisons between Figure 5-3 and either Figures 5-1 or 5-2 are not plausible.

In order to determine what portions of the regulated and unregulated gases were transferred to the cooling water during exhaust scrubbing, comparisons between Dry and Wet tests were made. Both individual mode and total test emissions data were averaged and the standard deviations calculated for Dry, TW, and STW data sets. The Dry data sets for the MerCruiser engine included tests 12/12/96/1-4 and 1/15/97/1-4 shown in Figure 5-1 (Standard) and tests 2/24/97/1-9 shown in Figure 5-4 (Maladjustment). The TW data sets for the MerCruiser engine included tests 1/27/97/1-5 shown in Figure 5-2 (Standard) and tests 2/14/97/2-8 and 2/25/97/1-4 shown in Figure 5-4 (Maladjustment). The STW data sets for the MerCruiser engine included tests 1/28/97/1-5 shown in Figure 5-2 (Standard only). The TW and STW data sets for the Mercury engine included tests 5/28/97/1-5 and tests 5/29/97/1-3 shown in Figure 5-3.

Results for River Water versus Tap Water Tests

Comparisons of continuous exhaust gas emissions data for tests 10/22/96/1-3 and tests 10/29/96/1-2 in Figure 5-2 and Appendix A shows very small differences in emissions levels for the test run using RW (10/29/96/1) versus tests run using TW. Similar findings were presented by the WVU Department of Chemistry for analysis of DNPH cartridges and aqueous samples. These results prompted the use of TW for all remaining tests.

Results for Standard Tests

Comparisons of Dry versus Wet continuous exhaust sampling data for Standard tests were made. Average values and standard deviations for total brake specific emissions were calculated for Dry, TW, and STW data sets and are shown below in Table 5-1. Average values and standard deviations for the individual mode data are shown

in Appendix C. Gaseous HC emissions for the Mercury engine were approximately 8700% higher than for the MerCruiser engine. This lends credit to EPA's decision to regulate only OB/PWC engines.

Table 5-1: Average Total Brake Specific Gaseous Emissions for Standard Tests

	MerCruiser Dry (g/kW-hr)	MerCruiser Wet, TW (g/kW-hr)	MerCruiser Wet, STW (g/kW-hr)	Mercury Wet, TW (g/kW-hr)	Mercury Wet, STW (g/kW-hr)
HC	5.36 ± 0.76	4.67 ± 0.35	5.15 ± 1.05	408.36 ± 11.42	411.97 ± 19.66
CO	110.93 ± 14.06	113.11 ± 11.87	119.92 ± 16.28	333.27 ± 6.03	318.35 ± 5.78
NO_X	16.40 ± 0.58	16.73 ± 0.45	16.21 ± 0.38	3.03 ± 0.56	3.32 ± 0.38
CO_2	1083.92 ± 25.42	1064.64 ± 16.64	1092.38 ± 19.04	723.42 ± 7.05	760.85 ± 16.18

Having calculated the average total brake specific emissions and standard deviations, comparisons between tests run under different test conditions (Dry, TW, STW) were made. First, the average Wet test values (both TW and STW) were subtracted from the average Dry test values for the MerCruiser engine. Next, the average STW values were subtracted from the average TW values for both engines. All values were obtained from Table 5-1. These differences, along with the larger of the two standard deviations, are shown in Table 5-2. Individual modal data is shown in Appendix C.

Table 5-2: Dry-Wet Values of Total Brake Specific Gaseous Emissions for Standard Tests

	MerCruiser Dry – TW (g/kW-hr)	MerCruiser Dry - STW (g/kW-hr)	MerCruiser TW – STW (g/kW-hr)	Mercury TW – STW (g/kW-hr)
HC	0.69 ± 0.76	0.21 ± 1.05	-0.48 ± 1.05	-3.61 ± 19.66
CO	-2.18 ± 14.06	-8.99 ± 16.28	-6.81 ± 16.28	14.92 ± 6.03
NO_X	-0.33 ± 0.58	0.19 ± 0.58	0.52 ± 0.45	-0.29 ± 0.56
CO_2	19.28 ± 25.42	-8.46 ± 25.42	-27.74 ± 19.04	-37.43 ± 16.18

The values in columns two and three of Table 5-2 represent the probable amounts of brake specific emissions transferred to the engine cooling water due to exhaust scrubbing. Values for both TW and STW are shown. Negative values mean that the emissions levels were actually higher during Wet testing. Columns four and five represent the difference in emissions levels retained in TW versus STW. Positive values represent the amounts of gaseous emissions retained in STW that were not retained in TW.

Since all four constituents (HC, CO, NO_X, and CO_2) are either soluble or contain compounds that are soluble, all values shown in columns two and three of Table 5-2 should be positive. However, this is clearly not the

case. Closer inspection of Table 5-2 shows that in most cases, the emissions values are smaller than the corresponding standard deviations. Therefore, all results in columns two and three of Table 5-2 are within the error margins of the data, and no definite conclusions can be drawn regarding exhaust gas contamination of engine cooling water using continuous sampling data.

Similarly, TW versus STW values in columns four and five of Table 5-2 are for the most part within the error margins of the data, with a few exceptions. The NO_X value for the MerCruiser engine in column four is slightly larger than its corresponding standard deviation. Although no definite conclusion can be drawn because of the very small difference in the numbers, the data appears to show that at least one of the NO_X constituents is somewhat more soluble in saline solution than in fresh water. This trend cannot be verified with the Mercury data, because the TW-STW NO_X value for the Mercury engine is smaller than the corresponding error margin.

The CO value for the Mercury engine in column five of Table 5-2 is also slightly larger than its corresponding standard deviation. Again, no definite conclusion can be drawn because of the small difference in the numbers, but the data appears to show that CO is somewhat more soluble in saline solution than in fresh water. This trend cannot be verified with the MerCruiser data, because the TW-STW CO value for the MerCruiser engine is smaller than the corresponding error margin.

The inverse of the CO versus water type relationship mentioned above appears to be true for CO_2. The negative CO_2 values in columns four and five of Table 5-2 mean that more CO_2 passed through the STW than the TW during testing of both engines. Therefore, CO_2 appears to be less soluble in saline solution than in fresh water.

Results for Maladjustment Tests

Dry versus Wet Comparisons

Comparisons of Dry versus Wet continuous exhaust sampling data for Maladjustment tests were made for all three engine conditions (Normal, TDC, and Lean). Average values and standard deviations for total brake specific emissions were calculated for Dry and TW data sets and are shown below in Table 5-3. Average values and standard deviations for the individual mode data are shown in Appendix D.

Having calculated the average total brake specific emissions and standard deviations, comparisons between tests run under different test conditions (Dry and TW) were made by subtracting the TW values from the Dry values

for each of the three engine conditions. These results along with the larger of the two corresponding standard deviation values are listed in

Table 5-4.

Table 5-3: Average Total Brake Specific Gaseous Emissions for Maladjustment Tests

	MerCruiser	MerCruiser	MerCruiser	MerCruiser	MerCruiser	MerCruiser
	Dry	Wet, TW	Dry	Wet, TW	Dry	Wet, TW
	Normal	Normal	TDC	TDC	Lean	Lean
	(g/kW-hr)	(g/kW-hr)	(g/kW-hr)	(g/kW-hr)	(g/kW-hr)	(g/kW-hr)
HC	3.73 ± 0.05	2.80 ± 0.31	3.41 ± 0.26	2.79 ± 0.34	2.57 ± 0.02	2.10 ± 0.09
CO	29.22 ± 3.14	19.37 ± 3.77	29.81 ± 4.54	22.17 ± 2.74	5.06 ± 0.12	5.57 ± 0.19
NO_X	18.67 ± 0.26	18.14 ± 1.08	14.07 ± 0.05	14.56 ± 0.45	16.38 ± 2.13	15.15 ± 0.94
CO_2	1035.58 ± 5.35	1048.42 ± 11.16	1041.56 ± 13.94	1075.25 ± 6.68	1043.39 ± 8.88	1055.42 ± 14.95

Table 5-4: Dry-Wet Values of Total Brake Specific Gaseous Emissions for Maladjustment Tests

	MerCruiser	MerCruiser	MerCruiser
	Dry – TW	Dry – TW	Dry – TW
	Normal	TDC	Lean
	(g/kW-hr)	(g/kW-hr)	(g/kW-hr)
HC	0.93 ± 0.31	0.62 ± 0.34	0.47 ± 0.09
CO	9.85 ± 3.77	7.64 ± 4.54	-0.51 ± 0.19
NO_X	0.53 ± 1.08	-0.49 ± 0.45	1.23 ± 2.13
CO_2	-12.84 ± 0.11	-33.69 ± 0.14	-12.03 ± 0.15

Difference values from

Table 5-4 are within the error margins for only a couple of cases. The data seems to follow the expected trend where a small portion of each gas is lost in the cooling water, with the exception of CO_2. In all cases, the difference values for CO_2 outweigh the standard deviation values by nearly two orders of magnitude, giving the data a fair amount of certainty. The negative CO_2 values mean that CO_2 output was greater for Wet tests for all three engine conditions. The percent increase in CO_2 is approximately 2% for these tests. Since CO_2 is known to be soluble in water, an explanation for the unexpected results was needed. One possibility was that the higher CO_2 output during Wet tests was a result of higher exhaust back-pressures present during Wet tests than during Dry tests.

Maladjustment Comparisons

Comparisons between the different engine conditions were also made using continuous exhaust data. Differences were calculated for Normal minus TDC and Normal minus Lean averages for both Dry and TW data

from Table 5-3. These values and the larger of the two corresponding standard deviation values are listed in Table 5-5. Individual modal comparisons are shown in Appendix F.

Table 5-5: Maladjustment Comparisons for Total Brake Specific Gaseous Emissions from Maladjustment Tests

	MerCruiser Normal - TDC Dry (g/kW-hr)	MerCruiser Normal – TDC Wet, TW (g/kW-hr)	MerCruiser Normal – Lean Dry (g/kW-hr)	MerCruiser Normal – Lean Wet, TW (g/kW-hr)
HC	0.32 ± 0.26	0.00 ± 0.34	1.16 ± 0.05	0.69 ± 0.31
CO	-0.59 ± 4.54	-2.81 ± 3.77	24.16 ± 3.14	13.80 ± 3.77
NO_X	4.60 ± 0.26	3.58 ± 1.08	2.29 ± 2.13	2.99 ± 1.08
CO_2	-5.98 ± 0.14	-26.82 ± 0.11	-7.81 ± 0.09	-6.99 ± 0.15

The results shown in Table 5-5 verify expected results for the engine conditions used. Retarding ignition timing is know to result in a drop in combustion temperatures and pressures with a corresponding drop in NO_X output. The positive NO_X values in columns two and three of Table 5-5 reflect this. Overall, a 20% decrease in NO_X output was attained by retarding the ignition timing to TDC. A slight (2.5% at most) increase in CO_2 output was also noted for TDC versus Normal tests. This result was unexpected, as CO_2 output is commonly used as an indicator of combustion efficiency. Therefore, CO_2 would be expected to decrease with retarded ignition timing.

Manufacturer recommended carburetor adjustments for the MerCruiser engine result in a somewhat rich fuel mixture during normal engine operation. Therefore, lean operation of the engine during Maladjustment testing does not mean that the engine was operated with a leaner than stoichiometric air-fuel ratio, it simply means that the engine was operated at a leaner air-fuel ratio than specified by the manufacturer. The fuel mixture was still on the rich side of stoichiometric. Leaner operation is known to increase fuel efficiency (and subsequently CO_2 and NO_X output) while decreasing HC and CO output. This was the case for the lean tests run on the MerCruiser engine, as seen in Table 5-5. HC and CO output were reduced by approximately 20% and 75% respectively, while CO_2 output increased by approximately 0.8%. Results for NO_X were within the error margins of the data, so no definite conclusion regarding effects of engine operation on NO_X output can be made for the Lean tests.

Equivalence Ratio Calculations

In order to track changes in the air/fuel ratio, the equivalence ratio (Φ) was calculated for each tests. Continuous exhaust sampling data was used for the calculations. Equivalence ratio calculations were based on the combustion reaction shown in Equation 5-1.

Equation 5-1

$$aC_8H_{13.4} + b(O_2 + 3.76N_2) \rightarrow cCO_2 + dCO + eHC + fH_2O + gNO + hN_2$$
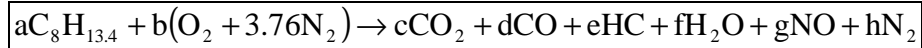
According to Heywood, NO_X production in spark ignited engines is dominated by NO formation, and very little NO_2 is produced [20]. Therefore, NO is used in Equation 5-1 instead of an $NO:NO_2$ ratio. The carbon to hydrogen ratio (8:13.4) used in Equation 5-1 is an estimate for gasoline also referenced from Heywood [20]. Raw oxygen (O_2) was not considered in the products of Equation 5-1 because no method of measurement was included in the testing scheme. Since both engines were tuned to run rich under all operating conditions, omission of O_2 production should only induce very small errors into the equivalence ratio calculations.

Values for c, d, e, and g from Equation 5-1 can be calculated from continuous exhaust sampling data, as shown in Equation Set 5-2. Values for a and b in Equation 5-1 are required to calculate Φ. They are found by performing carbon, hydrogen, and oxygen balances on Equation 5-1. These are shown in Equation Set 5-3.

Equation Set 5-2

$$c = \frac{m_{CO_2}}{MW_{CO_2}}$$

$$d = \frac{m_{CO}}{MW_{CO}}$$

$$e = \frac{m_{HC}}{MW_{HC}}$$

$$g = \frac{m_{NO_X}}{MW_{NO_X}}$$

$$m = mass$$

$$MW = molecular\ weight$$

Equation Set 5-3

$$C: a = \frac{c+d+e}{8}$$

$$H: f = \frac{13.4a - e}{2}$$

$$O: b = \frac{2c+d+f+g}{2}$$

Knowing a and b, the air-fuel ratio (A/F) for Equation 5-1 is calculated on a mass basis as shown in Equation 5-4. Finally, Φ is calculated using Equation 5-5. Since rich fueling results in air-fuel ratios less than stoichiometric, they also result in Φ values greater than unity.

Equation 5-4

$$A/F = 4.76 \times \frac{b}{a} \times \frac{MW_{air}}{MW_{fuel}}$$

$$MW_{air} = 28.97 \tfrac{g}{mol} = \text{molecular weight of air}$$

$$MW_{fuel} = 109.8 \tfrac{g}{mol} = \text{molecular weight of fuel}$$

Equation 5-5

$$\ddot{O} = \frac{A/F_s}{A/F}$$

$$A/F_s = 14.6 = \text{stoichiometric air : fuel ratio}$$

Equivalence ratios were calculated for each mode of each test using Equation 5-1 through Equation 5-5. Additionally, an average Φ was calculated for each test by summing the modal emissions for each constituent (HC, CO, NO_X, and CO_2) and performing the same calculations. As was the case for the gaseous emissions, Φ values were averaged for each data set (Dry, TW, and STW) for both engines and the standard deviations were calculated. Modal and total test equivalence ratios for all tests are shown in the Appendices. Average modal and total test equivalence ratios and their corresponding standard deviations for Standard tests are shown in Table 5-6. Since only one mode was used for Maladjustment testing, total test and modal equivalence ratios were the same. Average equivalence ratios and their corresponding standard deviations for Maladjustment tests are shown in Table 5-7. Although the modes were not run in the appropriate order on the Mercury engine, data in Table 5-6 was rearranged to reflect the correct order.

Table 5-6: Average Equivalence Ratios for Standard Tests

Mode	MerCruiser Dry	MerCruiser Wet, TW	MerCruiser Wet, STW	Mercury Wet, TW	Mercury Wet, STW
1	1.185 ± 0.004	1.203 ± 0.002	1.204 ± 0.003	1.722 ± 0.008	1.716 ± 0.019
2	1.025 ± 0.001	1.021 ± 0.001	1.022 ± 0.000	1.967 ± 0.072	2.005 ± 0.105
3	1.051 ± 0.009	1.042 ± 0.005	1.042 ± 0.005	1.858 ± 0.017	1.804 ± 0.068
4	1.098 ± 0.032	1.085 ± 0.031	1.094 ± 0.045	2.390 ± 0.056	2.324 ± 0.044
5	1.053 ± 0.007	1.066 ± 0.011	1.078 ± 0.038	3.261 ± 0.025	3.097 ± 0.137
Total Test	1.083 ± 0.006	1.083 ± 0.005	1.086 ± 0.006	2.192 ± 0.024	2.172 ± 0.053

Table 5-7: Average Equivalence Ratios for Maladjustment Tests

MerCruiser Dry Normal	MerCruiser Wet, TW Normal	MerCruiser Dry TDC	MerCruiser Wet, TW TDC	MerCruiser Dry Lean	MerCruiser Wet, TW Lean
1.041 ± 0.002	1.033 ± 0.002	1.043 ± 0.003	1.036 ± 0.002	1.026 ± 0.001	1.026 ± 0.001

Table 5-6 shows that the MerCruiser engine had the highest Φ during mode 1 (WOT at rated speed) and the lowest during mode 2. This means that fuel efficiency was highest during mode 2 and lowest during mode 1. The same was not true for the Mercury engine. Table 5-6 shows that fuel efficiency was highest during mode 1 (WOT at rated speed) and lowest during mode 5 (idle). Table 5-7 shows that retarding the ignition timing had little effect on the fuel efficiency of the MerCruiser engine, at least in mode 3. Installing the lean carburetor jets increased fuel efficiency by approximately 1% for mode 3 operation of the MerCruiser engine.

<u>Fuel Consumption</u>

Engine fuel consumption was continuously monitored and recorded during testing by recording the mass of the fuel feed/return container at a rate of 1 Hertz. This allowed for calculations of individual mode and total test fuel consumption. Comparisons between actual fuel consumption and emissions output were made via a carbon balance. First, the number of moles of fuel (a) required to produce the carbon-containing combustion products (c, d, and e) shown in Equation Set 5-3 were calculated for each test. The moles of fuel were then converted to mass using Equation 5-6.

Equation 5-6

$$m_{fuel,CP} = aMW_{fuel} = a\left(109.8\,\tfrac{g}{mol}\right)\left(\frac{1kg}{1000g}\right)\left(\frac{2.205lb_m}{1kg}\right)$$
$$m_{fuel,CP} = \text{fuel mass from combustion products}$$

Next, the amount of fuel consumed during each mode was summed for each test to find the actual fuel mass consumed ($m_{fuel,ACT}$). Finally, the ratio $m_{fuel,CP}$:$m_{fuel,ACT}$ was calculated as a percentage as shown in Equation 5-7

Equation 5-7

$$\left(\frac{m_{fuel,CP}}{m_{fuel,ACT}} \right) \times 100$$

Equation 5-7 was referred to as the "carbon mass ratio." Like the other gaseous emissions data comparisons, carbon mass ratios were averaged for the three data sets and standard deviations were calculated. Carbon mass ratios calculated for each test are shown in the Appendices. Average carbon mass ratios for Standard and Maladjustment tests are shown in Table 5-8.

Table 5-8: Average Carbon Mass Ratios for Standard Tests

MerCruiser	MerCruiser	MerCruiser	Mercury	Mercury
Dry	Wet, TW	Wet, STW	Wet, TW	Wet, STW
(%)	(%)	(%)	(%)	(%)
103.88 ± 1.82	102.50 ± 2.01	104.90 ± 0.98	92.35 ± 1.45	91.94 ± 0.71

Table 5-9: Average Carbon Mass Ratios for Maladjustment Tests

MerCruiser	MerCruiser	MerCruiser	MerCruiser	MerCruiser	MerCruiser
Dry	Wet, TW	Dry	Wet, TW	Dry	Wet, TW
Normal	Normal	TDC	TDC	Lean	Lean
(%)	(%)	(%)	(%)	(%)	(%)
101.23 ± 1.41	99.54 ± 1.56	113.10 ± 20.85	100.93 ± 0.37	100.27 ± 0.63	100.71 ± 1.46

Carbon mass ratios greater than 100% corresponded to a scenario where more carbon was accounted for in gaseous emissions than was consumed by the engine. Since this was not possible, the discrepancy must have been the result of calibration errors. Nearly all carbon ratios shown in Table 5-8 and Table 5-9 were slightly greater than 100% for tests run on the MerCruiser engine. Although they should all be less than 100%, the fact that nearly all of them are within 5% of unity shows that instrument calibration was maintained at reasonable levels. No discernable differences were noted when comparing carbon mass ratios for Dry and Wet tests run on the MerCruiser engine. This leads to the conclusion that the amount of HC's transferred to the cooling water due to exhaust scrubbing must have been within the error margins of the data (less than 2%).

Carbon mass ratios from Table 5-8 for the Mercury engine were approximately 92% for TW and STW tests. This information, along with the very high equivalence ratios shown in Table 5-6, hint that as much as 7% of total HC's are possibly transferred from exhaust gases to engine cooling water during operation of the Mercury engine.

Engine Certification Results

In order to compare gaseous emissions results with current and future EPA emissions standards, the 1998 (first year) and 2006 (final year) HC+NO$_X$ emissions standards were calculated. Although IB/SD engines are not currently regulated, they do represent EPA's goal for OB/PWC engines from an emission standpoint. Therefore, the HC+NO$_X$ standard was calculated for both test engines using Equation 2-2. The brake specific HC+NO$_X$ output was calculated for each test and averaged over all data sets. The HC+NO$_X$ output was then divided by both 1998 and 2006 EPA standards to yield ratios of actual to standard emissions levels. Results are shown as percentages in Table 5-10. The MerCruiser regulated emissions output was approximately 50% of EPA final year standards. Mercury engine regulated emissions output was 260% and 860% of EPA first and final year standards. These results did not include HC species transferred to the test water during exhaust scrubbing. Engines tested using ICOMIA recommended procedures (no exhaust scrubbing) would fail by a slightly wider margin. The data shows that large improvements in OB/PWC engine fueling will be required for this class of engine to pass the new EPA standards.

Table 5-10: Average HC+NO$_X$ Emissions Levels as Percentages of EPA Standards

Standard	MerCruiser Dry	MerCruiser Wet, TW	MerCruiser Wet, STW	Mercury Wet, TW	Mercury Wet, STW
	(%)	(%)	(%)	(%)	(%)
1998	14.58 ± 0.58	14.35 ± 0.43	14.31 ± 0.68	262.86 ± 7.62	265.36 ± 12.77
2006	47.30 ± 1.87	46.53 ± 1.40	46.42 ± 2.20	857.05 ± 24.85	865.19 ± 41.65

Results for Carbonyls Extracted from Gaseous Emissions

The target carbonyl species were formaldehyde, acetaldehyde and acetone. Carbonyls were captured in DNPH cartridges and speciated using high performance liquid chromatography. Table 5-11 was generated by calculating brake specific mass emissions from values presented in Table 3.3 of the Thesis by Vanyo, which provides a detailed description of the techniques used for sample analysis [2]. Results showed that the mass of Formaldehyde and Acetaldehyde collected for Wet versus Dry tests of the MerCruiser engine were reduced. Therefore, a portion of these species must have been retained in the test water or chemical reactions in the scrubbing

process reduced their production. The opposite trend was shown for Acetone species production. Collected mass emissions of Acetone showed a nearly order of magnitude increase for Wet versus Dry tests of the MerCruiser engine. Similar high levels of Acetone were not collected for the Mercury engine. However, emissions of Acetaldehyde were nearly an order of magnitude larger for the Mercury engine than for the MerCruiser. Results for retention of carbonyls in TW versus STW were inconclusive for gaseous emissions collection.

Table 5-11: Carbonyl Compounds Captured from Gaseous Exhaust

Compound	MerCruiser Dry (mg/kW-hr)	MerCruiser Wet, TW (mg/kW-hr)	MerCruiser Wet, STW (mg/kW-hr)	Mercury Wet, TW (mg/kW-hr)	Mercury Wet, STW (mg/kW-hr)
Formaldehyde	13.95±0.31	9.56±0.82	1.56±0.09	2.77±0.27	13.62±6.91
Acetaldehyde	46.06±16.48	20.38±3.99	14.49±0.55	120.74±4.52	159.57±48.40
Acetone	8.48±0.27	67.58±5.72	46.96±1.52	7.82±0.32	5.85±0.53

Results for Aqueous Emissions

Aqueous emissions were extracted and analyzed from test water samples using gas chromatography. Table 5-12 was complied from Tables 3.1 and 3.2 in the Thesis by Vanyo, which provides a detailed description of the techniques used for sample analysis [2]. Target HC species for aqueous sample analysis were acetone, ethanol, methanol, formaldehyde and acetaldehyde. None of these oxygenates appear to concentrate with any regularity to a certain portion of the water column.

TW contaminated by operation of the Mercury engine contained detectable concentrations of all five species. Of particular interest was the approximately 275 ppm concentrations of acetone found in those TW samples. Similar high concentrations of acetone were not found in the Mercury STW or either of the MerCruiser samples. However, high concentrations of acetone were detected in the exhaust stream of the MerCruiser engine for tests that employed exhaust scrubbing. Interestingly, similar high concentrations of acetone were not found in the either the exhaust gases or aqueous samples for Mercury engine tests using STW. In general, concentrations of alcohols were similar for aqueous samples from both engines.

Table 5-12: Concentrations of Hydrocarbon Species Detected in Aqueous Samples

Hydrocarbon Species	Sample Location	MerCruiser TW (ppm)	MerCruiser STW (ppm)	Mercury TW (ppm)	Mercury STW (ppm)
Acetone	Surface	ND	ND	293.3	ND
	Middle	ND	ND	272.4	ND
	Bottom	ND	ND	262.4	ND
Ethanol	Surface	21.1±9.0	12.1	16.9±10.7	53.9±46.2
	Middle	26.3±9.3	5.9±6.0	19.1±13.0	56.1
	Bottom	14.6	12.5±7.3	20.2±13.4	21.7
Methanol	Surface	3.5±2.6	ND	10.5±3.25	7.1
	Middle	3.2±1.1	3.0±1.7	1.1±0.1	ND
	Bottom	24.9±0.1	10.7±11.9	5.2±3.3	2.9±2.4
Formaldehyde	Surface	ND	ND	6.8±3.7	10.2±0.6
	Middle	ND	ND	29.6±10.2	9.8±4.5
	Bottom	ND	ND	16.6±2.7	45.3±39.0
Acetaldehyde	Surface	ND	ND	8.65±0.8	ND
	Middle	ND	ND	6.9±0.3	ND
	Bottom	ND	ND	13.6±3.6	ND

6. Conclusions

The primary objective of this research was to determine the effects of exhaust gas scrubbing on recreational marine engine gaseous and aqueous emissions. Secondary objectives were to develop the equipment and testing procedures needed to complete the required tasks. Prior research had attempted to determine the effects of exhaust scrubbing on the marine environment by analyzing pre and post scrubbing exhaust gas. This research attempted to achieve the same goal through analysis of water samples that had been contaminated by marine engine operation. Gaseous emissions analysis was performed, and generally agreed with results presented by other investigators [8, 13, 14]. Although some general trends can be deduced from aqueous sample analysis data, it was difficult to draw definitive conclusions about the presence and retention of carbonyl species in the marine environment. Therefore, the real value of this research lies in the development of equipment and testing procedures used for aqueous sample generation during modal testing of recreational marine engines.

Engine cooling water handling systems were developed for both inboard and outboard engines that made it possible to load and circulate cooling water during modal testing while avoiding exhaust/cooling water interactions during startup and between mode transients. This made it possible to perform the EPA testing procedures under conditions much more like those associated with real world engine operation. Equipment and procedures were created that made it possible to collect aqueous samples from three points in the water column.

The following noteworthy conclusions were drawn based on gaseous and aqueous analysis:

1. The two-cycle Mercury engine produced 87 times as much gaseous HCs and 15 times less NO_X than the four-cycle MerCruiser.

2. CO_2 emissions were higher for Wet tests than for Dry tests run on the MerCruiser engine. This was possibly due to differences in backpressure experienced by the engine during the two different types of tests.

3. The Mercury engines $HC+NO_X$ emissions were 2.6 and 8.6 times the respective first and last year EPA emissions standard.

4. Acetone production appeared to increase significantly as a result of exhaust scrubbing. However, the tendency for it to stay in solution or bubble out was difficult to pinpoint due to inconsistencies in the data.

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7. Recommendations for Future Research

This research was a first attempt at analyzing total emissions (gaseous and aqueous) from recreation marine engines operated according to EPA certification requirements. Attempts were made to quantify carbonyls in the post scrubbing exhaust gases and carbonyls and alcohols in the aqueous samples. Theses compounds represent only a small portion of the total array of HC species that could be present in gaseous and/or aqueous emissions. Therefore, more comprehensive speciation work would be beneficial in understanding the true effects of exhaust scrubbing on marine engine emissions.

Although test water was allowed to settle for ten minutes before samples were collected, it is unlikely that the solutions reached chemical equilibrium in this short period of time. Therefore, water samples collected represented the pollutants present in the test water only a short period of time after testing. No attempt was made to determine the rate at which HC species evaporate from the water surface or settle to a particular location in the water column. Therefore, time studies of post scrubbing cooling water would provide realistic data on the life cycles of HC pollutants in the aqueous environment.

The high levels of acetone detected in post-scrubbing exhaust gases from the MerCruiser engine are of concern. Since this engine was chosen to represent EPA's goal for marine engine emissions levels, verification of these results would be beneficial in determining if replacing older carbureted two-cycle engines with more modern and efficient four-cycle and direct injection two-cycle engines will actually have adverse effects on the marine environment. Therefore, a similar study on several newer emissions compliant engines would be very beneficial.

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Appendix A: Gaseous Emissions Data for ISO E4 Modal Testing of MerCruiser 3.0LX Engine

Run #	9/9/96/1	9/9/96/3	9/9/96/4	9/9/96/10	9/12/96/1	9/12/96/2	9/12/96/3	10/15/96/	10/15/96/
Time (s)	600	600	600	600	600	600	600	600	600
Test Type	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry

Modal emissions by mass (g)

MODE 1
HC	4.59	5.31	4.66	3.69	3.67	3.53	3.46	4.88	4.02
CO	225.07	17.93	17.96	18.16	246.20	241.71	242.28	210.88	189.50
NO_x	4.40	4.62	4.49	3.06	3.29	2.95	2.96	5.80	5.21
CO_2	604.58	602.67	598.62	580.86	544.99	548.83	550.22	612.92	618.79
ER	1.19	1.06	1.06	1.06	1.21	1.21	1.21	1.18	1.17

MODE 2
HC	3.17	3.56	3.51	3.39	3.34	3.19	3.20	2.84	2.65
CO	28.76	41.68	42.68	43.12	75.02	56.70	57.29	23.51	21.26
NO_x	23.39	19.63	17.36	16.87	12.98	18.49	18.56	22.97	21.65
CO_2	1063.90	974.04	922.05	964.00	790.23	967.17	976.10	1006.88	963.09
ER	1.04	1.05	1.05	1.05	1.08	1.06	1.06	1.03	1.03

MODE 3
HC	2.85	2.28	2.43	2.28	2.95	2.80	2.80	2.68	2.74
CO	70.06	30.69	43.43	45.16	121.95	95.56	95.98	81.38	88.88
NO_x	5.68	6.48	3.81	3.46	1.07	3.79	3.73	4.05	2.97
CO_2	543.94	506.88	441.63	446.16	325.08	469.31	474.38	458.47	420.53
ER	1.10	1.06	1.09	1.09	1.20	1.13	1.13	1.12	1.14

MODE 4
HC	3.36	3.01	2.57	2.77	14.12	6.03	6.27	3.47	3.59
CO	105.46	73.99	63.41	74.19	179.33	227.74	227.85	127.57	121.89
NO_x	0.50	0.29	0.22	0.16	0.04	0.14	0.15	0.33	0.31
CO_2	369.25	317.46	292.96	285.97	193.44	264.31	267.03	294.85	296.63
ER	1.17	1.15	1.15	1.16	1.40	1.32	1.32	1.22	1.21

MODE 5
HC	5.04	18.18	19.55	2.39	26.46	26.78	27.66	2.28	2.25
CO	13.37	119.68	113.91	22.86	188.28	188.22	186.73	38.00	25.42
NO_x	0.06	0.00	0.01	0.00	-0.01	0.00	0.01	0.09	0.07
CO_2	294.57	186.29	218.69	294.32	195.84	189.50	200.54	242.54	239.04
ER	1.10	1.42	1.39	1.09	1.50	1.51	1.50	1.13	1.10

Total emissions by mass (g)

HC	19.01	32.34	32.72	14.52	50.54	42.33	43.39	16.15	15.25
CO	442.72	283.97	281.39	203.49	810.78	809.93	810.13	481.34	446.95
NO_x	34.03	31.02	25.89	23.55	17.37	25.37	25.41	33.24	30.21
CO_2	2876.24	2587.34	2473.95	2571.31	2049.58	2439.12	2468.27	2615.66	2538.08
ER	1.11	1.11	1.11	1.08	1.23	1.20	1.20	1.12	1.12

Total brake specific emissions (g/bhp-hr)

HC	5.30	9.01	9.11	4.04	14.08	11.79	12.09	4.50	4.25
CO/10	12.33	7.91	7.84	5.67	22.58	22.56	22.57	13.41	12.45
NO_x	9.48	8.64	7.21	6.56	4.84	7.07	7.08	9.26	8.42
CO_2/100	8.01	7.21	6.89	7.16	5.71	6.79	6.88	7.29	7.07

Fuel consumption (lbm)

Mode 1	0.61	0.63	0.62	0.61	0.61	0.61	0.61	0.62	0.61
Mode 2	0.71	0.68	0.64	0.68	0.62	0.71	0.71	0.70	0.66
Mode 3	0.43	0.36	0.34	0.33	0.36	0.43	0.44	0.41	0.40
Mode 4	0.35	0.31	0.26	0.26	0.37	0.44	0.45	0.34	0.35
Mode 5	0.21	0.34	0.32	0.21	0.38	0.38	0.38	0.18	0.17
Total	2.31	2.32	2.17	2.09	2.34	2.57	2.58	2.25	2.19

Carbon balance (lbm of $C_8H_{13.4}$)

(%)	108.19	93.28	95.79	96.98	102.67	103.27	103.80	104.89	103.34

Exhaust temperatures (deg F)

Mode 1	---	---	---	---	---	---	---	---	---
Mode 2	---	---	---	---	---	---	---	---	---
Mode 3	---	---	---	---	---	---	---	---	---
Mode 4	---	---	---	---	---	---	---	---	---
Mode 5	---	---	---	---	---	---	---	---	---

Appendix A: Gaseous Emissions Data for ISO E4 Modal Testing of MerCruiser 3.0LX Engine

Run #	10/15/96/	10/16/96/	10/16/96/	10/16/96/	10/16/96/	10/16/96/	10/16/96/	12/12/96/	12/12/96/
Time (s)	600	600	600	600	600	600	600	600	600
Test Type	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry
Modal emissions by mass (g)									
MODE 1									
HC	4.03	4.53	4.49	4.30	4.44	4.82	4.54	5.02	4.89
CO	202.34	216.08	214.95	210.48	211.34	236.47	240.59	213.24	211.05
NO_x	4.80	4.59	5.50	6.00	6.38	5.08	4.60	5.29	5.54
CO_2	617.91	605.33	613.66	632.50	622.65	594.36	584.00	606.11	601.23
ER	1.17	1.19	1.18	1.18	1.18	1.20	1.20	1.19	1.18
MODE 2									
HC	2.64	2.76	2.78	2.89	2.94	2.93	2.88	2.77	2.85
CO	20.79	20.55	20.09	24.34	23.51	27.90	27.96	11.79	13.52
NO_x	20.72	24.97	24.49	22.89	26.29	25.42	25.39	27.01	27.48
CO_2	946.99	1057.33	1042.45	1016.87	1088.28	1060.98	1054.49	1085.16	1086.28
ER	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03
MODE 3									
HC	2.72	2.63	2.62	1.90	2.57	2.67	2.60	2.31	2.43
CO	99.20	60.96	68.98	14.74	51.51	67.75	66.24	31.57	37.09
NO_x	2.45	6.36	5.17	7.92	8.12	6.10	6.34	8.35	8.54
CO_2	406.99	525.69	496.95	522.20	567.37	517.94	522.83	561.83	556.77
ER	1.15	1.09	1.10	1.04	1.08	1.10	1.10	1.06	1.06
MODE 4									
HC	3.24	3.55	3.59	3.23	3.60	3.75	3.67	3.08	2.62
CO	112.57	133.33	129.73	109.91	137.72	146.85	144.94	65.87	64.24
NO_x	0.25	0.30	0.27	0.28	0.51	0.53	0.35	0.57	0.68
CO_2	276.24	290.09	287.62	295.23	348.29	315.47	317.32	382.85	386.39
ER	1.21	1.23	1.22	1.20	1.21	1.23	1.22	1.13	1.12
MODE 5									
HC	2.42	2.37	2.31	2.25	2.25	2.39	2.25	1.68	1.71
CO	36.39	36.62	31.45	33.05	29.40	34.71	32.77	11.70	10.62
NO_x	0.06	0.08	0.07	0.07	0.07	0.31	0.04	0.00	0.00
CO_2	231.16	227.74	232.52	251.18	250.11	229.43	245.85	283.02	283.81
ER	1.13	1.13	1.12	1.11	1.11	1.13	1.12	1.06	1.06
Total emissions by mass (g)									
HC	15.05	15.84	15.79	14.57	15.80	16.56	15.94	14.86	14.50
CO	471.29	467.54	465.20	392.52	453.48	513.68	512.50	334.17	336.52
NO_x	28.28	36.30	35.50	37.16	41.37	37.44	36.72	41.22	42.24
CO_2	2479.29	2706.18	2673.20	2717.98	2876.70	2718.18	2724.49	2918.97	2914.48
ER	1.12	1.12	1.12	1.10	1.11	1.12	1.12	1.09	1.09
Total brake specific emissions (g/bhp-hr)									
HC	4.19	4.41	4.40	4.06	4.40	4.61	4.44	4.14	4.04
CO/10	13.13	13.02	12.96	10.93	12.63	14.31	14.28	9.31	9.37
NO_x	7.88	10.11	9.89	10.35	11.52	10.43	10.23	11.48	11.77
$CO_2/100$	6.91	7.54	7.45	7.57	8.01	7.57	7.59	8.13	8.12
Fuel consumption (lbm)									
Mode 1	0.61	0.64	0.61	0.62	0.63	0.63	0.63	0.62	0.61
Mode 2	0.65	0.74	0.71	0.69	0.73	0.82	0.71	0.73	0.72
Mode 3	0.38	0.43	0.41	0.36	0.44	0.42	0.42	0.41	0.42
Mode 4	0.32	0.35	0.34	0.33	0.39	0.38	0.37	0.33	0.32
Mode 5	0.16	0.20	0.18	0.19	0.17	0.16	0.17	0.17	0.18
Total	2.12	2.36	2.25	2.19	2.36	2.42	2.30	2.27	2.26
Carbon balance (lbm of $C_8H_{13.4}$)									
(%)	105.94	102.02	105.56	106.08	106.09	101.77	107.04	105.99	106.34
Exhaust temperatures (deg F)									
Mode 1	---	---	---	---	---	---	---	---	---
Mode 2	---	---	---	---	---	---	---	---	---
Mode 3	---	---	---	---	---	---	---	---	---
Mode 4	---	---	---	---	---	---	---	---	---
Mode 5	---	---	---	---	---	---	---	---	---

Appendix A: Gaseous Emissions Data for ISO E4 Modal Testing of MerCruiser 3.0LX Engine

Run #	12/12/96/	12/12/96/	1/15/97/1	1/15/97/2	1/15/97/3	1/15/97/4
Time (s)	600	600	600	600	600	600
Test Type	Dry	Dry	Dry	Dry	Dry	Dry

Modal emissions by mass (g)

MODE 1

HC	4.79	4.76	4.94	4.68	4.77	4.68
CO	210.85	200.85	217.81	218.72	214.52	208.68
NO_x	5.64	6.23	5.79	5.25	5.46	5.55
CO_2	602.92	608.05	602.95	586.76	592.40	597.82
ER	1.18	1.18	1.19	1.19	1.19	1.18

MODE 2

HC	2.83	2.61	2.68	2.72	2.59	2.80
CO	17.46	14.20	11.71	12.42	10.42	12.55
NO_x	27.42	27.62	27.75	28.15	28.86	27.89
CO_2	1082.36	1080.74	1066.25	1053.75	1058.16	1055.05
ER	1.03	1.03	1.02	1.02	1.02	1.03

MODE 3

HC	2.08	1.75	2.09	2.24	2.19	2.10
CO	24.94	12.16	16.62	25.78	28.12	21.39
NO_x	9.48	9.31	10.71	9.84	9.36	9.95
CO_2	564.71	565.51	560.77	551.69	546.04	557.08
ER	1.05	1.04	1.04	1.05	1.05	1.05

MODE 4

HC	1.58	8.05	1.91	2.61	2.59	2.04
CO	16.21	4.18	25.53	64.68	67.69	26.42
NO_x	1.17	1.15	1.70	1.07	0.94	1.70
CO_2	427.04	466.63	402.35	363.33	361.35	399.12
ER	1.05	1.08	1.07	1.13	1.13	1.07

MODE 5

HC	1.57	1.93	1.27	1.24	1.37	2.01
CO	4.07	4.40	4.67	2.82	5.59	2.19
NO_x	0.00	0.00	0.06	0.06	0.07	0.03
CO_2	294.89	296.05	276.34	263.20	271.73	250.66
ER	1.05	1.05	1.05	1.04	1.05	1.05

Total emissions by mass (g)

HC	12.85	19.10	12.89	13.49	13.51	13.63
CO	273.53	235.79	276.34	324.42	326.34	271.23
NO_x	43.71	44.31	46.01	44.37	44.69	45.12
CO_2	2971.92	3016.98	2908.66	2818.73	2829.68	2859.73
ER	1.08	1.08	1.09	1.09	1.09	1.08

Total brake specific emissions (g/bhp-hr)

HC	3.58	5.32	3.59	3.76	3.76	3.80
CO/10	7.62	6.57	7.70	9.04	9.09	7.56
NO_x	12.18	12.34	12.82	12.36	12.45	12.57
$CO_2/100$	8.28	8.40	8.10	7.85	7.88	7.97

Fuel consumption (lbm)

Mode 1	0.61	0.61	0.63	0.63	0.63	0.62
Mode 2	0.73	0.73	0.74	0.73	0.73	0.73
Mode 3	0.41	0.40	0.41	0.39	0.41	0.39
Mode 4	0.30	0.33	0.30	0.32	0.34	0.31
Mode 5	0.22	0.21	0.20	0.19	0.20	0.17
Total	2.27	2.27	2.28	2.26	2.31	2.21

Carbon balance (lbm of $C_8H_{13.4}$)

(%)	104.36	104.71	102.32	102.74	101.07	103.48

Exhaust temperatures (deg F)

Mode 1	---	---	1040	1050	1040	1050
Mode 2	---	---	980	975	980	980
Mode 3	---	---	740	740	740	750
Mode 4	---	---	510	510	500	520
Mode 5	---	---	135	140	140	140

Appendix A: Gaseous Emissions Data for ISO E4 Modal Testing of MerCruiser 3.0LX Engine

Run #	10/22/96/	10/22/96/	10/22/96/	10/29/96/	10/29/96/	12/5/96/1	12/5/96/2	12/5/96/3	1/27/97/1
Time (s)	600	600	600	600	600	600	600	600	600
Test Type	TW	TW	TW	RW	TW	TW	TW	TW	TW

Modal emissions by mass (g)

MODE 1

HC	4.94	4.66	4.67	4.72	4.90	1.75	2.33	2.36	4.18
CO	262.68	259.67	257.90	256.13	268.32	75.03	111.20	111.57	231.38
NO_x	3.10	3.25	3.27	3.55	3.15	11.03	9.21	9.16	4.62
CO_2	543.52	531.04	530.46	543.80	543.74	669.56	645.90	646.66	558.27
ER	1.22	1.22	1.22	1.22	1.23	1.08	1.11	1.11	1.20

MODE 2

HC	2.72	2.70	2.66	2.51	2.50	1.36	1.35	1.36	1.95
CO	24.08	25.49	22.62	15.26	14.64	4.34	3.79	3.66	7.82
NO_x	22.99	25.07	24.38	23.95	24.11	24.22	24.57	24.81	28.72
CO_2	1065.90	1071.26	1069.67	1060.38	1081.81	1118.21	1104.87	1101.18	1068.41
ER	1.03	1.03	1.03	1.03	1.03	1.02	1.02	1.02	1.02

MODE 3

HC	2.61	2.63	2.58	2.52	2.62	3.81	1.53	0.91	1.70
CO	68.43	63.81	75.87	67.74	70.14	5.51	3.67	2.06	16.02
NO_x	5.63	7.27	5.34	5.67	5.54	1.08	1.91	6.56	11.19
CO_2	516.84	556.81	513.88	523.69	524.01	648.85	615.65	589.07	573.90
ER	1.10	1.09	1.11	1.10	1.10	1.05	1.03	1.03	1.04

MODE 4

HC	3.81	3.74	3.64	3.61	3.68	3.07	2.82	3.05	2.06
CO	155.06	148.94	142.31	150.35	152.48	115.21	100.33	128.89	29.92
NO_x	0.30	0.30	0.28	0.30	0.30	0.41	0.68	0.39	1.69
CO_2	313.22	304.61	302.83	309.29	311.55	343.85	376.25	329.20	403.09
ER	1.23	1.23	1.23	1.23	1.23	1.19	1.16	1.20	1.08

MODE 5

HC	2.68	2.89	2.12	2.34	2.30	2.03	2.05	1.97	1.78
CO	42.39	74.41	40.44	39.99	38.41	30.65	37.96	42.83	6.37
NO_x	0.05	0.04	0.02	0.06	0.05	0.04	0.06	0.07	0.03
CO_2	231.53	237.45	191.80	234.78	231.91	272.94	265.45	257.92	304.79
ER	1.14	1.19	1.15	1.13	1.13	1.10	1.12	1.12	1.05

Total emissions by mass (g)

HC	16.76	16.62	15.67	15.70	16.00	12.02	10.08	9.65	11.67
CO	552.64	572.32	539.14	529.47	543.99	230.74	256.95	289.01	291.51
NO_x	32.07	35.93	33.29	33.53	33.15	36.78	36.43	40.99	46.25
CO_2	2671.01	2701.17	2608.64	2671.94	2693.02	3053.41	3008.12	2924.03	2908.46
ER	1.13	1.13	1.13	1.13	1.13	1.07	1.07	1.08	1.08

Total brake specific emissions (g/bhp-hr)

HC	4.67	4.63	4.36	4.37	4.46	3.35	2.81	2.69	3.25
CO/10	15.39	15.94	15.02	14.75	15.15	6.43	7.16	8.05	8.12
NO_x	8.93	10.01	9.27	9.34	9.23	10.25	10.15	11.42	12.88
CO_2/100	7.44	7.52	7.27	7.44	7.50	8.51	8.38	8.14	8.10

Total brake specific emissions (g/kw-hr)

HC	6.25	6.20	5.85	5.86	5.97	4.49	3.76	3.60	4.35
CO/10	20.62	21.36	20.12	19.76	20.30	8.61	9.59	10.78	10.88
NO_x	11.97	13.41	12.42	12.51	12.37	13.72	13.59	15.29	17.26
CO_2/100	9.97	10.08	9.73	9.97	10.05	11.39	11.22	10.91	10.85

Fuel consumption (lbm)

Mode 1	0.62	0.63	0.63	0.63	0.62	0.52	0.54	0.54	0.62
Mode 2	0.73	0.76	0.72	0.72	0.74	0.74	0.74	0.73	0.74
Mode 3	0.42	0.45	0.42	0.43	0.42	0.44	0.42	0.40	0.41
Mode 4	0.38	0.38	0.37	0.38	0.38	0.36	0.37	0.37	0.31
Mode 5	0.21	0.25	0.21	0.22	0.21	0.22	0.23	0.23	0.22
Total	2.35	2.47	2.36	2.38	2.38	2.29	2.29	2.28	2.30

Carbon balance (lbm of $C_8H_{13.4}$)

(%)	105.39	101.93	102.44	102.82	104.25	103.77	103.58	103.05	101.86

Exhaust temperatures (deg F)

Mode 1	---	---	---	---	---	---	---	---	155 – 65
Mode 2	---	---	---	---	---	---	---	---	145 – 55
Mode 3	---	---	---	---	---	---	---	---	125 –35
Mode 4	---	---	---	---	---	---	---	---	120 – 25
Mode 5	---	---	---	---	---	---	---	---	115 – 20

Water temperatures (deg F)

Before	---	---	---	---	---	---	---	---	57
After	---	---	---	---	---	---	---	---	105
Rise	---	---	---	---	---	---	---	---	48

Appendix A: Gaseous Emissions Data for ISO E4 Modal Testing of MerCruiser 3.0LX Engine

Run #	1/27/97/2	1/27/97/3	1/27/97/4	1/27/97/5	1/28/97/1	1/28/97/2	1/28/97/3	1/28/97/4	1/28/97/5
Time (s)	600	600	600	600	600	600	600	600	600
Test Type	TW	TW	TW	TW	STW	STW	STW	STW	STW

Modal emissions by mass (g)

MODE 1

HC	4.12	4.13	4.37	4.21	4.21	4.03	4.03	3.94	4.11
CO	234.11	228.89	232.47	224.47	241.39	242.92	240.32	239.94	241.31
NO_x	4.35	4.56	4.46	4.75	4.24	3.95	4.38	4.03	4.27
CO_2	552.36	552.55	543.02	547.37	552.25	566.03	573.26	573.32	573.41
ER	1.20	1.20	1.21	1.20	1.21	1.21	1.20	1.20	1.20

MODE 2

HC	1.99	2.04	2.27	1.95	2.01	2.06	1.93	2.08	2.15
CO	9.30	9.92	12.99	8.81	9.23	11.04	9.37	9.94	9.14
NO_x	27.84	28.23	28.42	29.10	27.57	27.52	27.31	27.77	27.66
CO_2	1073.69	1067.91	1048.97	1056.88	1072.65	1098.49	1109.31	1110.37	1109.66
ER	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02

MODE 3

HC	1.87	1.83	1.80	1.55	1.65	1.95	1.59	1.96	1.90
CO	21.83	21.59	19.35	13.27	14.09	24.05	13.92	22.22	18.80
NO_x	10.08	10.02	10.52	10.43	10.77	9.75	9.46	10.16	10.29
CO_2	562.20	557.10	548.35	560.81	569.87	580.27	576.71	580.41	582.80
ER	1.05	1.05	1.04	1.04	1.04	1.05	1.04	1.05	1.04

MODE 4

HC	2.32	2.24	2.28	1.24	2.10	2.78	1.28	2.35	2.48
CO	50.51	48.48	50.28	2.68	33.96	94.24	2.61	46.59	45.77
NO_x	1.22	1.07	1.19	1.58	1.75	0.67	1.83	1.34	1.39
CO_2	381.60	373.84	376.83	428.94	397.49	357.73	465.73	400.18	401.06
ER	1.10	1.10	1.11	1.03	1.08	1.16	1.03	1.10	1.10

MODE 5

HC	1.79	1.84	2.02	5.11	1.97	2.18	9.92	1.99	2.30
CO	12.14	12.33	7.77	3.04	4.46	16.97	3.43	5.13	6.10
NO_x	0.03	0.03	0.02	0.01	0.42	0.09	0.17	0.15	0.24
CO_2	277.50	284.19	275.18	288.41	283.23	270.25	262.46	285.44	285.50
ER	1.07	1.07	1.06	1.08	1.05	1.08	1.14	1.05	1.06

Total emissions by mass (g)

HC	12.09	12.08	12.74	14.06	11.94	13.00	18.75	12.32	12.94
CO	327.89	321.21	322.86	252.27	303.13	389.22	269.65	323.82	321.12
NO_x	43.52	43.91	44.61	45.87	44.75	41.98	43.15	43.45	43.85
CO_2	2847.35	2835.59	2792.35	2882.41	2875.49	2872.77	2987.47	2949.72	2952.43
ER	1.09	1.09	1.09	1.08	1.08	1.10	1.08	1.08	1.08

Total brake specific emissions (g/bhp-hr)

HC	3.37	3.36	3.55	3.92	3.33	3.62	5.22	3.43	3.60
CO/10	9.13	8.95	8.99	7.03	8.44	10.84	7.51	9.02	8.94
NO_x	12.12	12.23	12.43	12.78	12.47	11.69	12.02	12.10	12.21
$CO_2/100$	7.93	7.90	7.78	8.03	8.01	8.00	8.32	8.22	8.22

Total brake specific emissions (g/kw-hr)

HC	4.51	4.51	4.75	5.25	4.46	4.85	7.00	4.60	4.83
CO/10	12.23	11.99	12.05	9.41	11.31	14.52	10.06	12.08	11.98
NO_x	16.24	16.38	16.65	17.12	16.70	15.66	16.10	16.21	16.36
$CO_2/100$	10.62	10.58	10.42	10.76	10.73	10.72	11.15	11.01	11.02

Fuel consumption (lbm)

Mode 1	0.62	0.62	0.62	0.61	0.63	0.62	0.63	0.61	0.63
Mode 2	0.73	0.74	0.74	0.74	0.73	0.73	0.74	0.74	0.73
Mode 3	0.41	0.40	0.41	0.40	0.39	0.41	0.40	0.42	0.40
Mode 4	0.32	0.31	0.32	0.30	0.30	0.35	0.30	0.32	0.31
Mode 5	0.22	0.21	0.20	0.11	0.20	0.21	0.20	0.20	0.20
Total	2.29	2.28	2.28	2.16	2.26	2.31	2.27	2.29	2.27

Carbon balance (lbm of $C_8H_{13.4}$)

(%)	102.04	101.90	100.74	105.98	103.43	104.85	105.12	104.94	106.19

Exhaust temperatures (deg F)

Mode 1	155 – 65	155 – 65	155 – 65	155 – 65	175 – 80	175 – 80	175 – 80	175 – 80	175 – 80
Mode 2	145 – 55	145 – 55	145 – 55	145 – 55	150 – 55	150 – 55	150 – 55	150 – 55	150 – 55
Mode 3	125 –35	125 –35	125 –35	125 –35	130 – 35	130 – 35	130 – 35	130 – 35	130 – 35
Mode 4	120 – 25	120 – 25	120 – 25	120 – 25	115	115	115	115	115
Mode 5	115 – 20	115 – 20	115 – 20	115 – 20	80 – 100	80 – 100	80 – 100	80 – 100	80 – 100

Water temperatures (deg F)

Before	55	53	55	55	59	58	52	52	52
After	100	99	97	97	104	100	99	97	97
Rise	45	47	42	42	45	42	47	45	45

Appendix B: Gaseous Emissions Data for ISO E4 Modal Testing of Mercury 650 Engine

Run #	5/28/97/1	5/28/97/2	5/28/97/3	5/28/97/4	5/28/97/5	5/29/97/1	5/29/97/2	5/29/97/3
Time (s)	300	300	300	300	300	300	300	300
Test Type	TW	TW	TW	TW	TW	STW	STW	STW

Modal emissions by mass (g)

MODE 1

HC	53.47	50.29	47.86	46.89	48.16	47.74	46.66	48.91
CO	52.92	51.26	50.30	49.12	49.85	51.14	46.77	50.11
NO_x	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO_2	57.63	58.84	61.52	60.79	60.54	68.78	61.17	63.75
ER	2.48	2.42	2.35	2.34	2.37	2.27	2.35	2.35

MODE 2

HC	30.38	30.19	28.79	29.33	28.88	25.25	26.83	29.39
CO	46.13	43.52	42.95	42.83	42.43	37.38	39.01	40.62
NO_x	0.09	0.01	0.00	0.00	0.00	0.00	0.00	0.00
CO_2	81.64	79.88	81.25	83.54	81.52	90.81	80.94	80.91
ER	1.87	1.88	1.85	1.84	1.85	1.73	1.82	1.87

MODE 3

HC	59.08	52.35	50.33	64.97	61.90	50.17	66.57	66.52
CO	34.97	37.42	38.09	34.92	36.96	30.18	32.19	34.67
NO_x	1.09	0.80	0.62	1.07	1.07	0.87	1.29	1.26
CO_2	146.58	147.49	142.33	147.84	152.28	145.67	147.52	155.80
ER	1.99	1.90	1.89	2.06	2.00	1.89	2.09	2.04

MODE 4

HC	28.47	28.32	28.34	28.29	28.33	28.49	28.50	28.50
CO	28.91	25.51	28.02	27.30	28.14	22.45	25.93	26.74
NO_x	0.86	0.88	0.83	0.79	0.80	0.99	0.97	0.84
CO_2	103.55	107.13	107.76	105.04	106.19	105.73	112.77	106.55
ER	1.73	1.72	1.71	1.73	1.72	1.73	1.69	1.72

MODE 5

HC	86.66	84.14	84.30	82.03	83.74	86.17	86.76	87.45
CO	45.49	44.96	45.02	44.02	45.43	50.92	48.35	46.12
NO_x	0.25	0.07	0.03	0.00	0.00	0.00	0.02	0.03
CO_2	47.85	44.76	47.86	45.05	47.56	64.49	56.80	50.66
ER	3.27	3.29	3.24	3.27	3.23	2.96	3.10	3.23

Total emissions by mass (g)

HC	258.06	245.29	239.62	251.51	251.01	237.82	255.32	260.77
CO	208.42	202.67	204.38	198.19	202.81	192.07	192.25	198.26
NO_x	2.41	1.76	1.48	1.86	1.87	1.86	2.28	2.13
CO_2	437.25	438.10	440.72	442.26	448.09	475.48	459.20	457.67
ER	2.22	2.18	2.16	2.20	2.19	2.11	2.19	2.21

Total brake specific emissions (g/bhp-hr)

HC	314.71	299.13	292.22	306.72	306.11	290.02	311.37	318.01
CO	254.17	247.16	249.24	241.70	247.33	234.23	234.45	241.78
NO_x x 100	293.90	214.63	180.49	226.83	228.05	226.83	278.05	259.76
CO_2 / 2	266.62	267.13	268.73	269.67	273.23	289.93	280.00	279.07

Total brake specific emissions (g/kw-hr)

HC	423.05	402.11	392.82	412.31	411.49	389.87	418.56	427.49
CO	341.67	332.25	335.05	324.90	332.48	314.87	315.16	325.02
NO_x x 100	395.08	288.52	242.62	304.92	306.56	304.92	373.77	349.18
CO_2 / 2	358.40	359.10	361.25	362.51	367.29	389.74	376.39	375.14

Fuel consumption (lbm)

Mode 1	0.24	0.24	0.23	0.24	0.20	0.24	0.21	0.24
Mode 2	0.17	0.18	0.16	0.18	0.18	0.19	0.16	0.18
Mode 3	0.27	0.27	0.24	0.27	0.29	0.24	0.29	0.30
Mode 4	0.21	0.19	0.20	0.19	0.21	0.19	0.20	0.19
Mode 5	0.32	0.34	0.34	0.31	0.35	0.34	0.35	0.33
Total	1.20	1.21	1.16	1.18	1.22	1.19	1.21	1.23

Carbon balance (lbm of $C_8H_{13.4}$)

Mass (lbm)	93.67	90.51	93.12	93.37	91.08	91.14	92.49	92.19

Water temperatures (deg F)

Before	68.0	68.0	67.1	65.0	64.8	73.8	66.2	64.6
After	88.1	84.4	84.0	83.2	83.5	89.5	84.5	82.3
Rise	20.1	16.4	16.9	18.2	18.7	15.7	18.3	17.7

Appendix C: Gaseous Emissions Data for Maladjustment Testing of MerCruiser 3.0LX Engine

Run #	2/24/97/4	2/24/97/5	2/24/97/6	2/24/97/7	2/24/97/8	2/24/97/9	2/24/97/1	2/24/97/2	2/24/97/3
Time (s)	360	360	360	360	360	360	360	360	360
Test Type	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry
Engine Condition	normal	normal	normal	ET=TDC	ET=TDC	ET=TDC	lean	lean	lean
Emissions by mass (g)									
HC	8.08	7.95	8.15	6.72	7.62	7.74	5.60	5.53	5.52
CO	58.41	60.03	70.90	53.10	69.34	70.72	10.64	11.01	11.15
NO_x	40.49	39.70	40.79	30.39	30.50	30.28	40.68	32.48	33.00
CO_2	2239.47	2224.20	2246.88	2284.53	2232.33	2232.45	2274.95	2248.57	2237.62
ER	1.04	1.04	1.04	1.04	1.04	1.04	1.02	1.03	1.03
Brake specific emissions (g/bhp-hr)									
HC	2.79	2.74	2.81	2.32	2.63	2.67	1.93	1.91	1.90
CO	20.14	20.70	24.45	18.31	23.91	24.39	3.67	3.80	3.84
NO_x	13.96	13.69	14.07	10.48	10.52	10.44	14.03	11.20	11.38
CO_2	772.23	766.97	774.79	787.77	769.77	769.81	784.47	775.37	771.59
Brake specific emissions (g/kw-hr)									
HC	3.74	3.68	3.77	3.11	3.53	3.58	2.59	2.56	2.56
CO	27.04	27.79	32.82	24.58	32.10	32.74	4.93	5.10	5.16
NO_x	18.75	18.38	18.88	14.07	14.12	14.02	18.83	15.04	15.28
CO_2	1036.79	1029.72	1040.22	1057.65	1033.49	1033.54	1053.22	1041.00	1035.94
Fuel consumption (lbm)									
Mass (lbm)	1.58	1.61	1.62	1.63	1.61	1.19	1.57	1.57	1.56
Carbon balance (lbm of $C_8H_{13.4}$)									
Mass (lbm)	-0.04	0.00	-0.02	-0.01	-0.02	-0.44	-0.02	0.00	0.00
Exhaust temperatures (deg F)									
Temp	755	756	760	758	760	754	780	781	784
Water temperatures (deg F)									
Before	NA	NA	NA	NA	NA	NA	NA	NA	NA
After	NA	NA	NA	NA	NA	NA	NA	NA	NA
Rise	NA	NA	NA	NA	NA	NA	NA	NA	NA

Appendix C: Gaseous Emissions Data for Maladjustment Testing of MerCruiser 3.0LX Engine

Run #	2/25/97/1	2/25/97/3	2/25/97/4	2/14/97/2	2/14/97/3	2/14/97/5	2/14/97/6	2/14/97/7	2/14/97/8
Time (s)	360	360	360	360	360	360	360	360	360
Test Type	TW	TW	TW	TW	TW	TW	TW	TW	TW
Engine Condition	normal	normal	normal	ET=TDC	ET=TDC	ET=TDC	lean	lean	lean
Emissions by mass (g)									
HC	5.29	6.57	6.27	6.88	5.50	5.73	4.75	4.51	4.37
CO	32.48	47.32	45.69	53.32	41.57	48.80	12.24	12.28	11.55
NO_x	36.50	40.75	40.29	32.45	31.34	30.53	31.76	31.37	35.05
CO_2	2273.97	2282.60	2237.22	2305.89	2331.49	2330.21	2316.58	2266.04	2256.48
ER	1.03	1.04	1.03	1.04	1.03	1.04	1.03	1.03	1.02
Brake specific emissions (g/bhp-hr)									
HC	1.82	2.27	2.16	2.37	1.90	1.98	1.64	1.56	1.51
CO	11.20	16.32	15.76	18.39	14.33	16.83	4.22	4.23	3.98
NO_x	12.59	14.05	13.89	11.19	10.81	10.53	10.95	10.82	12.09
CO_2	784.13	787.10	771.46	795.13	803.96	803.52	798.82	781.39	778.10
Brake specific emissions (g/kw-hr)									
HC	2.45	3.04	2.90	3.19	2.55	2.65	2.20	2.09	2.02
CO	15.04	21.91	21.15	24.69	19.25	22.59	5.67	5.69	5.35
NO_x	16.90	18.87	18.65	15.02	14.51	14.13	14.70	14.52	16.23
CO_2	1052.76	1056.76	1035.75	1067.54	1079.39	1078.80	1072.49	1049.09	1044.67
Fuel consumption (lbm)									
Mass (lbm)	1.60	1.64	1.64	1.65	1.65	1.65	1.58	1.57	1.59
Carbon balance (lbm of $C_8H_{13.4}$)									
Mass (lbm)	-0.01	0.00	0.04	-0.01	-0.01	-0.02	-0.04	-0.01	0.01
Exhaust temperatures (deg F)									
Temp	125	127	122	122	120	121	115	117	116
Water temperatures (deg F)									
Before	55	55	53	54	54	53	53	52	52
After	83	82	81	81	80	82	81	81	81
Rise	28	27	28	28	26	29	28	29	29