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MARINE GASOLINE ENGINE AND BOAT TESTING

By

James N. Carroll

FINAL REPORT

Prepared for the

Environmental Protection Agency
2000 Traverwood Drive
Ann Arbor, Michigan 48105

September 2002

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Work Assignments 2-02 & 3-02
EPA Contract 68-C-98-158

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2000 Traverwood Drive
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DEPARTMENT OF EMISSIONS RESEARCH
AUTOMOTIVE PRODUCTS AND EMISSIONS RESEARCH DIVISION

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EXECUTIVE SUMMARY

Outboard spark-ignition marine engines began to be regulated federally in 1998 under 40 CFR Part 91, and in California starting in 2001. The primary emission reduction technologies for this category were replacement of conventional two-stroke engines with either four-stroke engines or electronic direct fuel-injected two-stroke engines. EPA regulations required reducing emissions from the average new engine by a factor of 5 between 1998 and 2006. California regulations required new engines in California to have their emissions reduced by a factor of 5 by 2001, and then further reduced by a factor of 2 by 2008.

Another significant class of marine engines is inboard spark-ignition engines. These are almost as numerous as outboards, and are present in much higher horsepower ranges. *Many are automotive in origin. In July 2001, the California Air Resources Board added* emission standards for inboard and sterndrive marine engines to its existing spark-ignition marine engine regulations. Emission standards for 2003 engines were set to 16.0 g/kw-hr HC+NO_x over California's marine engine test cycle. Beginning in 2009, the emission standard drops to 5 g/kw-hr HC+NO_x, which is considered a "catalyst forcing" level. In 2009, these engines will also be required to meet the standard for their useful life, which is defined as ten years or 480 hours, whichever comes first.

Automotive engines have been successfully emission controlled by applying feedback electronic air-fuel control, electronically-controlled exhaust gas recirculation, and three-way catalysts. These emission reduction strategies had been shown as effective in a previous test program with a Mercruiser 7.4L MPI V8 engine, and EPA was interested in demonstrating the effectiveness of catalyst technology in a boat. The purpose of this project was to further investigate the levels of emission control that could be achieved with gasoline marine engines using exhaust gas recirculation (EGR) and catalytic aftertreatment. There were five objectives to the test program:

1) Set up a marine engine in the laboratory in three configurations (baseline, exhaust gas recirculation, catalytic control).

2) Age the catalysts.

3) For each of the three test configurations, test the engine for emissions and performance during steady-state operation.

4) Integrate the catalyst with an engine in a boat, and test in fresh and salt water.

5) Retest the catalyst in the laboratory in order to measure any deterioration in performance.

A General Motors 4.3L V-6 spark-ignited, fuel-injected engine was tested in this study This engine has its origin in automotive usage. It was marinized using earlier engine model Mercury Marine hardware, by the attachment of watercooled exhaust manifolds and a fuel pump, plus a "sea pump," coolant manifold, and cooling water plumbing. The engine control module was supplied by GM. General Motors and Mercury Marine supplied the engine, boat, materials, and developmental support to the project.

Emissions were measured in eight modes of engine operation. A subset of these eight modes was the ISO E4 recreational marine boat engine test cycle, which is also the California and Federal marine engine test cycle. The engine was emission tested in open-loop control configuration. The ECM was then modified to operate in closed-loop control using a heated exhaust gas oxygen sensor, and an exhaust gas recirculation system was attached to the engine. Results from the program are summarized in the following table.

SUMMARY OF ISO E4 MARINE ENGINE TEST RESULTS

Emission Test	HC + NO_x, g/kW-hr	CO, g/kW-hr	Power, hp
Baseline (Open-Loop)	16.6	110.8	205
Closed-Loop Baseline without Catalyst	14.8	101.0	206
Closed-Loop Baseline with Catalyst	4.10	70.4	206
Closed-Loop with Catalyst After On-Boat Operation	4.50	73.2	201
Open-Loop With Exhaust Gas Recirculation	9.51	92.0	198

In open-loop without any emission-reduction technologies, the engine produced 16.6 grams HC+NO_x/kW-hr and 110.8 grams CO/kW-hr over the E4 test cycle. By applying exhaust gas recirculation and adjusting the air/fuel ratio, HC+NO_x emissions were reduced by 43 percent to 9.51 g/kW-hr, and CO emissions were reduced 17 percent to 92.0 g/kW-hr.

With the engine in closed-loop control without catalysts, the HC+NO_x emissions were reduced by 11 percent to 14.8 g/kW-hr, and CO emissions were reduced to 101.0 g/kW-hr. SwRI then attached two catalysts (48 in^3) of 300 CPSI cell density, which were aged with a rapid aging cycle for 50 hours. With the aged catalysts on the engine in closed-loop control, HC+NO_x emissions were reduced by 75 percent to 4.1 g/kW-hr, and CO emissions were reduced to 70.4 g/kW-hr. Following engine testing on the boat, the engine was re-tested and HC+NO_x emissions had increased to 4.5 g/kW-hr, and CO emissions had increased to 73.2 g/kW-hr.

The use of catalytic exhaust aftertreatment, exhaust gas recirculation, and closed-loop control was shown to effectively reduce marine gasoline engine emissions. Although emission rates from the engine slightly increased after on-boat testing, the cause for this increase is unknown. The increase may be due to factors other than catalyst deterioration such as test-to-test repeatability. The catalysts were inspected after on-boat usage and were found intact with no visible signs of water damage. Durability of aftertreatment designs must still be addressed by long-term on-boat tests.

I. INTRODUCTION

As part of its program for developing emission standards for sterndrive and inboard marine gasoline engines, the Environmental Protection Agency (EPA) issued Work Assignments 2-02 and 3-02 under EPA Contract 68-C-98-158 to SwRI® to continue to investigate the levels of control that were achievable for marine gasoline engines using exhaust gas recirculation and catalytic aftertreatment. In addition, the catalyst-equipped engine was installed in a boat, and operated on both fresh and saltwater to assess engine operation, and to assess any effects from water ingestion in the catalyzed exhaust system.

The Work Assignment Manager for EPA was Mr. Michael Samulski. The SwRI project manager was Mr. Jim Carroll. Engine support from General Motors was supplied by Mr. Doug French. Engine and boat support from Mercury Marine was supplied by Mr. Glen Martin, and additional support was provided by Messrs. Steve Griffin, Glenn Boehle, and Jeff White of SwRI.

DISCLAIMER

II. DESCRIPTION OF PROGRAM

A. Marine Engine

The engine chosen for this project was a General Motors 4.3L spark-ignited V6, as described in Table 1. This engine was chosen, with input from Mercury Marine and General Motors Powertrain, because it had hardware and software capabilities for exhaust gas recirculation (EGR) control, and closed-loop control of the air/fuel ratio. In addition, the V6 configuration was chosen because it was represented to be especially susceptible to water ingestion, which could cause failure of the catalysts. The marine industry commonly refers to water ingestion as a combination of water reversion, which is water flowing in reverse back up the exhaust pipes, and condensation of exhaust gases when water collects in marine engine exhaust manifolds. This engine is considered representative of the marine engine population. Marinizing hardware for this engine was taken from an earlier model Mercury Marine 4.3L engine.

The major differences between an on-road engine and a marine engine are found in their cooling and exhaust systems. All liquid-cooled on-road engines use closed-loop cooling systems with air-to-water radiators. Marine engines use open-loop cooling systems in which sea or lake water is drawn to the engine's water pump by a sea pump. Plus, marine engines use water-cooled exhaust manifolds, and mix all the sea pump's water with the exhaust gases. Another difference from its on-road counterpart is that this engine's fuel pump and engine oil are water-cooled.

With marine cooling systems, until the engine reaches operating temperatures, a thermostat closes off flow through the engine, and all the sea pump's flow is routed to water-cooled exhaust manifolds. Once the engine is hot, a portion of the sea pump's flow cools the engine and is then re-mixed with the flow to the exhaust manifolds. Thus, all of the sea pump's flow is mixed with hot exhaust gases as they exit the exhaust manifolds. The reason for using water-cooled exhaust manifolds and for mixing the engine's cooling water with the exhaust flow, is to keep all surface temperatures within the boat below 200°F. This allows the engine operator to work around the engine without getting burned, and keeps the exhaust pipes from potentially causing a fire.

Due to the corrosive nature of salt water, many ocean-going marine engines use a liquid-to-liquid heat exchanger in a closed-loop engine cooling system. In that case, the engine block coolant is a mixture of anti-freeze and fresh water just like an on-road engine. However, all the water from the sea-pump is still used to cool the exhaust manifolds and exhaust gases. Stainless steel is sometimes used for salt-water cooled exhaust systems.

TABLE 1. DESCRIPTION OF TEST ENGINE

Engine Manufacturer	General Motors
Engine Serial Number	102LJ T10530044
Marine Engine Model/Year	4.3L Port Fuel Injected / 2001
Rated Power and Speed	210 hp at 4600 rpm
Idle Speed	600 rpm
Operating Cycle	Four-stroke - naturally aspirated
Displacement	4.3 Liters
Cylinders	*V6*
Cooling Systems	First system: Open-loop total loss system from sea pump through engine and out through exhaust manifolds Second system: Closed-loop through heat exchanger, *engine block and heads, utilizing total loss system from* sea pump to liquid-liquid heat exchanger and out through exhaust manifolds
Exhaust System	Water jacketed manifolds to 'Y'-pipe *(Bullhorn), all water* though manifolds mixed with exhaust gases at entrance to Bullhorn, exhaust released underwater through *propeller*
Engine Control System	Marine Electronic Fuel Injection V.4 (MEFI4) produced by Delphi for GM, all fuel injectors fired simultaneously
Exhaust Gas Recirculation	GM heavy-duty on-road engine EGR system with positional feedback control
Fuel System	*Multi-port fuel injection with water-cooled fuel pump at* 30 psi
Ignition System	Capacitive Discharge Ignition (CDI) through distributor
Engine Oil	10W-40
Spark Plug	AC Delco 41-932

B. Boat

The boat used for on-water testing of the catalyst-equipped engine was a Sea Ray 190 stern-drive boat donated by MerCruiser, and it is shown in Figure 1. Figure 2 shows *an earlier model MerCruiser 4.3L, throttle-body injection (TBI), V6 engine, which had been* used in a previous project to study water ingestion. Marinizing hardware from the engine in Figure 2 was used to marinize the PFI engine in this project.

FIGURE 1. SEA RAY 190 BOAT

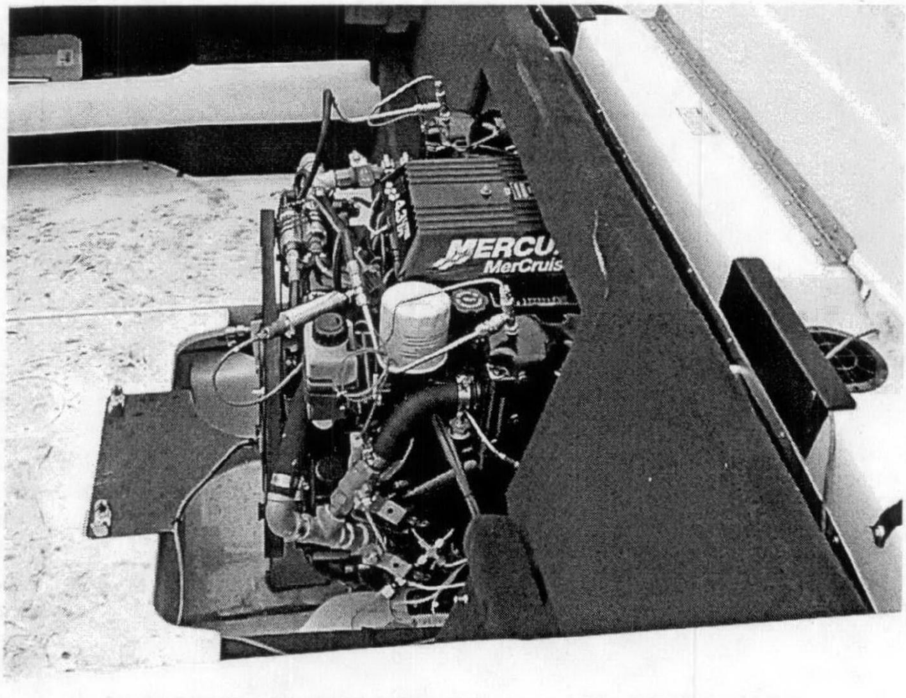

FIGURE 2. MERCRUISER 4.3L TBI V6 ENGINE

C. Test Facility

The 4.3L marine engine was tested in an SwRI gasoline engine test cell. The engine was mounted on a bed plate using jack stands, and connected to the dynamometer using a clutched U-joint coupling. A 400hp GE dynamometer was used to control engine speed and load. Engine load was set using the throttle. The engine was instrumented for measurement of various temperatures and pressures. Fuel consumption was measured using a Micromotion coriolis-effect mass flowmeter. A front view of the marine engine in the test cell is shown in Figure 3.

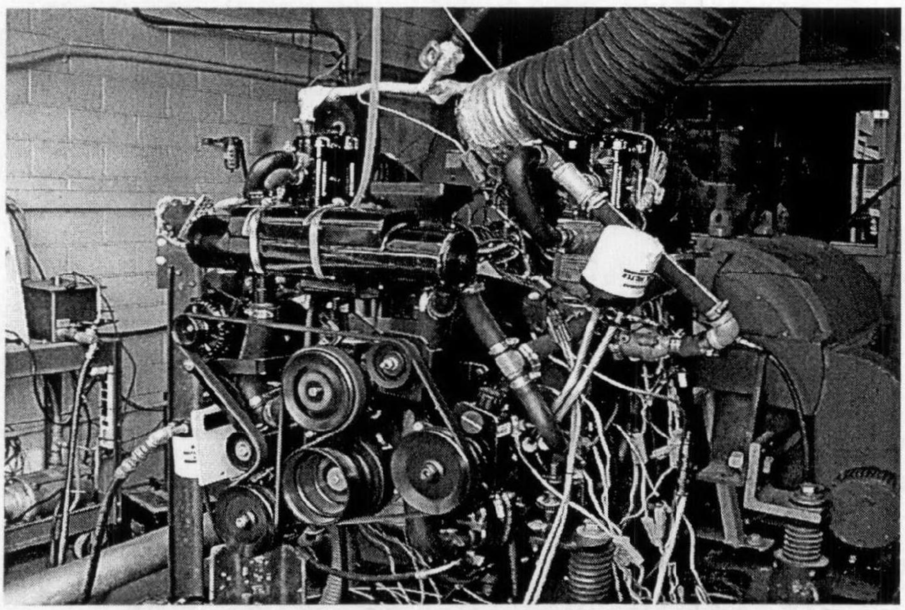

FIGURE 3. FRONT VIEW OF MARINIZED 4.3L PFI ENGINE

A rear view showing the exhaust 'Y' pipe or bullhorn connecting to the exhaust manifolds is shown in Figure 4. Note that unlike vehicular exhaust systems, the exhaust manifold directs exhaust up and through an 'exhaust riser'. Exhaust risers are put on marine engines to raise the height of the exhaust system above the water-line of the boat, otherwise water could flow into the boat through the exhaust and engine. If the engine were to be mounted further below the water line, additional straight risers could be put before the 'elbow' riser, which directs the exhaust rearward. Both the exhaust manifolds and risers are double-walled and water-cooled. After the elbow riser directs exhaust rearward, the water flowing through the manifold and riser is mixed with the exhaust at the point where the rubber coupling and hose clamps are visible. In a boat, the cooled exhaust and coolant water then flows down the bullhorn and exits through the propeller drive and steering system. In the test cell, the exhaust and coolant are directed to a drum where water collects and overflows to a storm drain. Exhaust was directed up from the drum through a pipe to the atmosphere.

The sea pump was supplied with water from our local utility using a large tub of water that was kept at a constant level with a float-controlled petcock. Figure 5 shows the water supply for the sea pump near the engine, just outside the test cell. The figure also shows the exhaust pipe from the bullhorn out to the water separation drum in the foreground.

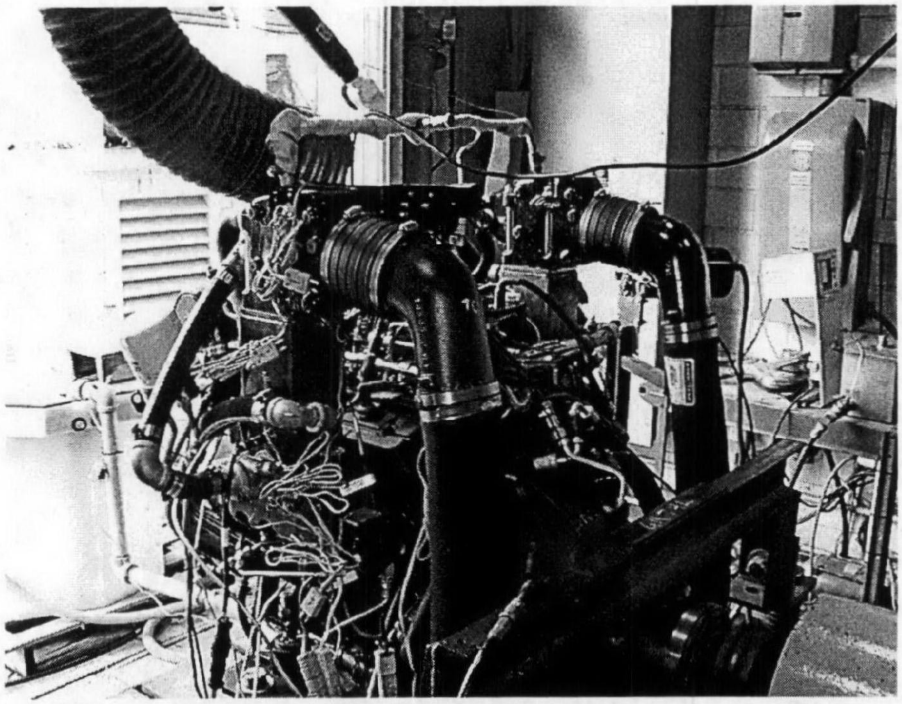

FIGURE 4. SIDE VIEW OF MARINIZED 4.3L PFI ENGINE

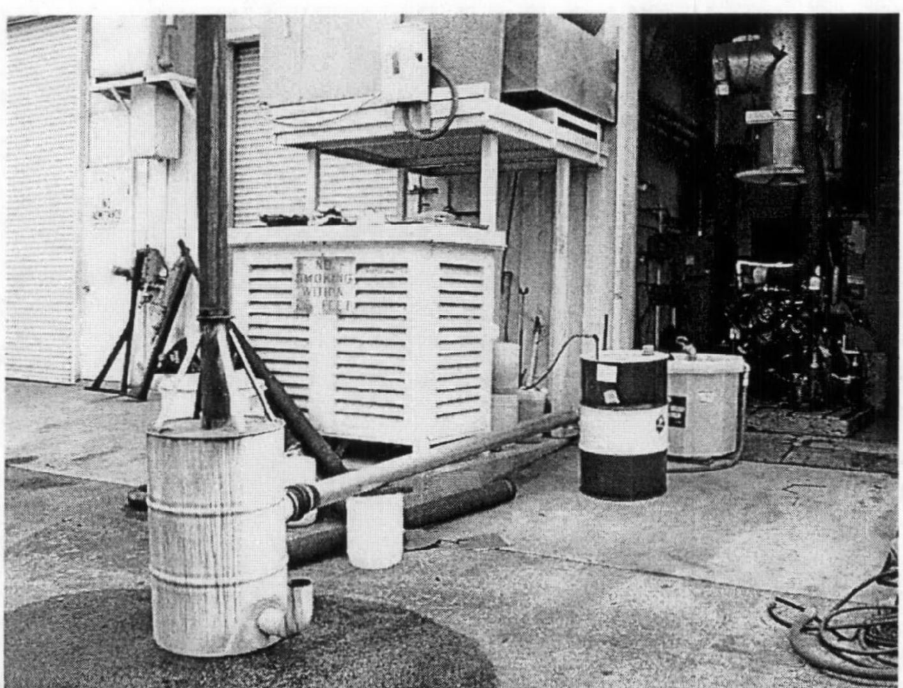

FIGURE 5. MARINE ENGINE WATER SUPPLY AND EXHAUST PIPE

D. Test Program

In order to achieve project objectives, SwRI collaborated with General Motors (GM) Powertrain and Mercury Marine (Mercury) for technical and material support. GM Powertrain furnished the 4.3L PFI engine in non-marinized form, plus control software for the engine and instructions in its use. Mercury Marine furnished the Sea Ray boat with a completely marinized engine with wiring harness. Catalysts were supplied by DCL International Inc. in support of the project. Table 2 lists the Work Assignment tasks for this program.

TABLE 2. WORK ASSIGNMENT TASKS

Task	Task Objective
Task 1	Collect open-loop engine baseline emissions data. (regulated emissions plus air toxics)
Task 2	Age catalysts to the equivalent of 500 hours use.
Task 3	Collect closed-loop engine emission data after equipping and calibrating the engine with catalysts. (regulated emissions plus air toxics)
Task 4	Install the catalyst-equipped engine on a boat and operate it on freshwater.
Task 5	Operate the boat on saltwater with the catalyst-equipped engine.
Task 6	Collect catalyst-equipped engine emission data after engine operation in the boat. (without air toxics)
Task 7	Collect open-loop engine data after equipping and calibrating the engine with an exhaust gas recirculation (EGR) system.

E. Emission Test Cycle and Fuels

Emissions were measured using an eight-mode steady-state engine test cycle that included all the modes contained in the ISO-8178-E4 and Bodensee (BSO) marine test cycles. The eight test modes are shown in Table 3.

All emission tests were performed using federal certification grade fuel coded EM-2977-F. An analysis of the emission test fuel is shown in Table 4. During on-water testing, the boat was fueled with commercial grade, regular-octane gasoline.

TABLE 3. STEADY-STATE TEST MODES

Mode	Speed	Torque
1*	rated	100% of torque at rated speed
2	90% of rated	85% of torque at rated speed
3*	80% of rated	72% of torque at rated speed
4	70% of rated	59% of torque at rated speed
5*	60% of rated	47% of torque at rated speed
6	50% of rated	35% of torque at rated speed
7*	40% of rated	25% of torque at rated speed
8*	idle	- -

* Modes included in ISO E4 duty cycle.

TABLE 4. CERTIFICATION GASOLINE FUEL ANALYSIS

SUPPLIER HALTERMANN PRODUCTS

BATCH NO. 00C-11 SwRI CODE EM-2997-F

Item	CFR Specification [a]		Supplier Analysis	SwRI Analysis
	ASTM	Unleaded		
Octane, [R+M]/2	D2699 D2700	89.9±3.1	93.1	93.1
Pb (organic), gm/U.S., gal	D3237	0.05[b]	<0.01	<0.001
Distillation Range:				
IBP, °F	D86	71-110	84	95
10% Point, °F	D86	118-138	125	129
50% Point, °F	D86	200-230	218	217
90% Point, °F	D86	300-340	311	313
EP, °F	D86	415 (max.)	391	389
Sulfur, wt. %	D2622	0.10 (max.)	<0.001	0.001
Phosphorus, gm/U.S., gal	D3231	0.005 (max.)	<0.0008	0.0002
RVP, psi	D323	8.0-9.2	9.2	9.15
Hydrocarbon Composition:				
Aromatics, %	D1319	35 (max.)	29.0	31.8
Olefins, %	D1319	10 (max.)	0.6	0.5
Saturates, %	D1319	[c]	70.4	67.7

[a] Gasoline fuel specification in CFR 91 for marine gasoline vehicles.
[b] Maximum.
[c] Remainder.

Supplier Analyses
Date: 6/26/00

SwRI Analyses
by: Karen Kohl
Date: 8/9/00

F. Emissions Measurement and Calculations

Total hydrocarbons (THC), carbon monoxide (CO), nitrogen oxides (NO_X), and carbon dioxide (CO_2) emissions were measured from raw exhaust in every test. Instrumentation used included a heated flame ionization detector (HFID) for THC, non-dispersive infrared analyzers for CO and CO_2, and a chemiluminescent analyzer for NO_X. All instruments were laboratory-grade and calibrated to certification-quality levels. Emission rates were calculated in each mode using the fuel flow method from the Code of Federal Regulations Part 91.419 (c) "Raw Emission Sampling Calculations" for gasoline spark ignition engines.

In Task 1 and Task 3 for the modes contained in the ISO E4 duty cycle, the following air toxics were measured: benzene, formaldehyde, acetaldehyde, 1,3 butadiene, acrolein, styrene, gaseous polycyclic aromatic hydrocarbons (PAH), chromium, and manganese.

Polycyclic aromatic hydrocarbons are of interest because this class of hydrocarbons contains quite a number of compounds which have been shown to have carcinogenic or mutagenic effects in animal and microbial studies. Only vapor phase PAH samples were analyzed. Vapor phase samples of diluted exhaust were obtained using XAD-2 resin sandwiched between two pieces of polyurethane foam (PUF). Vapor phase polycyclic aromatic hydrocarbons were captured at the same time as the metal samples by placing the PUF cartridges after the particulate filters which captured the metals and any solid-phase PAHs.

The PUFs and XAD-2 resin were extracted together with dichloromethane (DCM) for 18 hours. One hundred µL of a surrogate solution containing 2-methylnaphthalene, benzo(b)fluoranthene, and dibenz(a,h)anthracene-d14 at 1.0 ng/µL was spiked to the media just prior to extraction, to monitor extraction efficiency. The sample extracts were then solvent exchanged into hexane, and subjected to a cleanup procedure described in US EPA Method 610.

Samples were analyzed on a FISONS MD800 GC/MS in selected ion recording (SIR) mode. Separation of PAHs was accomplished by injecting a two microliter aliquot of the sample extract onto a 30m DB-5 capillary column. A set of six PAH calibration standards containing target PAHs and deuterated PAHs as internal standards were also analyzed. A relative response factor (RRF) for each PAH in relation to a deuterated PAH was established. For PAH quantization, the same deuterated PAH mixture was spiked into the sample extract at the time of analysis and then used for calculating PAH concentrations. Each sample was analyzed twice. The Electron Impact (EI) mode determined PAH species, and Chemical Ionization (CI) mode determined nitro- and dinitro-PAH species.

A sample of raw exhaust was filtered through particulate filters for each test, and analyzed to determine the capture weight of chromium and manganese. A single background air sample was taken for each test. Each particulate-laden filter was cut, and a portion was placed in a pre-cleaned, Teflon PFA microwave digestion vessel. Twelve milliliters of trace metals-grade acid (9 mL concentrated nitric acid and 3 mL concentrated hydrochloric) was added to each vessel. The vessel was capped and placed in a CEM MARS5 Microwave Accelerated Reaction System using the "Filter XP1500" microwave method. In this method, 1200W using the electrical power was applied to increase the temperature of the vessel contents to 240°C in 10 minutes; and then they were held at that temperature for an additional 10 minutes. Once the vessel cooled, the samples were transferred to centrifuge tubes and brought up to a final volume of 50 mL with deionized water. The digests of the samples were then analyzed using inductively coupled plasma atomic emission spectrometry (ICP-AES) for all elements. Detection limits range from 1 to 10 μg for each element per sample. Results of the analyses were used to compute the mass emission rate of metals in the exhaust.

Benzene, 1,3 butadiene, acrolein, and styrene levels were analyzed using Phase II Auto/Oil procedures, which can identify and quantify 223 individual C_1-C_{12} hydrocarbons using gas chromatography. Raw exhaust samples were captured in Tedlar® bags for delivery to the analyzer. Formaldehyde and acetaldehyde samples were captured by bubbling a measured volume of raw exhaust through a liquid reagent which was then analyzed by liquid chromatography.

It should be noted that the air toxic measurement techniques used at SwRI are designed to measure samples from diluted engine exhaust. Because marine engines inject cooling water into their exhaust, conventional dilution methods could not be used. Therefore, raw exhaust samples were taken from the engine before water was mixed with the exhaust. Because raw exhaust has a high moisture content, some water condensed out of the exhaust samples while they were taken. It is probable that some of the air toxics were scrubbed out of the exhaust by condensation, but what fraction was scrubbed is unknown. Therefore, air toxic rates presented in this report may be somewhat underestimated.

For test modes where EGR was used, the amount of EGR was calculated from the levels of CO_2 measured in the background air, intake manifold, and exhaust gases using the formula below. Figure 6 shows the shut-off valve above the two CO_2 sample probes in the intake manifold.

$$\text{EGR level, \%} = 100 \times \frac{(\text{Intake Manifold } CO_2\text{, \% - Background } CO_2\text{, \%})}{(\text{Exhaust Manifold } CO_2\text{, \% - Intake Manifold } CO_2\text{, \%})}$$

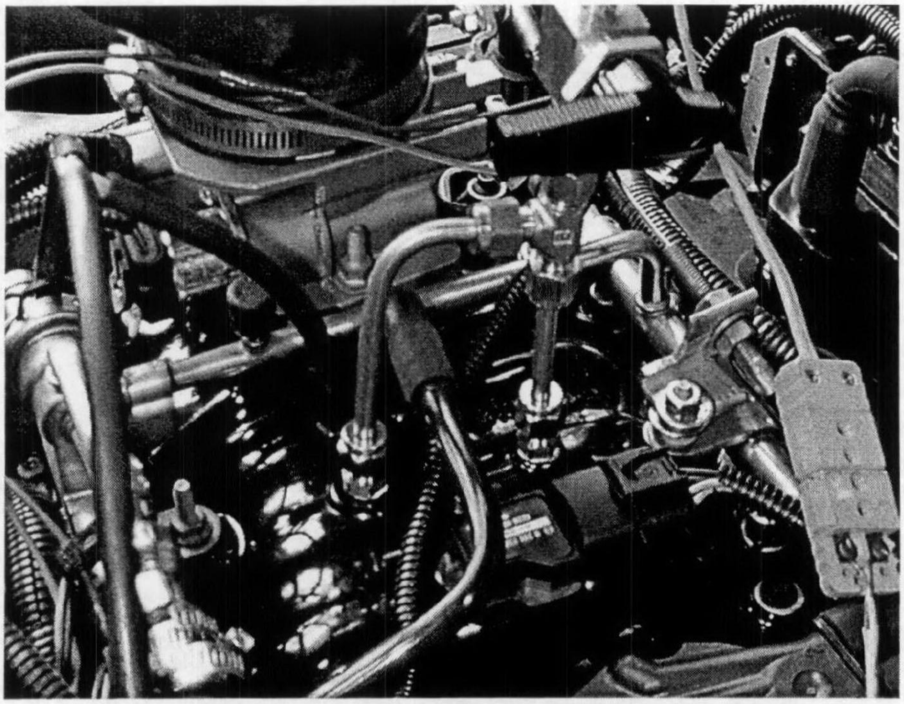

FIGURE 6. INTAKE MANIFOLD EGR PROBES

PAH and metals results are reported in µg/sample volume units. PAH and metals emission rates were calculated by multiplying sample analysis results by the total exhaust flow rate, and then dividing by the sample volume drawn through the PUF trap and filter. The engine's exhaust flow rate was calculated using its fuel flow rate and a carbon balance approach based on HC, CO, and CO_2 emission concentrations (SAE Technical Paper 910560, 'Emission Factors for Small Utility Engines').

Similarly, benzene, formaldehyde, acetaldehyde, 1,3-butadiene, acrolein, and styrene analysis results are reported as their concentrations in the raw exhaust. Sample concentrations, the density of the compounds, and the total exhaust flow were used to calculate the corresponding mass emission rates.

G. Engine Modifications

The General Motors 4.3L PFI engine as received required hardware and software modifications in order to meet the goals of the project. Modifications were made in order to operate the engine in closed-loop control with an exhaust gas oxygen (EGO) sensor, to use exhaust gas recirculation, and to add catalysts. In addition, marinizing hardware from an older model Mercury Marine 4.3L engine was utilized to prepare the engine for boat operation.

1. Engine Control Modifications

The engine uses GM's Marine Electronic Fuel Injection V.4 (MEFI4) control software and Electronic Control Module. The ECM calibration is accessible through a serial port interface on a personal computer (PC). The MEFI4 software was received with a "running" calibration from GM which is supplied to GM's customers for general engine operation. GM supplies this open-loop calibration to their OEM clients to get the engine running in preparation for the OEM's calibrations.

Although these functions are not used by any of GM's clients, MEFI4 has closed-loop control capability with the addition of an exhaust gas oxygen (EGO) sensor; it also has exhaust gas recirculation control capability with the addition of an EGR valve. Mr. Doug French of GM Powertrain prepared the software for closed-loop (CL) and EGR control, removed its password, and instructed SwRI personnel in its operation. Mr. French also augmented the engine wiring harness with power and control connections between the ECM and the EGR valve and EGO sensor. In addition, he set up the software to be able to monitor, through the PC interface, the air/fuel ratio using a Universal Exhaust Gas Oxygen (UEGO) sensor. Mr. French explained that the MEFI4 ECM can control air/fuel ratio using feedback from either the EGO or UEGO. In this project, closed-loop feedback was supplied by the EGO sensor only. The EGO sensor was mounted in a one-inch riser placed between the exhaust riser and the catalyst.

The 4.3L PFI engine uses an intake manifold which already has an inlet port for EGR. However, the exhaust manifold did not have an EGR port, nor was there an EGR valve to control EGR flow. A one-inch water-jacketed marine riser was modified to accept an EGR pipe, and GM heavy-duty on-road engine EGR valve and pipes were attached between the ports. Figure 7 shows the one-inch riser mounted at the exit of the left manifold, along with the EGR pipe to the EGR valve. Figure 8 shows a top view of the EGR hardware.

Mercury Marine and GM warned SwRI that, due to water condensation and water reversion within the exhaust system, the EGR pipe and valve could experience high water flows which could be transferred to the intake manifold and thence into the cylinders. A large cylindrical water trap was put in-line between the exhaust manifold and the EGR valve to capture any liquid which could have been drawn into the intake system. The large water trap can be seen in Figures 7 and 8. A drain petcock was placed at the bottom of the water trap. No significant amounts of water were drained from the water trap during this project and it was probably unnecessary to mount the trap.

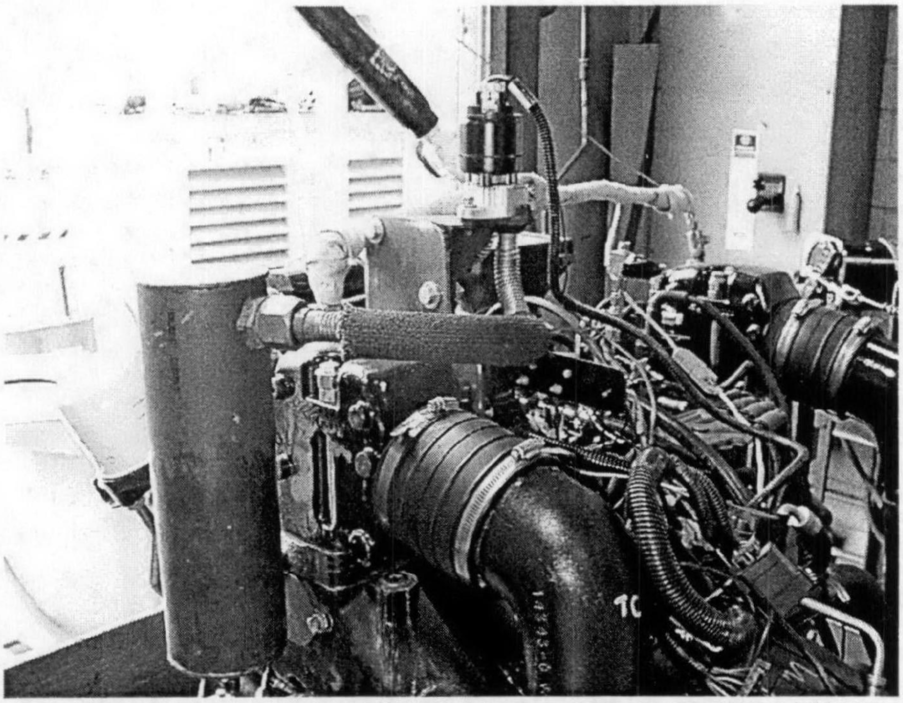

FIGURE 7. SIDE-VIEW OF ENGINE SHOWING EGR VALVE AT TOP AND EGR PIPE TO EXHAUST MANIFOLD

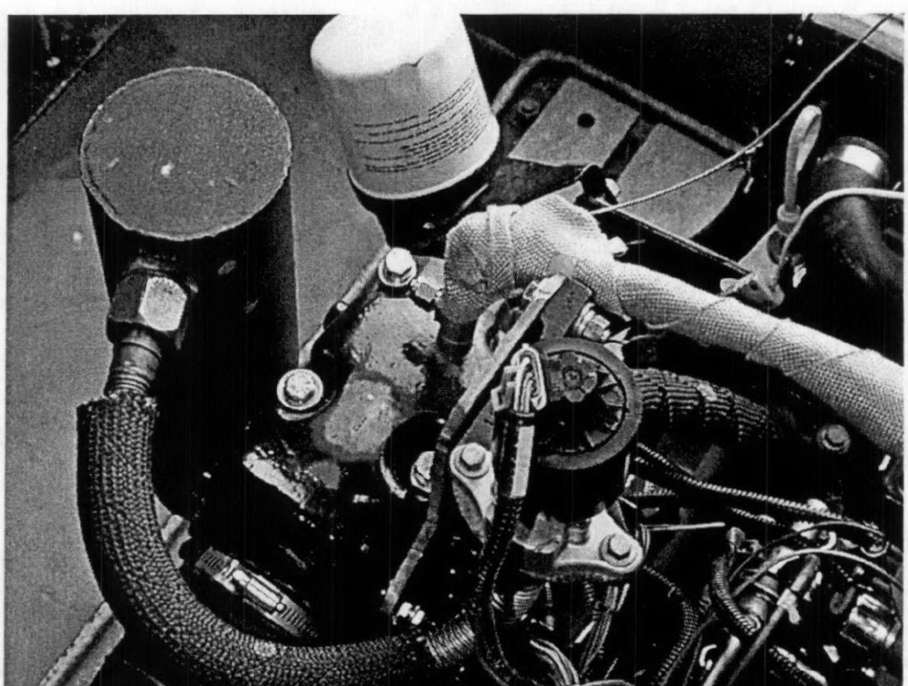

FIGURE 8. TOP VIEW OF ENGINE SHOWING EGR VALVE IN CENTER AND EGR PIPES

2. Engine Exhaust Modifications

In order to keep all surface temperatures below 200°F, the catalysts required water-cooled jackets. Figure 9 shows the catalysts in their canisters, as received from DCL International. Figure 10 shows a catalyst with water jacket and coolant hose fittings as it was mounted on the engine.

Since the catalyst has a ceramic substrate and washcoat and operates at high temperatures, there were concerns that water ingestion during on-boat operation could cause the catalyst's surface coatings to spall from the substrate and even cause the substrate to crack. In addition, there was a concern that, if exposed to it, salt water could poison the catalyst. In order to minimize the chances of catalyst failure due to water ingestion, the exhaust manifolds were modified using techniques learned in a previous SwRI project for the California Air Resources Board ("Marine Exhaust System Modifications", CARB Contract No. 99-641). That project was performed with a 2000 Mercury Marine 4.3L TBI (Throttle Body Injection) engine in the Sea Ray 190.

During that project, it was found that small amounts of water could collect in the exhaust manifolds from condensation. This was minimized by controlling the exhaust manifold wall temperature above the exhaust gas dewpoint of 120-130°F. Control of manifold wall temperatures was accomplished by blocking the normal flow of cooling water out of the manifold at the exhaust flange, and installing a 180°F thermostat in the exhaust manifold. A 'T' fitting was installed in the coolant hose into the manifold so that until the thermostat opened, all coolant was routed to the catalyst water jacket. From the catalyst jacket, coolant flowed to another 'T' fitting where coolant from the thermostat was mixed before entering the exhaust elbow. The thermostat housing can be seen in the lower part of Figure 10. The hose from the thermostat joins the hose from the catalyst at the upper right of Figure 10 at the 'T' into the exhaust elbow. Figure 11 shows cones inserted by SwRI into the exhaust elbows to help prevent water reversion back up the exhaust.

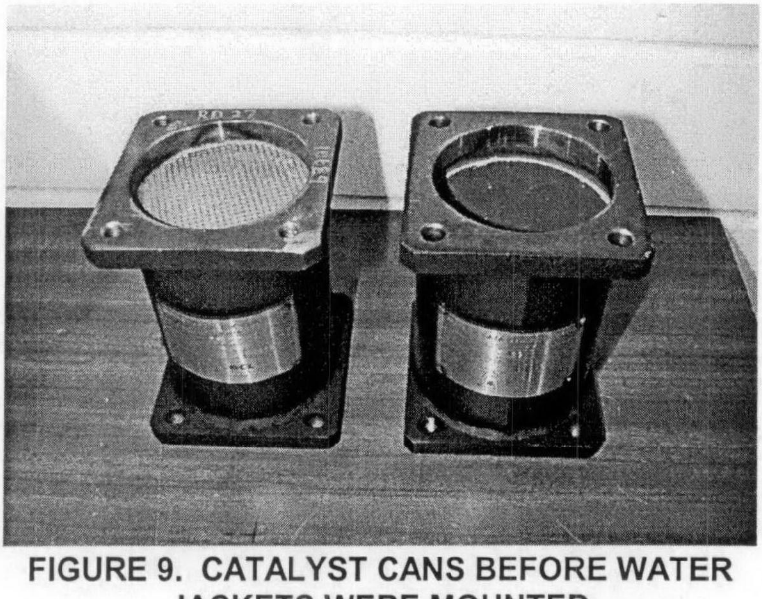

FIGURE 9. CATALYST CANS BEFORE WATER JACKETS WERE MOUNTED

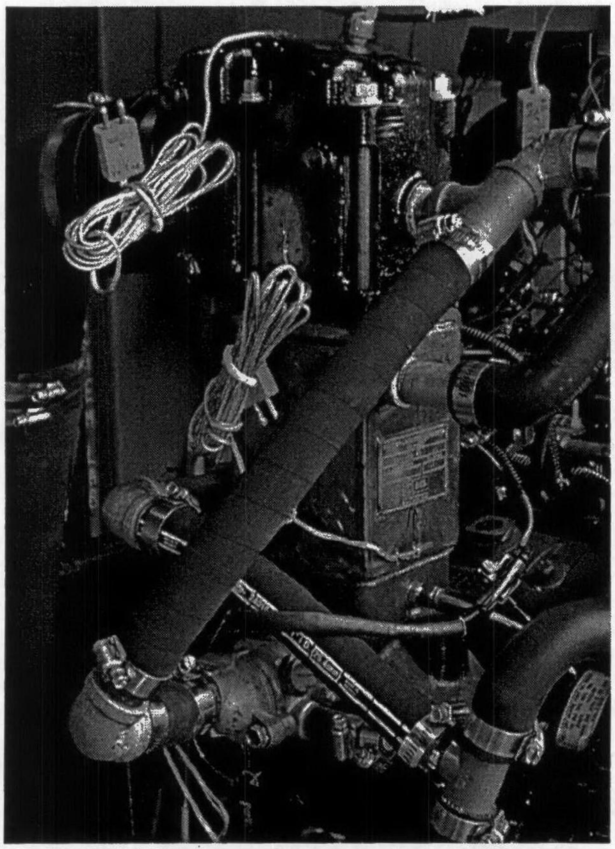

FIGURE 10. WATER JACKETED CATALYST MOUNTED TO ENGINE WITH COOLANT PLUMBING

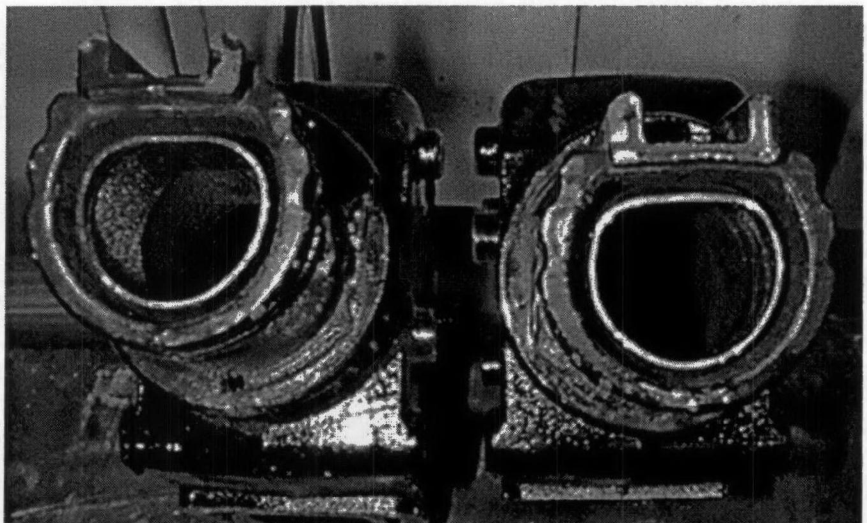

FIGURE 11. WATER REVERSION CONES INSERTED IN EXHAUST ELBOWS

III. RESULTS AND DISCUSSION

A. Task 1 - Engine Open-Loop Baseline Emissions Test

Because the open-loop calibration for this engine was not a production marine engine calibration, the engine air/fuel ratio settings as received were deemed not representative of a marine baseline calibration. However, the air/fuel ratios of Mercury Marine's throttle body injected 4.3L engine were recorded with a UEGO sensor during the water ingestion project mentioned earlier. For this baseline emission test, the engine was operated in open-loop configuration with its air/fuel ratio set to those measured in the field. Ignition timing was left as received because a production marine calibration was unavailable. GM's ignition timing for this engine was set for power with a safety factor to preclude engine knock, which is consistent with marine engine calibrations.

Modal emissions from all eight modes of the test cycle are included in Appendix Table 1. The spreadsheet file which contains all data from these tests is named 'GM 4.3L Marine Baseline.XLS', and has been supplied separately by electronic media.

Within the eight-mode test matrix of the project's test program (Table 3), the five modes of the ISO E4 marine duty cycle are Modes 1, 3, 5, 7, and 8. E4 cycle weighted emissions are shown in Table 5, and are consistent with levels measured from spark-ignited engines prior to emission regulations, without catalytic aftertreatment or exhaust gas recirculation.

TABLE 5. ISO E4 OPEN-LOOP BASELINE EMISSION TEST

ISO E4 Mode	Weight Factor	Power, hp	HC, g/hr	NO_x, g/hr	HC+NO_x, g/hr	CO, g/hr
1	0.06	205.0	602.6	958.3	1560.9	27457
2	0.14	116.8	249.3	1519.7	1769.0	2568
3	015	58.3	174.3	597.9	772.2	2807
4	0.25	20.5	78.2	38.3	116.5	2181
5	0.40	0	99.3	1.2	100.5	1346
Weighted Total		g/hp-hr	3.68	8.70	12.38	82.6
		g/kW-hr	4.94	11.67	16.61	110.8

B. Task 2 - Accelerated Catalyst Aging

Under this task, the catalysts were to be aged to an equivalent of 480 hours on-boat operation. The two catalysts supplied by DCL International Inc. were loaded at 1.0 g/L Pt:Rh at a 4:1 ratio. The catalysts were cylindrical, were 3 ¼" diameter by 4" long, and had a ceramic substrate of 400 cpsi structure. Information regarding on-boat catalyst operation is not yet available, and accelerated aging equivalencies have yet to be established. SwRI routinely uses accelerated aging cycles for automotive clients, and our experience is that at least 100 hours of accelerated aging is required for 100,000 mile light-duty vehicle on-road equivalency. At an average speed of 50 mph, 100,000 miles is equivalent to 2000 hours of on-road operation; 500 hours of on-road vehicle operation would be equivalent to 25 hours of accelerated aging. We decided to err on the side of over-aging, and chose to perform 50 hours of accelerated aging on these catalysts.

The two DCL catalysts were aged for 50 hours on a gasoline engine at SwRI following the General Motors (GM) RAT-A Rapid Aging Test cycle, which incorporates various air-fuel ratios and air injection periods to produce high catalyst bed exotherms. The GM RAT-A aging cycle is composed of four segments, and is described in Table 6. A large displacement V-8 engine operated on commercial gasoline was used to age the units.

TABLE 6. GENERAL MOTORS RAT-A CATALYST AGING CYCLE SPECIFICATIONS

Mode No.	Description	Parameter	Specification
1	Stoichiometric Air-Fuel Ratio	Inlet Temperature Flow rate (per catalyst) Time Duration CO concentration O_2 concentration	800°C 84 SCFM 40 seconds ≤1.0% ≤1.0%
2	Fuel-Rich Operation (Power Enrichment)	Time Duration CO concentration O_2 concentration	6 seconds 2.9% 3.0%
3	Fuel-Rich Operation with Air Injection	Time Duration CO concentration O_2 concentration Catalyst Bed Temperature	10 seconds 2.9% 3.0% approximately 950-1000°C
4	Stoichiometric Operation with Air Injection	Time Duration O_2 concentration	4 seconds 3.0%

Exhaust gas emission measurements were made at the beginning and end of aging in order to assess aging affects, as shown in Tables 7 and 8, respectively. Emissions were measured in modes 2 and 4 of the RAT A cycle, which are labeled Rich and Lean, respectively. Aging the catalysts reduced rich NO_x efficiency from 83 to 50 percent. In lean operation, HC reduction efficiencies were not affected by aging. However, CO reduction efficiency dropped slightly from 96 percent to 92 percent. These reductions were measured only at single points in the RAT A cycle, and are not comparable to the overall reduction efficiencies measured during modal marine engine emission tests.

TABLE 7. CATALYST EMISSION TEST RESULTS BEFORE AGING

Catalyst	Mode 2 Rich Mixture			Mode 4 Lean Mixture		
	HC, ppm	NO_x, ppm	CO, %	HC, ppm	NO_x, ppm	CO, %
Before Catalyst 1	1640	1233	3.00	135	1732	0.41
After Catalyst 1	750	219	2.73	15	1687	0.02
Reduction Efficiency	54%	82%	9%	89%	3%	96%
Before Catalyst 2	1675	1246	3 00	165	1761	0.41
After Catalyst 2	740	211	2 80	15	1699	0.02
Reduction Efficiency	56%	83%	7%	91%	3%	96%

TABLE 8. CATALYST EMISSION TEST RESULTS AFTER AGING

Catalyst	Mode 2 Rich Mixture			Mode 4 Lean Mixture		
	HC, ppm	NO_x, ppm	CO, %	HC, ppm	NO_x, ppm	CO, %
Before Catalyst 1	1980	1183	3.09	150	1617	0.39
After Catalyst 1	1125	611	2.99	10	1575	0 03
Reduction Efficiency	43%	48%	3%	93%	3%	91%
Before Catalyst 2	2000	1167	3.09	115	1603	0 36
After Catalyst 2	1025	586	2 99	10	1562	0.03
Reduction Efficiency	49%	50%	3%	91%	3%	92%

C. <u>Task 3 - Engine Closed-Loop Baseline Emission Tests</u>

DCL International furnished 300 cpsi catalysts in 6-inch long canisters that were water jacketed at SwRI and aged for 50 hours with a rapid-aging cycle. The catalyst dimensions in the 6-inch riser were 3 inches in diameter by 6 inches long. Volume per riser was 42 in^3.

Mode 1 was run in open-loop control at a 12.5:1 air/fuel ratio to preclude overheating, and all other modes were tested in closed-loop control at stoichiometric. In Mode 1, exhaust back pressure was 5.1 inches of mercury (in. Hg), compared to the non-catalyst equipped baseline back pressure of 4.6 in. Hg. The higher back pressure with the catalysts did not affect engine power.

Engine emissions were measured before and after the catalyst after engine air/fuel ratios in modes 2 through 5 were calibrated for minimum $HC+NO_X$ after the catalyst. Modal emissions measured before and after the catalyst from all eight modes of the test cycle are included in Appendix Tables 2 and 3, respectively. The spreadsheet file which contains all data from these tests is named 'CL BASELINE SUM.XLS', and has been supplied separately by electronic media. Table 9 shows results from emissions measured in front of the catalyst, and Table 10 shows results from emissions measured behind the catalyst.

TABLE 9. ISO E4 CLOSED-LOOP BASELINE EMISSION TEST WITHOUT CATALYST

ISO E4 Mode	Weight Factor	Power, hp	HC, g/hr	NO_x, g/hr	HC+NO_x, g/hr	CO, g/hr
1	0.06	205.8	560.5	927.2	1487.7	24968
2	0.14	119.4	270.9	1335.6	1606.5	5028
3	0.15	59.0	198.3	514.6	712.9	4381
4	0.25	20.5	49.6	47.8	97.5	1006
5	0.40	0	74.6	1.1	75.8	320
Weighted Total		g/hp-hr	3.34	7.72	11.06	75.3
		g/kW-hr	4.48	10.36	14.83	101.0
Change from open-loop baseline,%			-9	-11	-11	-9

TABLE 10. ISO E4 CLOSED-LOOP BASELINE EMISSION TEST WITH CATALYST

ISO E4 Mode	Weight Factor	Power, hp	HC, g/hr	NO_x, g/hr	HC+NO_x, g/hr	CO, g/hr
1	0.06	205.9	427.0	506.6	933.6	24894
2	0.14	118.3	95.8	202.0	297.9	2804
3	0.15	56.6	19.2	35.6	54.9	681
4	0.25	22.3	19.7	3.5	23.2	692
5	0.40	0	48.7	0.2	48.9	234
Weighted Total		g/hp-hr	1.54	1.51	3.05	52.5
		g/kW-hr	2.07	2.03	4.10	70.4
Change from open-loop baseline, %			-58	-83	-75	-36

Results in Table 9 show that the engine without the catalysts produced 9 percent less HC, 11 percent less NO_X, and 11 percent less combined HC+NO_X, compared to the engine's open-loop baseline results. Air/fuel ratio control reduced CO emissions by 9 percent. Results in Table 10 show that the engine with the catalysts produced 58 percent less HC, 83 percent less NO_X, and 75 percent less combined HC+NO_X, compared to the engine's open-loop baseline results. The use of a catalyst reduced CO emissions by 37 percent.

D. Task 4 - Engine In-Boat Operation on Fresh Water

1. Boat Engine Installation

Following the closed-loop baseline emissions tests, the catalyzed engine and control systems were installed in the Sea Ray 190 boat pictured in Figure 1. The catalysts increased the height of the exhaust system such that the exhaust elbows at the top of the manifolds interfered with the front section of the transom (Figure 12). Through discussion with Mercury Marine we received permission to remove two small sections of fiberglass from the transom since it would not degrade the boat's structural integrity. Figure 13 shows the interfering fiberglass sections of the transom before they were cut out, marked in black. Figure 14 shows the engine installation as it was tested on water, with exhaust elbows passing through the cutout sections.

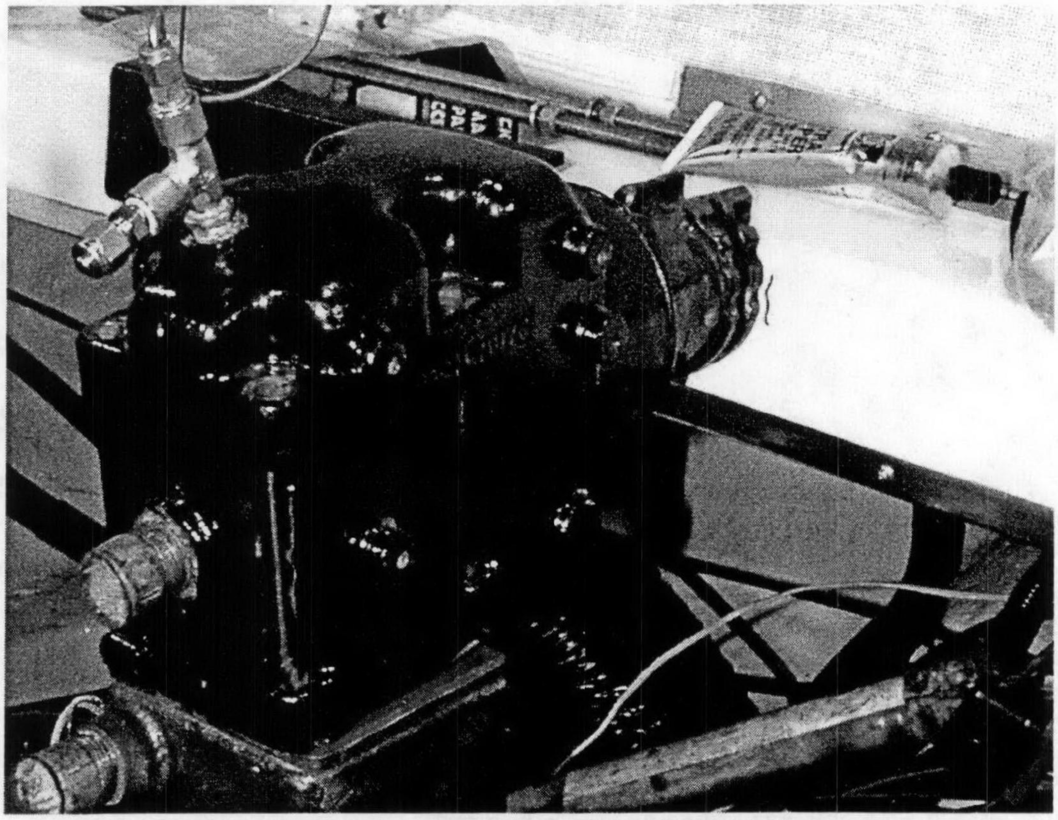

FIGURE 12. BOAT TRANSOM INTERFERENCE WITH EXHAUST ELBOW

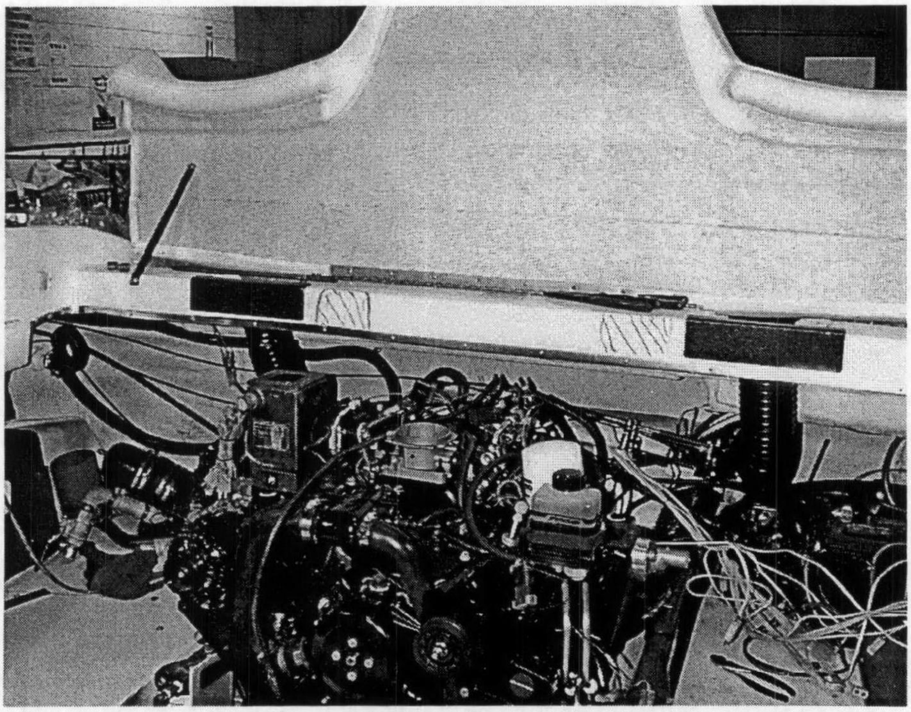

FIGURE 13. INTERFERING SECTIONS OF BOAT TRANSOM BEFORE REMOVAL MARKED IN BLACK

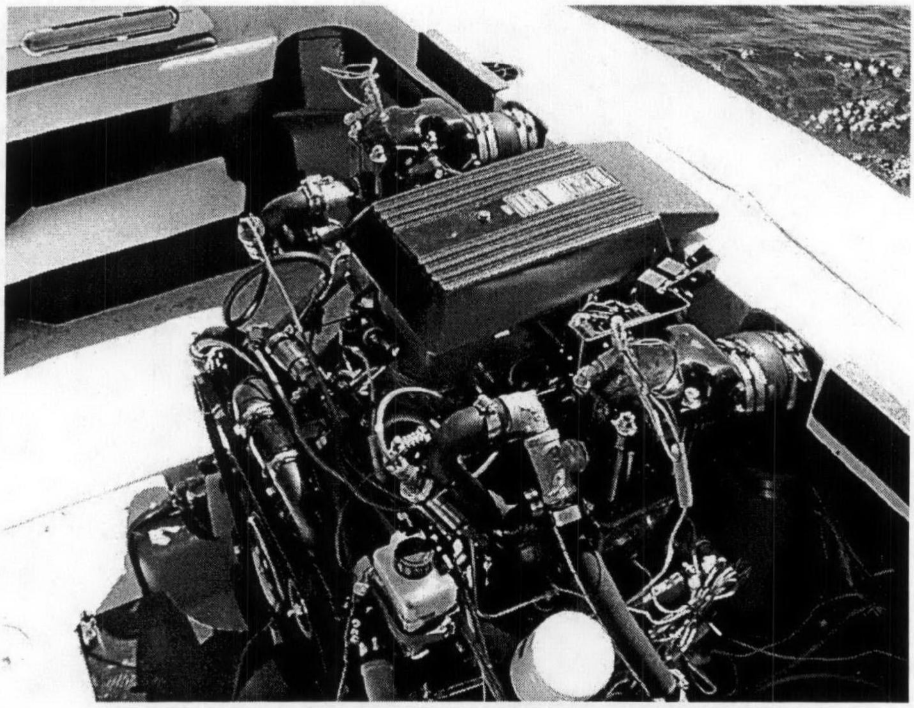

FIGURE 14. CATALYST-EQUIPPED ENGINE AS TESTED IN BOAT

2. In-Boat Operation on Fresh Water

In-boat testing of the catalyst-equipped engine was conducted on a fresh water lake near San Antonio to subject the catalysts to conditions which could produce water ingestion. Test conditions and procedures were specified in a National Marine Manufacturers Association (NMMA) letter submitted to the Manufacturers of Emission Controls Association (MECA) in February, 2000. A copy of the letter is provided in Appendix B. It outlines a set of durability, safety, and performance tests that are generally accepted by industry for heat soak, water ingestion, and engine exhaust back pressure characterization. SwRI's test program focused on the following water ingestion tests.

- 15 minute Idle - Neutral
- 15 minute Idle - Drive
- 45 minute Idle - Neutral
- 45 minute Idle - Drive
- 1500 rpm deceleration in gear
- 1500 rpm deceleration in neutral
- 2500 rpm deceleration in gear
- 2500 rpm deceleration in neutral
- 3500 rpm deceleration in gear
- 3500 rpm deceleration in neutral

SwRI also conducted additional tests that were thought to induce water reversion. These tests included:

- Start-up from boat trailer and motor to dock (5 minutes)
- Five hard throttle tip-ins/tip-outs (snaps) in and out of gear
- Three successive moderate-to-hard boat reversal operations
- Motoring at 1500 rpm for 5 min.
- Motoring at 3000 rpm for 5 min.
- Motoring at 3000 rpm for 1 min., motoring at full-throttle (1 min.), come to rest in gear, idle (1 min.), soak engine

The boat's engine exhaust manifolds were also instrumented with stainless steel water sample tubes connected to a ball valve for each bank, as shown in Figure 15. The sample tubes were purged before each test with the engine running, and at the end of each test with the engine off. No water was found in the exhaust manifolds after any of the water ingestion tests on fresh water.

The engine was instrumented with a Campbell CR23X Data Recorder that received inputs from thermocouples, pressure transducers, and the engine speed sensor. Data was sampled at 0.5 Hz to accommodate the large number of channels that were sampled, and the long steady-state tests at idle and light loads.

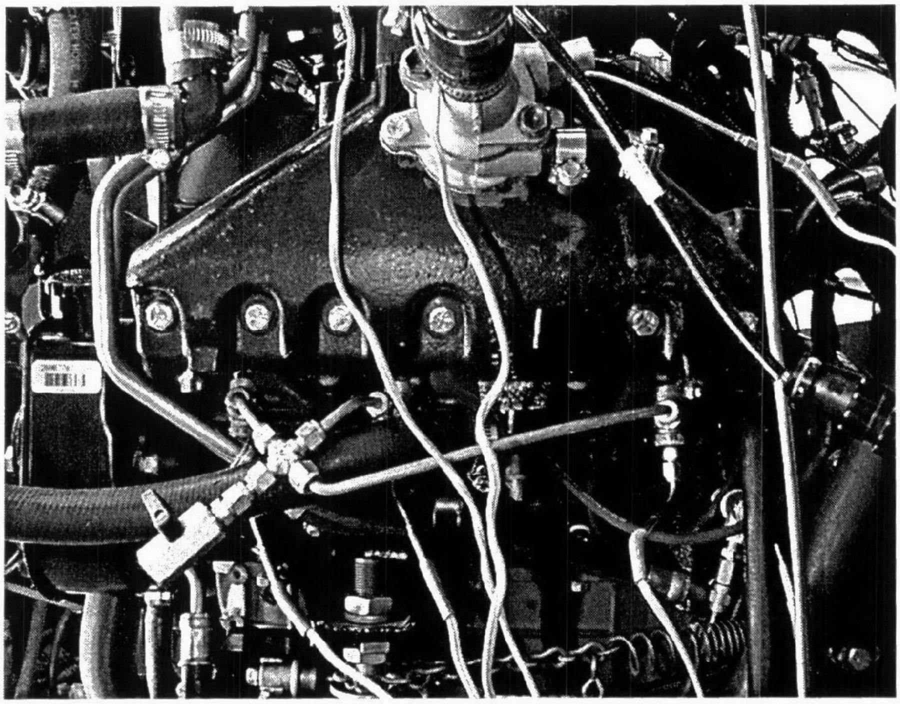

FIGURE 15. EXHAUST MANIFOLD AND INGESTION WATER COLLECTION TUBES

Both catalysts had surface thermocouples installed at three locations: at the center of the coolant jacket, near the inlet flange, and near the outlet flange. During most fresh water tests, temperatures remained below 200°F. However, during the tests when the engine was at 3000 rpm sustained operation, and when at full load for 1 minute, surface temperatures near the flanges of the catalysts reached peak values of 226°F. Skin temperature near the center of the catalyst during this same period peaked at 122°F.

When fresh water tests were completed, the catalysts were inspected with a borescope, and photographs were taken of the surface of the catalyst outlet. No signs of water damage were noted during these inspections.

E. Task 5 - Engine In-Boat Operation on Salt Water

Following fresh water testing, the boat was trailered to Port Aransas, Texas for salt water testing in the bay. Water ingestion tests were repeated at Port Aransas. Figure 16 shows the boat during testing at Port Aransas.

After the 45 minute idle in drive test, three drops of water were measured from each manifold. After the 15 minute idle in neutral test, two drops of water were measured from the right manifold. Also, after the 45 minute idle in neutral test, two drops of water were measured from the left manifold.

FIGURE 16. WATER INGESTION TESTING AT PORT ARANSAS, TEXAS

During most of the salt water tests, exhaust system surface temperatures were below 200°F. However, during the tests when the engine was at sustained 3000 rpm operation, and when at full load for 1 minute, surface temperatures near the non-water jacketed flanges of the catalysts reached peak readings of 230°F. The flange temperatures could be reduced by changing the water jacket design. Skin temperature near the center of the catalyst during this same period peaked at 165°F.

F. Task 6 - Closed-Loop Emissions Test After In-Boat Operation

After the salt water ingestion tests were performed, the engine was removed from the boat and re-installed in the test cell. During the installation, the catalysts were inspected for water contact and degradation. No signs of water contact, spalling, or cracking were noted. Figures 17 and 18 show the inlet and outlet of the right catalyst, respectively.

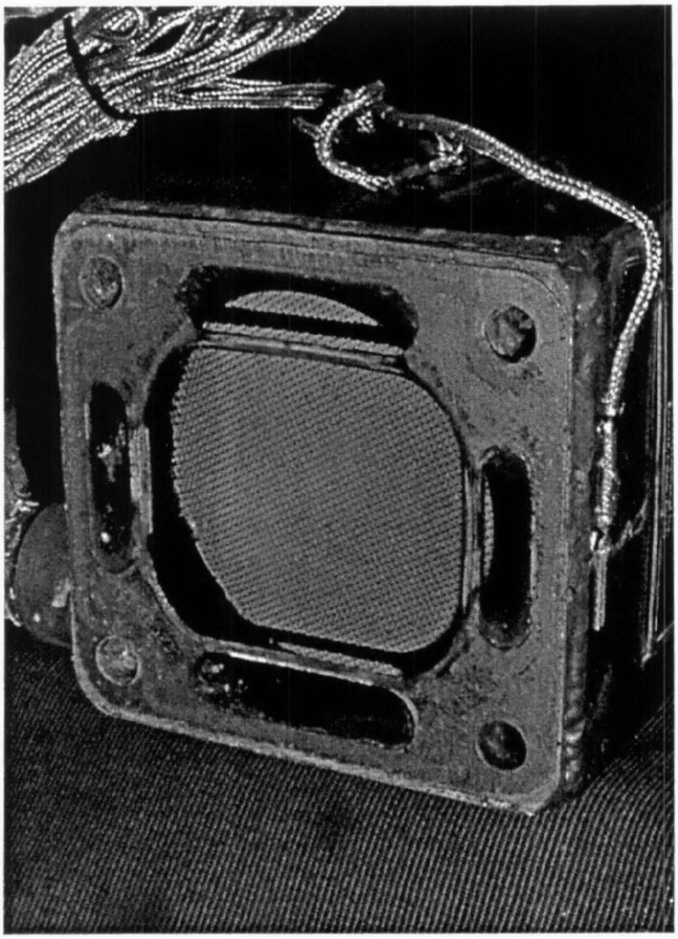

FIGURE 17. INLET OF RIGHT CATALYST AFTER WATER INGESTION TESTING

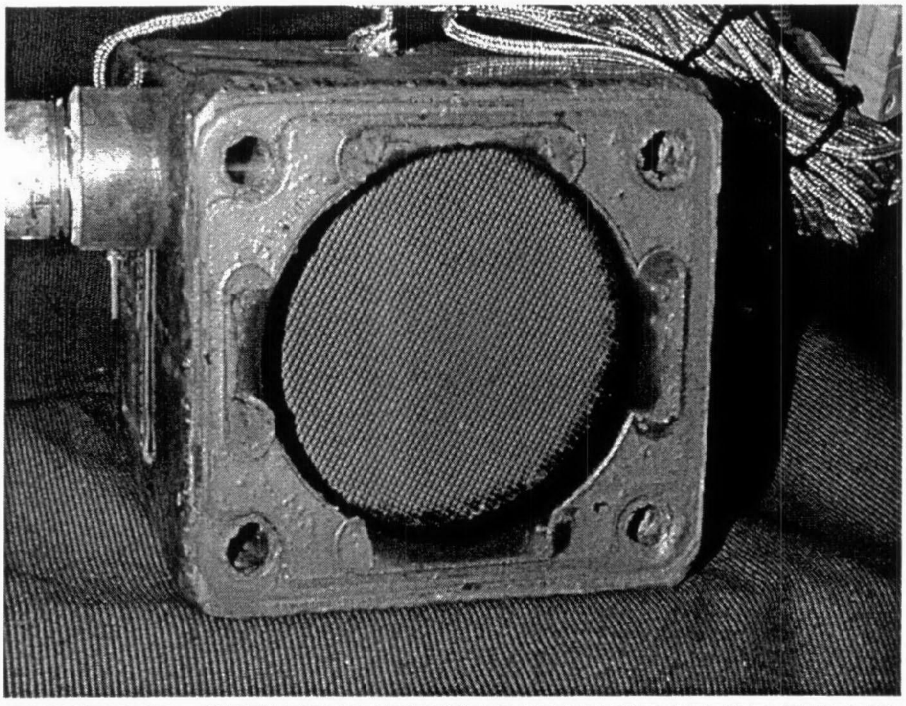

FIGURE 18. OUTLET OF RIGHT CATALYST AFTER WATER INGESTION TESTING

The complete closed-loop catalyzed engine was re-mounted in the test cell and an eight-mode emissions test was performed. Modal emissions from all eight modes of the test cycle are included in Appendix Table 4. The spreadsheet file which contains all data from these tests is named 'CL AFTER BOAT TESTING.XLS', and has been supplied separately by electronic media.

E4 cycle modal emissions are shown in Table 11. Results show that after subjecting the catalysts to water ingestion tests on fresh and salt water, the engine still produced 55 percent less HC, 80 percent less NO_X, and 73 percent less combined HC+NO_X compared to the engine's open-loop baseline results. The catalyst reduced CO emissions by 34 percent. HC+NO_X emission rates increased from 4.1 before to 4.5 g/kw-hr after the water ingestion tests, and CO emission rates increased from 70.4 to 73.2 g/kw-hr. The increase may be due to factors other than catalyst deterioration such as test-to-test repeatability.

TABLE 11. ISO E4 CLOSED-LOOP EMISSION TEST WITH CATALYST AFTER ON-BOAT OPERATION

ISO E4 Mode	Weight Factor	Power, hp	HC, g/hr	NO_X, g/hr	HC+NO_X, g/hr	CO, g/hr
1	0.06	201.6	392.0	537.8	929.8	24324
2	0.14	119.0	109.2	236.0	345.2	3264
3	0.15	57.5	19.3	37.7	57.0	737
4	0.25	20.7	26.2	4.7	30.9	759
5	0.40	0	55.7	0.3	56.0	265
Weighted Total		g/hp-hr	1.66	1.70	3.36	54.6
		g/kW-hr	2.22	2.28	4.50	73.2
Change from open-loop baseline, %			-55	-80	-73	-34

G. Task 7 - Open-Loop Emissions Test With Exhaust Gas Recirculation

Table 12 summarizes ISO E4 cycle emission rates with EGR applied to the engine in open-loop control. Modes 2, 3, 4, and 5 of the E4 test cycle correspond to the project test Modes 3, 5, 7, and 8 listed in Table 3. The air/fuel ratio in Mode 1 was set to 12.5:1. Air/fuel ratios in modes 2, 3,and 4 were set to 14.5:1, and in Mode 5 (idle), it was set to 13.5:1 for smooth operation. Compared to E4 emissions from the baseline engine, operation with EGR reduced HC emissions by 15 percent, and NO_X emissions were reduced by 54 percent. Combined HC+NO_X emissions were reduced by 43 percent, and CO emissions were reduced by 17 percent.

TABLE 12. ISO E4 OPEN-LOOP EMISSION TEST WITH EXHAUST GAS RECIRCULATION

ISO E4 Mode	EGR, %	Weight Factor	Power, hp	HC, g/hr	NO_X, g/hr	HC+ NO_X, g/hr	CO, g/hr
1	0	0.06	198.5	618.4	724.7	1343.1	30899
2	5.2	0.14	113.7	175.5	662.2	837.7	2368
3	11.1	0.15	56.1	166.5	144.5	311.0	1357
4	9.7	0.25	19.8	61.2	19.1	80.3	766
5	0	0.40	0	67.7	1.3	69.0	613
Weighted Total			g/hp-hr	3.13	3.96	7.09	68.6
			g/kW-hr	4.20	5.31	9.51	92.0
Change from open-loop baseline, %				-15	-54	-43	-17

Modal emissions from all eight modes of the test cycle in Table 3 are included in Appendix Table 5. The spreadsheet file which contains all data from these tests is named '4.3L Marine EGR.xls', and has been supplied separately by electronic media.

H. Air Toxic Emissions

In addition to regulated gaseous emissions measurement, raw exhaust samples were collected and analyzed for PAHs, chromium, manganese, and hydrocarbon species. It is important to note that although the analytical methods used to quantify these non-regulated emissions followed accepted practice, the collection of samples from raw exhaust for these analyses is not a recommended practice. The preferred practice is to direct the whole exhaust into a dilution tunnel before withdrawing samples for analysis. *Since marine engine coolant is pumped into the exhaust to reduce its temperature, this* method cannot be used. Emission samples were drawn from raw exhaust before coolant was mixed with it, and collected in Tedlar® bags for HC speciation, and on filters and PUF/XAD traps for metals and PAH analyses, respectively.

Due to the initial high temperature and moisture content of the raw exhaust (up to 9 percent water), water condensed in the sampling systems and the sample bags as the sample cooled. Condensation probably scrubbed some hydrocarbons from the exhaust. In addition, water vapor condensing from the raw exhaust sample reduced the volume of gaseous sample in the bags, and thus caused an increase in the measured concentration of the remaining hydrocarbons. This reduction in sample volume also caused errors in the sample volume measured by the flow meter in the filter and PUF/XAD sample system. These limitations of raw exhaust sampling were discussed with EPA before the project began, and SwRI was directed to proceed with this approach with the understanding that the accuracy of the results would be somewhat affected.

In order to increase the accuracy of toxic compound measurements, a different approach to sample collection should be devised to eliminate water condensation from the raw exhaust sample. One approach would be to use a mini-dilution tunnel to draw a partial sample of raw exhaust from the marine engine, and by dilution, reduce its water vapor fraction enough to preclude liquid water formation. Then, a particulate filter sample system could be incorporated in the tunnel for metals collection, bag samples could be collected for hydrocarbon speciation, and wet chemistry samples could be collected for aldehyde and alcohol analysis, using conventional methods. Title 40 CFR Part 92 details this approach for locomotive particulate measurement, and CFR Part 89 references similar ISO procedures for off-road engines.

Results of analyses for metals and PAHs are provided in mass units (nanograms) per sample. The engine exhaust flow rate was calculated using modal air/fuel ratios and fuel flow rates. The sample volume (cubic feet) drawn through the filters and PUF/XAD traps was then divided into the total exhaust flow rate (cubic feet/minute), and the result (sample/minute) was multiplied by the sample metals and PAH masses to give an emission rate in nanograms/minute. For HC species, the exhaust flow rate, species concentrations (from bag analysis), and species densities were used to calculate mass flow rates.

1. Open-Loop Baseline Emission Test

A summary of the vapor-phase PAH emissions in open-loop baseline configuration is shown in Table 13.

TABLE 13. SUMMARY OF VAPOR-PHASE PAH EMISSIONS FROM OPEN-LOOP BASELINE EMISSION TEST

ISO E4 MODE	1	2	3	4	5	WEIGHTED COMPOSITE		
WEIGHT FACTOR	0 06	0 14	0 15	0 25	0 4	1		
POWER, HP	205 0	116 8	58 3	20 5	0 0	42 5		
EMISSIONS RATES	ug/hr	ug/hr	ug/hr	ug/hr	ug/hr	ug/hr	ug/hp-hr	ug/kW-hr
NAPHTHALENE	1220000	159000	59500	15600	1730	109000	2570	3440
ACENAPHTHYLENE	97400	25700	2240	632	115	9980	235	315
ACENAPHTHENE	20100	8850	2150	429	81	2910	68	91
FLUORENE	12700	11500	595	361	86	2590	61	82
PHENANTHRENE	2170	1860	457	452	58	594	14	19
ANTHRACENE	294	301	23	23	3	70	2	3
FLUORANTHENE	371	186	50	34	5	66	2	3
PYRENE	217	97	27	14	2	35	1	1
BENZO(A)ANTHRACENE	62	27	9	ND*	ND	9	0	0
CHRYSENE	31	18	ND	ND	ND	4	0	0
BENZO(B)FLUORANTHENE	ND	ND	ND	ND	ND	0	0	0
BENZO(K)FLUORANTHENE	ND	ND	ND	ND	ND	0	0	0
BENZO(A)PYRENE	ND	ND	ND	ND	ND	0	0	0
INDENO(123-CD)PYRENE	15	ND	ND	ND	ND	1	0	0
DIBENZ(AH)ANTHRACENE	ND	ND	ND	ND	ND	0	0	0
BENZO(GHI)PERYLENE	15	9	ND	ND	ND	2	0	0
*ND = Not detected								

A summary of chromium and manganese results in open-loop baseline configuration is shown in Table 14. The open-loop baseline emissions test was performed after testing of the catalyzed closed-loop engine. During closed-loop engine emissions sampling, approximately four cubic feet of sample was drawn from the exhaust in five minutes. To reduce the amount of moisture condensation in the metals and PAH sampling system for the open-loop tests, the sample flow and volume was reduced by two-thirds over the same sample period. The reduced sample volume did not provide enough sample to allow manganese to be detected above the detection limit of 0.5 µg manganese per filter sample.

TABLE 14. SUMMARY OF METAL EMISSIONS FROM OPEN-LOOP BASELINE EMISSION TEST

ISO E4 MODE	1	2	3	4	5	WEIGHTED COMPOSITE		
WEIGHT FACTOR	*0 06*	*0 14*	*0 15*	*0 25*	*0 4*	*1*		
POWER, hp	105 0	116 8	58 3	20 5	0 0	42 5		
EMISSION RATES	µg/hr	µg/hr	µg/hr	µg/hr	µg/hr	µg/hr	µg/hp-hr	µg/kW-hr
CHROMIUM	64200	27900	19400	5510	295	12200	286	384
MANGANESE	ND*	ND	ND	ND	ND	ND	ND	ND

*ND - Not detected

A summary of hydrocarbon speciation results in open-loop baseline configuration is shown in Table 15 Only compounds requested by EPA, and the sum of all compounds analyzed are shown in Table 15. Detailed HC speciation results are shown in Appendix Table 6. Total weighted hydrocarbon rate measured by the HFID for the test was 4 94 g/kW-hr, which compares well with the weighted speciated hydrocarbon emission rate.

TABLE 15. SUMMARY OF HYDROCARBON SPECIATION RESULTS FROM OPEN-LOOP BASELINE EMISSION TEST

ISO E4 MODE	1	2	3	4	5	Weighted Composite
1,3-BUTADIENE, mg/min	46 9	0 0	11 0	12 6	12 2	12 5
BENZENE, mg/min	396	188	112	65 6	58 8	107
STYRENE, mg/min	0 0	0 0	0 0	0 0	0 0	0 0
FORMALDEHYDE, mg/min	396	104	48 4	26 5	14 3	58 0
ACETALDEHYDE, mg/min	29 0	23 6	12 7	3 5	28 8	9 0
ACROLEIN, mg/min	13 5	14 1	5 7	1 5	1 9	4 8
POWER, kW	153	87 1	43 5	15 3	0 0	31 7
1,3-BUTADIENE, mg/kW-hr	18 4	0 0	15 2	49 6	0 0	23 6
BENZENE, mg/kW-hr	156	130	155	257	0 0	202
STYRENE, mg/kW-hr	0 0	0 0	0 0	0 0	0 0	0 0
FORMALDEHYDE, mg/kW-hr	156	71 9	66 7	104	0 0	110
ACETALDEHYDE, mg/kW-hr	11 4	16 3	17 5	13 8	0 0	17 0
ACROLEIN, mg/kW-hr	5 3	9 7	7 9	6 0	0 0	9 1
SUM OF ALL SPECIATED COMPONENTS, mg/min	8100	3380	2350	1110	1370	2140
SUM OF ALL SPECIATED COMPONENTS, mg/kW-hr	3180	2330	3250	4350	NA	4050

2. Closed-Loop Baseline Emission Test With Catalyst

A summary of vapor-phase PAH emissions in closed-loop control with catalyst is show in Table 16. PAH emissions from the non-catalyzed engine in open-loop control are of the same order of magnitude. The reason for the similar PAH emission rates from the two configurations is unknown, and not consistent with the difference in total HC emissions.

TABLE 16. SUMMARY OF VAPOR-PHASE PAH EMISSIONS FROM CLOSED-LOOP BASELINE EMISSION TEST WITH CATALYST

ISO E4 MODE	1	2	3	4	5	WEIGHTED COMPOSITE		
WEIGHT FACTOR	0 06	0 14	0 15	0 25	0 4	1		
POWER, HP	205 9	118 3	56 6	22 3	0 0	43 0		
EMISSIONS RATES	*ug/hr*	*ug/hr*	*ug/hr*	*ug/hr*	*ug/hr*	*ug/hr*	*ug/hp-hr*	*ug/kW-hr*
NAPHTHALENE	855000	168000	29700	28100	66300	113000	2630	3520
ACENAPHTHYLENE	159000	20100	2810	814	1640	13500	317	425
ACENAPHTHENE	18300	5410	1060	326	488	2290	53	71
FLUORENE	44800	12300	2500	740	645	5230	122	164
PHENANTHRENE	24000	9920	2660	888	837	3790	88	118
ANTHRACENE	13400	5710	1410	522	244	2020	47	63
FLUORANTHENE	1870	1170	453	178	45	407	9	12
PYRENE	1590	1020	405	163	40	356	8	11
BENZO(A)ANTHRACENE	ND*	ND	ND	ND	ND	0	0	0
CHRYSENE	ND	ND	ND	ND	ND	0	0	0
BENZO(B)FLUORANTHENE	ND	ND	ND	ND	ND	0	0	0
BENZO(K)FLUORANTHENE	ND	ND	ND	ND	ND	0	0	0
BENZO(A)PYRENE	ND	ND	ND	ND	ND	0	0	0
INDENO(123-CD)PYRENE	15	ND	ND	ND	ND	1	0	0
DIBENZ(AH)ANTHRACENE	ND	ND	ND	ND	ND	0	0	0
BENZO(GHI)PERYLENE	15	9	ND	ND	ND	2	0	0

*ND = Not detected

A summary of chromium and manganese results from the catalyzed test engine in closed-loop control is shown in Table 17. In this engine configuration, manganese was detected in all modal samples. However, values are only on the order of three-times the detection limit of 0.5 μg, which is also the ratio of sample collection volume between these samples and those taken from the engine in open-loop non-catalyzed configuration. Therefore, it would be inaccurate to conclude that the engine's configuration affected manganese emission rates. The reason for the unexpected high chromium level measured from Mode 4 is unknown.

TABLE 17. SUMMARY OF METAL EMISSIONS FROM CLOSED-LOOP BASELINE EMISSION TEST WITH CATALYST

ISO E4 MODE	1	2	3	4	5	WEIGHTED COMPOSITE		
WEIGHT FACTOR	0 0 6	0 14	0 15	0 25	0 4	1		
POWER, hp	205 0	118 3	56 6	22 3	0 0	43 0		
EMISSION RATES	μg/hr	μg/hr	μg/hr	μg/hr	μg/hr	μg/hr	μg/hp-hr	μg/kW-hr
CHROMIUM	10400	8660	4170	84400	100	23600	549	736
MANGANESE	7080	4300	1780	7100	122	3120	73	98

A summary of hydrocarbon speciation results from the test engine in closed-loop control with catalyst is shown in Table 18. Only compounds requested by EPA, and the sum of all compounds analyzed are shown in Table 18. Detailed HC speciation results are shown in Appendix Table 6. Total weighted hydrocarbon rate measured by HFID for the test was 2.07 g/kW-hr which, compares reasonably well with the weighted speciated hydrocarbon emission rate.

TABLE 18. SUMMARY OF HYDROCARBON SPECIATION RESULTS FROM CLOSED-LOOP BASELINE EMISSION TEST WITH CATALYST

ISO E4 MODE	1	2	3	4	5	Weighted Composite
1,3-BUTADIENE, mg/min	4 0	1 9	0 3	0 2	0 6	0 8
BENZENE, mg/min	278	52 2	9 5	39 4	35 7	49 9
STYRENE, mg/min	0 0	0 0	0 0	0 0	0 0	0 0
FORMALDEHYDE, mg/min	15 1	11 2	0 8	0 1	0 6	2 9
ACETALDEHYDE, mg/min	11 0	4 7	0 5	0 2	0 4	1 6
ACROLEIN, mg/min	5 0	2 0	0 2	0 0	0 2	0 7
POWER, kW	154	88 2	42 2	16 6	0 0	32 1
1,3-BUTADIENE, mg/kW-hr	1 6	1 3	0 4	0 6	0 0	1 5
BENZENE, mg/kW-hr	109	35 5	13 6	142	0 0	93 4
STYRENE, mg/kW-hr	0 0	0 0	0 0	0 0	0 0	0 0
FORMALDEHYDE, mg/kW-hr	5 9	7 6	1 1	0 4	0 0	5 4
ACETALDEHYDE, mg/kW-hr	4 3	3 2	0 7	0 8	0 0	3 0
ACROLEIN, mg/kW-hr	1 9	1 4	0 3	0 1	0 0	1 3
SUM OF ALL SPECIATED COMPONENTS, mg/min	5030	1210	206	206	686	828
SUM OF ALL SPECIATED COMPONENTS, *mg/kW-hr*	1960	826	293	743	NA	1550

IV. SUMMARY

A 4.3L General Motors V-6 spark-ignited, fuel-injected engine was marinized with earlier engine model Mercury Marine hardware by the attachment of water-cooled exhaust manifolds and fuel pump, a "sea pump," coolant manifold, and cooling water plumbing. The engine was emission tested in open-loop control configuration. Emissions were also measured after the ECM was modified to operate in closed-loop control using a heated exhaust gas oxygen sensor. SwRI also installed two catalysts (48 in^3) which had been aged for 50 hours with an accelerated aging cycle. The feedback control system was calibrated to produce low after-catalyst $HC+NO_x$ emissions. The catalyzed engine system was then installed in a boat, and water ingestion tests were performed on both fresh and saltwater. Following boat testing, the engine was again emissions tested in the laboratory. The engine was then returned to open-loop control, and an exhaust gas recirculation system was installed. Emissions were measured with the EGR system calibrated to reduce NO_x emissions during part-load operation.

Emissions were measured in eight modes of engine operation. A subset of these eight modes is the ISO E4 recreational marine boat engine test cycle, which is also the California and Federal marine engine test cycle. A summary of all ISO E4 cycle results is shown in Table 19.

TABLE 19. SUMMARY OF ISO E4 MARINE ENGINE TEST RESULTS

Emission Test	$HC + NO_x$, g/kW-hr	CO, g/kW-hr	Power, hp
Baseline (Open-Loop)	16.6	110.8	205
Closed-Loop Baseline without Catalyst	14.8	101.0	206
Closed-Loop Baseline with Catalyst	4.10	70.4	206
Closed-Loop with Catalyst After On-Boat Operation	4.50	73.2	201
Open-Loop With Exhaust Gas Recirculation	9.51	92.0	198

In open-loop without any emission-reduction technologies, the engine produced 16.6 grams $HC+NO_x$/kW-hr, and 110.8 grams CO/kW-hr over the E4 cycle. By applying exhaust gas recirculation and adjusting the air/fuel ratio, $HC+NO_x$ emissions were reduced by 43 percent to 9.51 g/kW-hr, and CO emissions were reduced 17 percent to 92.0 g/kW-hr.

With the engine in closed-loop control without catalysts, $HC+NO_x$ emissions were reduced by 11 percent to 14.8 g/kW-hr, and CO emissions were reduced by 9 percent to 101.0 g/kW-hr. With the use of EGR in open-loop control, up to half of the NO_x emissions could be removed. With aged catalysts on the engine in closed-loop control, HC+NO_x emissions were reduced by 75 percent to 4.1 g/kW-hr, and CO emissions were reduced by 36 percent to 70.4 g/kW-hr. Following engine testing on the boat, the engine was re-tested and HC+NO_x emissions appeared to be slightly higher at 4.5 g/kW-hr, and CO emissions had increased to 73.2 g/kW-hr.

The use of catalytic exhaust aftertreatment, exhaust gas recirculation, and closed-loop control was shown to effectively reduce marine gasoline engine emissions. Although emission rates from the engine increased very slightly after on-boat testing, the cause for this increase is unknown. The increase may be due to factors other than catalyst deterioration such as test-to-test repeatability. The catalysts were inspected after on-boat usage and were found intact with no signs of water damage.

APPENDIX

MARINE ENGINE TEST RESULTS

TABLE A-1. OPEN-LOOP BASELINE EMISSIONS

Mode	Actual Time (s)	BSHC (g/hp-hr)	BSNOx (g/hp-hr)	BS HC+NOx (g/hp-hr)	BSCO (g/hp-hr)	BSCO2 (g/hp-hr)	BSFC (lb/hp-hr)	Power (hp)
1	120	2 94	4.67	7 61	134	511	0 51	205 0
2	120	1 99	11 0	13 0	31 4	597	0 45	157 2
3	120	2 14	13 0	15 2	22 0	601	0.45	116 8
4	120	3 05	13 4	16 4	32 7	620	0 47	83 5
5	120	2 99	10 3	13 3	48.2	609	0 48	58 3
6	120	3.57	5 18	8 75	82 7	663	0 56	35 6
7	120	3 81	1 87	5 68	106	824	0.70	20 5
8	120							

Mode	HC (g/hr)	Nox (g/hr)	CO (g/hr)	CO2 (g/hr)	C-B Fuel (lb/hr)	Intake Humidity (gr/lb)	Background Humidity (gr/lb)	Sample Kw
1	603	958	27457	104788	104 2	97 9	78.7	0 87
2	314	1726	4935	93841	71 3	97 9	81 4	0 88
3	249	1520	2568	70169	52 1	98 4	83 2	0 88
4	255	1115	2725	51710	39 5	98 3	81 7	0 88
5	174	598	2807	35483	28 1	94.5	79 8	0 88
6	127	184	2940	23567	19 9	97.6	79 4	0 88
7	78 2	38.3	2181	16907	14 3	97 5	81 9	0 88
8	99 3	1 2	1346	3403	4.1	97 0	82 5	0 88

Mode	Nox Kh	NOx Wet S (ppm)	CO Wet S (%)	HC S (ppm)	CO2 Wet S (%)	Calculated A/F	Speed (rpm)	Load (lb-ft)
1	1 12	860	4.54	2009	11 0	11 6	4597	234 2
2	1.12	1964	1 03	1326	12 5	14 1	4140	199 4
3	1 12	2316	0 72	1415	12 6	14 5	3678	166.7
4	1.12	2278	1 03	1945	12 4	14.2	3217	136 3
5	1 10	1784	1 51	1898	12 2	13 8	2757	111 0
6	1 12	792	2 32	2025	11 9	13 2	2297	81.3
7	1 12	227	2 40	1731	11 8	13 2	1839	58.6
8	1 12	29	6 06	9021	9.7	10 7	555	

Mode	Throttle (%)	HC Wet (ppm)	NOx Dry (ppm)	CO Dry (%)	CO2 Dry (%)	Intake Air Dewpoint (F)	Dilution Air Temp. (F)	Dilution Air RH (%)
1	100	2009	985	5 19	12 61	65 6	79 7	50 2
2	39	1326	2236	1 18	14 24	65 6	80 8	50 0
3	30	1415	2634	0 82	14 28	65 7	81 3	50 3
4	25	1945	2591	1.17	14.12	65.7	80.8	50.2
5	22	1898	2031	1 72	13 87	64 7	80 3	49 9
6	18	2025	903	2 65	13.52	65.5	80 0	50.1
7	15	1731	258	2 74	13 47	65 5	80 9	50 2
8		9021	33	6 89	11.09	65 4	81 1	50 2

TABLE A-1 (CONT'D). OPEN-LOOP BASELINE EMISSIONS

Mode	Barom. (mm Hg)	Intake Air (F)	Manifold Vacuum ("Hg)	Fuel Flow (lb/hr)	Water Out (F)	Water In (F)	Oil (F)	Cyl 1 (F)
1	737	81 3	0 6	104 2	161	75	256	1217
2	737	81 9	4 3	71.3	160	75	250	1244
3	737	81 5	7 9	52 1	158	74	237	1178
4	737	81.5	10.6	39 5	159	75	227	1096
5	738	78.2	12 9	28 1	159	74	214	1037
6	738	79 6	14 9	19 9	158	75	203	996
7	738	79.4	15 4	14 3	158	75	195	999
8	737	79 0	14 7	4.1	159	75	169	660
Mode	**Cyl 2 (F)**	**Cyl 3 (F)**	**Cyl 4 (F)**	**Cyl 5 (F)**	**Cyl 6 (F)**	**Exh. Man. H2O Out Right (F)**	**Target A/F Ratio**	**UEGO A/F Ratio**
1	1233	4695	1162	1247	1216	102	12 60	12 50
2	1267	4701	1153	1242	1221	100	14 50	14.20
3	1190	4702	1070	1175	1155	95	14.88	14 40
4	1095	4711	1021	1100	1074	92	14 50	14 30
5	1014	4712	961	1028	1018	89	14 00	13 90
6	973	4713	890	955	999	87	13 60	13 50
7	1028	4700	859	896	995	87	13 50	13 50
8	647	4642	552	603	629	85	12 00	12.00

ISO E4 CYCLE OPEN-LOOP BASELINE EMISSIONS

		ISO E4 WEIGHTED			
Mode	**Wt. Factor**	**Hp**	**HC (g/hr)**	**Nox (g/hr)**	**CO (g/hr)**
MODE 1	0 06	12 30	36 16	57 50	1647
MODE 3	0 14	16 35	34 91	212 8	359 6
MODE 5	0.15	8 74	26 14	89.69	421 1
MODE 7	0 25	5 13	19.55	9 56	545 4
MODE 8	0 4	0 00	39 72	0.48	538 2
	Total	42 5	156.5	370 0	3512

	HC	NOx	CO
g/hp-hr	3 68	8 70	82 6
g/kW-hr	4 94	11 7	111

TABLE A-2. BEFORE-CATALYST CLOSED-LOOP BASELINE EMISSIONS

The right catalyst outlet temperature read false for all tests

Mode	Actual Time (s)	BSHC (g/hp-hr)	BSNOx (g/hp-hr)	BSHC+NOx (g/hp-hr)	BSCO (g/hp-hr)	BSCO2 (g/hp-hr)	BSFC (lb/hp-hr)
BEFORE MODE 1	181	2 72	4 51	7 23	121 4	527	0.51
BEFORE MODE 2	180	2.62	8 80	11 4	56 6	574	0 47
BEFORE MODE 3	180	2 27	11.2	13 5	42 1	581	0 46
BEFORE MODE 4	180	2 51	12.2	14.7	36 3	599	0 46
BEFORE MODE 5	180	3.36	8 72	12 1	74 3	598	0.50
BEFORE MODE 6	180	2 94	7 25	10 2	47 9	680	0 53
BEFORE MODE 7	180	2 43	2 34	4.77	49 2	879	0 67
BEFORE MODE 8	180						

Mode	Power (hp)	HC (g/hr)	NOx (g/hr)	CO (g/hr)	CO2 (g/hr)	C-B Fuel (lb/hr)	Intake Humidity (gr/lb)
BEFORE MODE 1	205 8	560	927	24968	108532	104.0	85.5
BEFORE MODE 2	155 7	407	1370	8810	89371	72 7	84 9
BEFORE MODE 3	119 4	271	1336	5028	69415	54 4	83 1
BEFORE MODE 4	86 0	216	1047	3123	51499	39 7	83 1
BEFORE MODE 5	59 0	198	515	4381	35277	29 8	82 6
BEFORE MODE 6	37 0	109	268	1774	25170	19 7	82 1
BEFORE MODE 7	20 5	49 6	47.8	1006	17977	13 7	80 8
BEFORE MODE 8		74 6	1 14	320	4269	3 48	82.3

Mode	Background Humidity (gr/lb)	Sample Kw	NOx Kh	NOx Wet S (ppm)	CO Wet S (%)	HCS (ppm)	CO2 Wet S (%)
BEFORE MODE 1	73 6	0 88	1 05	860	4.00	1813	11 07
BEFORE MODE 2	75 3	0 88	1 05	1704	1 89	1762	12 18
BEFORE MODE 3	77 4	0 88	1 04	2177	1 40	1522	12 29
BEFORE MODE 4	78 1	0 88	1 04	2331	1 19	1656	12.45
BEFORE MODE 5	78 2	0 88	1.04	1604	2 33	2126	11 92
BEFORE MODE 6	78 7	0 88	1 03	1222	1.37	1697	12 39
BEFORE MODE 7	80 3	0 88	1 03	311	1 11	1101	12 57
BEFORE MODE 8	79.4	0 88	1 04	29	1 41	6635	11 96

Mode	Calculated A/F	Speed (rpm)	Load (lb-ft)	Throttle (%)	HC Wet (ppm)	NOx Dry (ppm)	CO Dry (%)
BEFORE MODE 1	12.13	4598	235 0	100	1813	982	4 57
BEFORE MODE 2	13 39	4139	197 6	36	1762	1944	2 15
BEFORE MODE 3	13 89	3682	170 3	29	1522	2479	1.59
BEFORE MODE 4	13.96	3222	140 2	24	1656	2655	1 35
BEFORE MODE 5	13.11	2764	112.1	21	2126	1831	2.66
BEFORE MODE 6	13 80	2302	84 5	17	1697	1393	1.56
BEFORE MODE 7	14 00	1838	58 4	13	1101	355	1 26
BEFORE MODE 8	13 68	583			6635	33	1 60

TABLE A-2 (CONT'D). BEFORE-CATALYST CLOSED-LOOP BASELINE EMISSIONS

Mode	CO2 Dry (%)	Intake Air Dewpoint (F)	Dilution Air Temp. (F)	Dilution Air RH (%)	Barom. (mm Hg)	Intake Air (F)	Manifold Vacuum ("Hg)
BEFORE MODE 1	12 64	61.8	77 9	49 7	735 0	73 4	0 5
BEFORE MODE 2	13 90	61 6	78 4	50.0	734.8	73 3	4 8
BEFORE MODE 3	14 00	61 0	79.2	50 1	735 5	73 1	7 8
BEFORE MODE 4	14 19	61 0	79 3	50 3	735 7	72 9	10 3
BEFORE MODE 5	13 61	60.8	79 4	50.3	735.4	72 8	12.8
BEFORE MODE 6	14 13	60 7	79 4	50 7	735 7	73.1	14 7
BEFORE MODE 7	14 34	60 2	80 0	50 6	736 0	73 8	15 3
BEFORE MODE 8	13 58	60 7	80 3	49.6	735 7	74 2	14 5
Mode	**Fuel (lb/hr)**	**Water Out (F)**	**Water in (F)**	**Oil (F)**	**Cyl 1 (F)**	**Cyl 2 (F)**	**Cyl 3 (F)**
BEFORE MODE 1	103 9	160	77	249	1239	1258	1237
BEFORE MODE 2	72 6	158	77	250	1239	1256	1175
BEFORE MODE 3	54.3	158	77	239	1177	1174	1072
BEFORE MODE 4	39 7	158	77	230	1106	1105	1030
BEFORE MODE 5	29 7	157	77	222	1019	1041	962
BEFORE MODE 6	19 7	156	77	206	1022	1031	919
BEFORE MODE 7	13 7	156	77	192	1047	1071	961
BEFORE MODE 8	3 48	158	77	179	692	720	637
Mode	**Cyl 4 (F)**	**Cyl 5 (F)**	**Cyl 6 (F)**	**Exh. Man. H20 Out Left (F)**	**Exh. Man. H2O Out Right (F)**	**Left Cat In (F)**	**Left Cat Out (F)**
BEFORE MODE 1	1180	1281	1261	184	185	1421	1480
BEFORE MODE 2	1156	1249	1238	182	183	1385	1475
BEFORE MODE 3	1064	1188	1183	180	181	1283	1413
BEFORE MODE 4	1014	1117	1110	179	181	1177	1336
BEFORE MODE 5	950	1029	1031	178	180	1038	1155
BEFORE MODE 6	917	973	1041	175	181	949	1046
BEFORE MODE 7	898	921	1039	176	180	895	990
BEFORE MODE 8	599	655	694	174	175	570	704

Mode	Left Cat Skin (F)	Right Cat In (F)	Right Cat Out (F)	Right Cat Skin (F)	Oxygen Dry (%)
BEFORE MODE 1	166	1485	False read	246	0 13
BEFORE MODE 2	168	1472	False read	242	0 25
BEFORE MODE 3	174	1352	False read	237	0.28
BEFORE MODE 4	179	1232	False read	233	0 37
BEFORE MODE 5	174	1096	False read	226	0 25
BEFORE MODE 6	172	1027	False read	223	0 31
BEFORE MODE 7	172	985	False read	221	0 30
BEFORE MODE 8	174	675	False read	201	1 00

TABLE A-2 (CONT'D). BEFORE-CATALYST CLOSED-LOOP BASELINE EMISSIONS

ISO E4 CYCLE BEFORE-CATALYST CLOSED-LOOP BASELINE EMISSIONS

		WEIGHTED			
Mode	Wt. Factor	Hp	HC (g/hr)	NOx (g/hr)	CO (g/hr)
MODE 1	0.06	12.35	33.6	55.6	1498
MODE 3	0 14	16.71	37.9	187.0	703.9
MODE 5	0.15	8.85	29.75	77.18	657.2
MODE 7	0 25	5.11	12.41	11.96	251.6
MODE 8	0.4	0.00	29.85	0.45	127.8
	Total	43.0	143.6	332.2	3239

	HC	NOx	CO
g/hp-hr	3.34	7.72	75.3
g/kW-hr	4.48	10 4	101.0

TABLE A-3. AFTER-CATALYST CLOSED-LOOP BASELINE EMISSIONS

After MODE 8A was repeated because the engine went into open-loop mode but it was only noticed after the test.
After Mode 8 and After 8A have similar results so it is probable that the engine went into open-loop after the test was over
The right catalyst outlet temperature read false for all tests

Mode	Actual Time (s)	BSHC (g/hp-hr)	BSNOx (g/hp-hr	BS HC-NOx (g/hp-hr)	BSCO (g/hp-hr)	BSCO2 (g/hp-hr)	BSFC (lb/hp-hr)
AFTER MODE 1	180	2 07	2 46	4 54	121	531	0 51
AFTER MODE 2	180	1 15	3.12	4 26	51 6	581	0 46
AFTER MODE 3	180	0 81	1 71	2 52	23 7	610	0 45
AFTER MODE 4	180	0.76	1 21	1 97	22 8	624	0 46
AFTER MODE 5	180	0 34	0 63	0 97	12.0	677	0 48
AFTER MODE 6	180	0 34	0 15	0 49	16 0	754	0 54
AFTER MODE 7	180	0 88	0 16	1 04	31 0	854	0 63
AFTER MODE 8	180						
AFTER MODE 8A	180						
Mode	**Power (hp)**	**HC (g/hr)**	**NOx (g/hr)**	**CO (g/hr)**	**CO2 (g/hr)**	**C-B Fuel (lb/hr)**	**Intake Humidity (gr/lb)**
AFTER MODE 1	205 9	427	507	24894	109221	104 1	78 0
AFTER MODE 2	160 2	184	500	8267	93040	74 1	75 1
AFTER MODE 3	118 3	96	202	2804	72160	53 4	77.1
AFTER MODE 4	84 9	64	103	1937	52980	39 1	75.3
AFTER MODE 5	56 6	19	36	681	38346	27 5	79 0
AFTER MODE 6	34 2	12	5	549	25814	18 6	76 9
AFTER MODE 7	22 3	20	4	692	19074	14 1	77 7
AFTER MODE 8		44	0	219	4390	3.4	77 1
AFTER MODE 8A		49	0	234	4292	3 4	76 0
Mode	**Background Humidity (gr/lb)**	**Sample Kw**	**NOx Kh**	**NOx Wet S (ppm)**	**CO Wet S (%)**	**HC S (ppm)**	**CO2 Wet S (%)**
AFTER MODE 1	75 2	0 87	1 01	488	3 99	1382	11 14
AFTER MODE 2	77 3	0.88	1 00	636	1 73	775	12 38
AFTER MODE 3	78 5	0 88	1 01	341	0.79	542	12 86
AFTER MODE 4	82 9	0 88	1 00	240	0.74	498	12.93
AFTER MODE 5	78.5	0 88	1 02	114	0 37	209	13 12
AFTER MODE 6	84.8	0.88	1 01	24 8	0 44	190	13.14
AFTER MODE 7	80 1	0 88	1 01	22.5	0 73	422	12 88
AFTER MODE 8	78 8	0 88	1 01	4.54	1 01	4072	12 76
AFTER MODE 8A	78 9	0 88	1 00	4 85	1 10	4599	12 76
Mode	**Calculated A/F**	**Speed (rpm)**	**Load (lb-ft)**	**Throttle (%)**	**HC Wet (ppm)**	**NOx Dry (ppm)**	**CO Dry (%)**
AFTER MODE 1	12.11	4599	235 1	100 00	1382	557 4	4 56
AFTER MODE 2	13 48	4149	202 8	37 56	775	726 4	1 98
AFTER MODE 3	14 15	3687	168 6	29 51	542	389 2	0 90
AFTER MODE 4	14 12	3223	138 3	23 69	498	274.4	0.85
AFTER MODE 5	14 43	2761	107 7	20.25	209	130 5	0.42
AFTER MODE 6	14.32	2299	78.2	16 56	190	28.3	0 50
AFTER MODE 7	14 20	1844	63 6	14 90	422	25 7	0 84
AFTER MODE 8	13 61	604			4072	5	1 15
AFTER MODE 8A	13 44	615			4599	6	1 26

TABLE A-3 (CONT'D). AFTER-CATALYST CLOSED-LOOP BASELINE EMISSIONS

Mode	CO2 Dry (%)	Intake Air Dewpoint (F)	Dilution Air Temp. (F)	Dilution Air RH (%)	Barom. (mm Hg)	Intake Air (F)	Manifold Vacuum ("Hg)
AFTER MODE 1	12 74	59.2	79.2	48 7	735 4	74 6	0 5
AFTER MODE 2	14 15	58 1	79.6	49 2	732.3	76 3	4.3
AFTER MODE 3	14 67	58 9	80 2	49 0	735 1	75 2	7 8
AFTER MODE 4	14 77	58 1	81 1	50 1	732 1	75.9	10 4
AFTER MODE 5	14 97	59 6	80 2	49 2	734 7	76.4	12 9
AFTER MODE 6	15.00	58.7	81.4	50.8	732.1	77 0	15.0
AFTER MODE 7	14 69	59 1	80.5	49 6	734.6	76 8	14.8
AFTER MODE 8	14 57	58 9	79 8	50 0	734 2	76 6	14 5
AFTER MODE 8A	14 58	58 4	79 3	50 8	732 6	75.5	14 5

Mode	Fuel Flow (lb/hr)	Water Out (F)	Water In (F)	Oil (F)	Cyl 1 (F)	Cyl 2 (F)	Cyl 3 (F)
AFTER MODE 1	104 1	160	78	248	1237	1274	1224
AFTER MODE 2	74 1	160	77	237	1233	1260	1179
AFTER MODE 3	53 4	158	77	247	1186	1191	1073
AFTER MODE 4	39 1	158	77	230	1090	1111	1035
AFTER MODE 5	27 4	157	77	219	1055	1067	972
AFTER MODE 6	18 6	157	78	204	1039	1042	943
AFTER MODE 7	14 1	157	78	200	1007	1065	918
AFTER MODE 8	3 39	159	78	177	690	655	625
AFTER MODE 8A	3.35	158	77	170	686	640	628

Mode	Cyl 4 (F)	Cyl 5 (F)	Cyl 6 (F)	Exh. Man. H2O Out Left (F)	Exh. Man. H2O Out Right (F)	Left Cat In (F)	Left Cat Out (F)
AFTER MODE 1	1187	1280	1268	185	186	1424	1482
AFTER MODE 2	1162	1255	1246	183	184	1390	1491
AFTER MODE 3	1080	1195	1197	181	186	1294	1435
AFTER MODE 4	1015	1110	1105	179	180	1168	1335
AFTER MODE 5	975	1044	1082	178	183	1068	1242
AFTER MODE 6	920	971	1061	176	181	963	1078
AFTER MODE 7	918	933	1037	176	181	908	1004
AFTER MODE 8	595	654	691	169	168	545	706
AFTER MODE 8A	590	646	684	172	174	544	677

Mode	Left Cat Skin (F)	Right Cat In (F)	Right Cat Out (F)	Right Cat Skin (F)	Oxygen Dry (%)
AFTER MODE 1	174	1488	False read	241	0 05
AFTER MODE 2	169	1477	False read	242	0 07
AFTER MODE 3	180	1366	False read	234	0.07
AFTER MODE 4	178	1227	False read	231	0 06
AFTER MODE 5	175	1128	False read	225	0 06
AFTER MODE 6	173	1032	False read	223	0 04
AFTER MODE 7	173	980	False read	221	0 03
AFTER MODE 8	169	653	False read	200	0 04
AFTER MODE 8A	172	657	False read	202	0 01

TABLE A-3 (CONT'D). AFTER-CATALYST CLOSED-LOOP BASELINE EMISSIONS

ISO E4 CYCLE AFTER-CATALYST CLOSED-LOOP BASELINE EMISSIONS

		WEIGHTED			
Mode	Wt. Factor	Hp	HC (g/hr)	NOx (g/hr)	CO (g/hr)
MODE 1	0.06	12.35	25.6	30.4	1494
MODE 3	0.14	16.56	13.4	28.3	393
MODE 5	0.15	8.49	2.88	5.35	102
MODE 7	0.25	5.58	4.93	0.88	173
MODE 8A	0.4		19.49	0.07	94
	Total	43.0	66 3	65.0	2255

	HC	NOx	CO
g/hp-hr	1 54	1.51	52.5
g/kW-hr	2.07	2.03	70.4

TABLE A-4. AFTER-CATALYST CLOSED-LOOP EMISSIONS AFTER BOAT TESTING

Mode 5 was re-run because the first run was at the wrong load

Mode	Actual Time (s)	BSHC (g/hp-hr)	BSNOx (g/hp-hr)	BS HC+NOx (g/hp-hr)	BSCO (g/hp-hr)	BSCO2 (g/hp-hr)	BSFC (lb/hp-hr)	Power (hp)
1	180	1 94	2 67	4 61	120 7	548	0 52	201 6
2	180	1 30	3 49	4 79	52 1	592	0.47	157 2
3	180	0 92	1 98	2 90	27.4	604	0 45	119 0
4	180	0 72	1 30	2 02	15 1	617	0 45	84 4
5	180	0.34	0 66	0 99	12 8	671	0 48	57 5
6	180	0 69	0 38	1 07	32 1	721	0 54	35.5
7	180	1 26	0 23	1 49	36 7	899	0 67	20 7
8	180							0 0

Mode	HC (g/hr)	NOx (g/hr)	CO (g/hr)	CO2 (g/hr)	C-B Fuel (lb/hr)	Intake Humidity (gr/lb)	Background Humidity (gr/lb)	Sample Kw
1	392 0	537 8	24324	110431	104 2	77 3	77 8	0 87
2	204.1	548.8	8194	93109	74 1	78.9	78 4	0 88
3	109 2	236 0	3264	71940	53 8	79.4	79 4	0 88
4	60 6	109 9	1277	52055	37 7	81 4	79.1	0 88
5	19 3	37 7	737	38592	27 7	72 4	77.6	0 88
6	24 5	13 5	1138	25581	19 1	82.7	80 0	0 88
7	26 2	4 7	759	18619	13.8	82 7	80 0	0.88
8	55 7	0 3	265	4647	3 64	81.1	80 9	0 88

Mode	NOx Kh	NOx Wet S (ppm)	CO Wet S (%)	HC S (ppm)	CO2 Wet S (%)	Calculated A/F	Speed (rpm)	Load (lb-ft)
1	1 01	518	3 89	1266	11 24	12.14	4597	230 3
2	1.02	686	1 71	861	12 38	13.49	4138	199 5
3	1 02	393	0 91	616	12 80	14 05	3680	169 9
4	1 03	255	0 50	480	13 00	14 36	3220	137 6
5	0 99	123	0 39	207	13 03	14 50	2761	109 4
6	1 04	61 9	0 89	385	12 81	14 10	2300	81 0
7	1.04	29 9	0.82	573	12 84	14.12	1841	59 1
8	1 03	7 0	1 14	4824	12 66	13 47	607	0 0

Mode	Throttle (%)	HC Wet (ppm)	NOx Dry (ppm)	CO Dry (%)	CO2 Dry (%)	Intake Air Dewpoint (F)	Dilution Air Temp. (F)	Dilution Air RH (%)
1	100	1266	593	4 45	12 86	59 1	79 9	49
2	36	861	783	1 96	14 14	59.7	80.1	49
3	27	616	449	1 04	14 60	59 9	80 5	49
4	22	480	291	0.57	14 83	60 5	80 5	49
5	19	207	141	0 45	14 86	57.4	79 7	50
6	14	385	70 6	1 01	14 62	61 0	80 8	49
7	11	573	34 2	0 94	14 65	61.0	80 7	49
8	0	4824	8 0	1 30	14 45	60.4	81 1	49

TABLE A-4 (CONT'D). AFTER-CATALYST CLOSED-LOOP EMISSIONS AFTER BOAT TESTING

Mode	Barom. (mm Hg)	Intake Air (F)	Manifold Vacuum ("Hg)	Fuel Flow (lb/hr)	Water Out (F)	Water In (F)	Oil (F)	Cyl 1 (F)
1	739 8	77 2	0 54	104 2	161	75	242	1253
2	739 6	78 2	4 30	74 1	160	75	256	1247
3	739 5	78 1	7 82	53.8	159	75	240	1178
4	739 1	78 3	10 49	37.7	159	75	226	1106
5	740 5	75.1	13 08	27 7	159	75	213	1056
6	738 6	77 4	14 92	19 1	157	75	206	1033
7	738 9	77.3	15.28	13 8	157	75	191	1023
8	738 7	77 0	13 91	3 6	158	75	163	710
Mode	Cyl 2 (F)	Cyl 3 (F)	Cyl 4 (F)	Cyl 5 (F)	Cyl 6 (F)	Exh. Man. H2O Out Left (F)	Exh. Man. H2O Out Right (F)	Left Cat In (F)
1	1277	1237	1177	1282	1248	180	157	1557
2	1276	1187	1159	1259	1231	179	156	1547
3	1205	1073	1075	1202	1162	177	139	1456
4	1129	1024	1018	1125	1093	176	137	1358
5	1048	4952	969	1055	1042	172	128	1252
6	1047	928	924	983	1035	159	120	1144
7	1078	915	895	946	1034	156	118	1095
8	199	639	156	685	686	165	101	772

Mode	*Left Cat Out (F)*	*Left Cat Skin (F)*	*Right Cat In (F)*	*Right Cat Out (F)*	*Right Cat Skin (F)*	*Oxygen Dry (%)*	*Exhaust Backpressure ("Hg)*
1	1587	96	1574	1599	91	0 05	8 0
2	1596	93	1578	1635	91	0 07	5.7
3	1535	91	1468	1545	88	0 07	3 6
4	1452	89	1356	1455	86	0.06	2.2
5	1352	87	1243	1356	84	0 02	1.2
6	1185	86	1157	1223	84	0.02	0 9
7	1097	85	1135	1165	83	0 02	0 7
8	880	84	724	954	83	0 05	0 1

ISO E4 CYCLE AFTER-CATALYST CLOSED-LOOP EMISSIONS AFTER BOAT TESTING

		WEIGHTED			
Mode	Wt. Factor	Hp	HC (g/hr)	NOx (g/hr)	CO (g/hr)
MODE 1	0 06	12 10	23 52	32 27	1459
MODE 3	0 14	16 67	15.28	33 04	457
MODE 5	0.15	8.62	2 89	5.66	110
MODE 7	0 25	5 18	6 55	1 18	190
MODE 8	0 4	0 00	22 30	0 11	106
	Total	42 6	70 5	72 3	2323

	HC	NOx	CO
g/hp-hr	1 66	1 70	54.6
g/kW-hr	2.22	2 28	73 2

TABLE A-5. OPEN-LOOP EMISSIONS WITH EXHAUST GAS RECIRCULATION

Mode	Actual Time (s)	BSHC (g/hp-hr)	BSNOx (g/hp-hr)	BS HC+NOx (g/hp-hr)	BSCO (g/hp-hr)	BSCO2 (g/hp-hr)	BSFC (lb/hp-hr)	Power (hp)
1	120	3 12	3 65	6.77	156	537	0 550	198.5
2	121	3 75	3 81	7 56	151	514	0 530	153 1
3	181	1 54	5 82	7.37	20 8	667	0 490	113.7
4	180	2 51	4.77	7 28	27.4	633	0 475	83 4
5	180	2 97	2 58	5 55	24.2	675	0 502	56 1
6	180	3 30	1 83	5 13	33 7	740	0 559	34 8
7	180	3 10	0 96	4 06	38.8	988	0.736	19 8
8	180							0 0

Mode	HC (g/hr)	NOx (g/hr)	CO (g/hr)	CO2 (g/hr)	C-B Fuel (lb/hr)	Intake Humidity (gr/lb)	Background Humidity (gr/lb)	Sample Kw
1	618	725	30899	106505	109 2	74 2	72.3	0 87
2	574	583	23052	78729	81.2	74.5	73.5	0.87
3	176	662	2368	75914	55 8	74.6	74 1	0 88
4	209	398	2285	52738	39.6	74.6	74 7	0.88
5	167	145	1357	37822	28.1	74 6	74 5	0.88
6	115	63 7	1174	25782	19 5	75 4	75.7	0 88
7	61 2	19 1	766	19520	14 5	76 1	73 2	0 88
8	67 7	1	613	4159	3 7	77 5	74 8	0 88

Mode	Background Kw	Intake Kw	NOx Kh	NOx Wet S (ppm)	CO Wet S (%)	HC S (ppm)	CO2 Wet S (%)	CO2 Wet Intake (%)
1	0 98	0 98	1 00	699	4 88	1971	10.70	0 05
2	0.98	0.98	1.00	758	4.91	2469	10.68	0.05
3	0 98	0 98	1.00	1063	0 62	932	12 72	0 68
4	0.98	0 97	1.00	913	0 86	1590	12 64	0.99
5	0 98	0 97	1 00	464	0 71	1768	12 67	1 30
6	0 98	0.97	1.00	298	0.90	1789	12.64	1 19
7	0 98	0 97	1 01	118	0 78	1265	12 71	1 17
8	0 98	0 98	1.01	35	2 71	6031	11 68	0.06

Mode	CO2 Dry B (%)	CO2 Wet B (%)	Calculated A/F	EGR (%)	Speed (rpm)	Load (lb-ft)	Throttle (%)	HC Wet (ppm)
1	0 051	0 050	11 6	0.00	4606	226.3	100	1971
2	0 051	0 050	11 5	0 00	4143	194.1	35	2469
3	0.051	0 050	14 5	5 19	3682	162 3	32	932
4	0 051	0 050	14 2	8 05	3222	135 9	25	1590
5	0 051	0 050	14 3	10 95	2761	106 7	21	1768
6	0 051	0 050	14 1	9 92	2304	79 4	17	1789
7	0 051	0 050	14.2	9.71	1836	56.5	14	1265
8	0 051	0 050	12 5	0 00	575	0 0	0	6031

TABLE A-5 (CONT'D). OPEN-LOOP EMISSIONS WITH EXHAUST GAS RECIRCULATION

Mode	NOx Dry (ppm)	CO Dry (%)	CO2 Dry (%)	Intake Air Dewpoint (F)	Dilution Air Temp. (F)	Dilution Air RH (%)	Barom. (mm Hg)	Intake Air (F)
1	800	5 58	12.23	58 2	79	47 8	745 4	72.6
2	866	5 61	12.20	58 4	79	47 9	745 6	72 9
3	1210	0 71	14.47	58 4	79	48 2	744.9	72.8
4	1040	0 98	14 40	58 4	80	48 3	744.8	74.3
5	528	0 81	14 42	58 4	80	48 1	744 3	74 8
6	340	1 03	14 41	58.6	80	48 4	743 4	73 8
7	135	0 89	14 49	58 9	79	48 3	743.8	73 0
8	40	3 09	13 33	59 4	79	48 7	743 5	72 9
Mode	**Intake CO2 dry (%)**	**Manifold Vacuum ("Hg)**	**Fuel Flow (lb/hr)**	**Water Out (F)**	**Water In (F)**	**Oil (F)**	**Cyl 1 (F)**	**Cyl 2 (F)**
1	0 05	0 4	109 1	161	73	260	1199	1213
2	0.05	5 1	81.2	159	73	264	1156	1165
3	0 69	5 5	55 7	159	73	240	1191	1211
4	1.01	8 6	39 6	158	73	223	1087	1113
5	1.33	10 5	28 1	158	74	209	1037	1043
6	1 22	13.3	19.5	157	74	197	1000	1007
7	1.20	13 4	14 5	158	74	190	1013	1017
8	0.06	14 7	3 7	159	74	159	689	692
Mode	**Cyl 3 (F)**	**Cyl 4 (F)**	**Cyl 5 (F)**	**Cyl 6 (F)**	**Exh. Man. H2O Out Right (F)**	**Oxygen Dry (%)**	**Measured Air/Fuel Ratio**	
1	1203	1137	1230	1199	101	0 14	12.10	
2	1085	1070	1157	1129	98	0 17	12.10	
3	1340	1126	1207	1190	96	0.51	14.50	
4	1351	1030	1104	1100	91	0 53	14 40	
5	1340	969	1042	1026	89	0 60	14 40	
6	1758	933	983	972	87	0 46	14 30	
7	941	919	967	975	87	0.43	14 50	
8	603	600	497	663	85	0 63	13 40	

ISO E4 CYCLE OPEN-LOOP EMISSIONS WITH EXHAUST GAS RECIRCULATION

		ISO E4 WEIGHTED			
Mode	Wt. Factor	Hp	HC (g/hr)	NOx (g/hr)	CO (g/hr)
MODE 1	0 06	11 91	37 10	43.48	1854 0
MODE 3	0 14	15.92	24 57	92 71	331 5
MODE 5	0 15	8 41	24 97	21 68	203 5
MODE 7	0 25	4 94	15 31	4 77	191 6
MODE 8	0 4	0 00	27 06	0 52	245 4
	Total	41.2	129 0	163 2	2826 0

	HC	NOx	CO
g/hp-hr	3 13	3.96	68 6
g/kW-hr	4 20	5.31	92 0

TABLE A-6. HYDROCARBON SPECIATION RESULTS

ISO E4 MODE	BASELINE OPEN-LOOP ENGINE CONFIGURATION						CLOSED-LOOP ENGINE CONFIGURATION WITH CATALYSTS					
	1	2	3	4	5	Weighted Composite	1	3	3	4	5	Weighted Composite
Weight Factor	0 06	0 14	0 15	0 25	0 4	1 0	0 06	0 14	0 15	0 25	0 4	1 0
Emission Rate	mg/min											
METHANE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
ETHANE	121 3	73 3	49 6	23 1	25 1	40 78	114 7	51 8	13 1	11 5	19 8	26 89
ETHYLENE	997 4	468 7	272 9	137 7	140 3	256 94	620 5	91 2	9 4	24 8	69 3	85 35
PROPANE	5 8	2 6	2 5	1 2	1 6	2 05	6 5	2 1	0 5	0 6	1 7	1 62
PROPYLENE	641 6	254 2	166 3	76 0	74 4	147 79	0 0	0 0	0 0	0 0	0 0	0 00
ACETYLENE	548 6	250 3	121 7	80 9	223 0	195 64	35 3	33 3	4 0	2 1	9 3	11 60
PROPADIENE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
BUTANE	86 2	35 6	16 7	9 7	7 9	18 25	31 0	7 3	0 5	0 1	8 2	6 24
TRANS-2-BUTENE	33 0	14 9	10 4	4 0	4 4	8 41	30 6	8 6	0 8	0 7	2 8	4 47
1-BUTENE	37 6	23 2	13 7	4 8	6 3	11 28	25 1	8 6	0 8	0 6	3 2	4 26
2-METHYLPROPENE (ISOBUTYLENE)	393 5	153 9	116 4	50 3	47 5	94 20	272 1	64 4	6 7	8 1	22 4	37 33
2,2-DIMETHYLPROPANE (NEOPENTANE)	25 5	10 9	7 9	3 2	3 4	6 40	0 0	0 0	0 0	0 0	0 0	0 00
PROPYNE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
1,3-BUTADIENE	46 9	0 0	11 0	12 6	12 2	12 49	4 0	1 9	0 3	0 2	0 6	0 82
2-METHYLPROPANE (ISOBUTANE)	76 7	50 9	23 0	10 1	20 7	25 98	0 0	0 0	0 0	0 0	0 0	0 00
1-BUTYNE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
METHANOL	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
CIS-2-BUTENE	2 7	0 9	1 0	0 3	0 4	0 68	26 6	6 4	0 6	0 1	0 0	2 60
3-METHYL-1-BUTENE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
ETHANOL	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
2-METHYLBUTANE (ISOPENTANE)	207 9	104 3	99 7	32 6	64 2	75 86	272 7	87 2	17 6	18 1	90 1	71 76
2-BUTYNE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
1-PENTENE	4 2	2 3	1 3	0 4	0 5	1 06	0 0	0 0	0 0	0 0	0 2	0 08
2-METHYL-1-BUTENE	13 6	9 3	6 5	2 2	2 8	4 77	11 2	4 3	0 5	0 4	1 2	1 94
PENTANE	75 9	36 1	32 1	11 5	22 7	26 38	60 0	17 1	3 1	3 7	18 2	14 66
UNIDENTIFIED C5 OLEFINS	9 4	8 4	4 2	1 6	1 3	3 29	9 1	5 2	0 1	0 2	0 8	1 66
2-METHYL-1,3-BUTADIENE	6 3	1 0	1 5	3 8	2 7	2 75	24 4	7 5	0 7	0 3	1 3	3 19
TRANS-2-PENTENE	3 6	2 3	1 6	0 6	0 7	1 19	2 5	1 0	0 1	0 1	0 3	0 46
3,3-DIMETHYL-1-BUTENE	1 6	1 4	1 0	0 3	0 3	0 63	0 6	0 4	0 1	0 0	0 1	0 14
CIS-2-PENTENE	2 0	1 1	1 0	0 4	0 4	0 69	1 5	0 6	0 1	0 1	0 2	0 28
2-METHYL-2-BUTENE	18 7	4 1	9 5	4 2	4 2	5 82	23 2	7 8	0 9	0 7	2 6	3 87
TERT-BUTANOL	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00

TABLE A-6. HYDROCARBON SPECIATION RESULTS

ISO E4 MODE	BASELINE OPEN-LOOP ENGINE CONFIGURATION						CLOSED-LOOP ENGINE CONFIGURATION WITH CATALYSTS					
	1	2	3	4	5	Weighted Composite	1	3	3	4	5	Weighted Composite
Weight Factor	0 06	0 14	0 15	0 25	0 4	1 0	0 06	0 14	0 15	0 25	0 4	1 0
Emission Rate	mg/min											
CYCLOPENTADIENE	9 2	0 0	1 7	5 9	4 2	3 97	26 0	9 7	1 3	0 3	1 0	3 58
2,2-DIMETHYLBUTANE	7 4	3 1	3 0	1 3	1 9	2 42	7 1	2 4	0 5	0 5	2 1	1 79
CYCLOPENTENE	3 0	1 8	1 3	0 5	0 5	0 93	1 8	0 6	0 1	0 1	0 2	0 31
4-METHYL-1-PENTENE	1 2	0 9	0 6	0 2	0 2	0 44	1 0	0 5	0 2	0 1	0 1	0 21
3-METHYL-1-PENTENE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
CYCLOPENTANE	7 8	3 2	2 8	1 2	2 1	2 48	6 7	1 7	0 3	0 4	1 6	1 41
2,3-DIMETHYLBUTANE	22 5	12 5	11 7	3 9	7 3	8 74	18 5	6 1	1 4	1 4	6 7	5 23
MTBE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
4-METHYL-CIS-2-PENTENE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
2-METHYLPENTANE	30 4	15 1	14 0	4 8	8 9	10 82	28 5	8 4	1 6	1 9	8 7	7 06
4-METHYL-TRANS-2-PENTENE	2 5	0 0	0 6	0 3	0 3	0 43	0 0	0 0	0 0	0 0	0 0	0 00
3-METHYLPENTANE	16 2	8 1	7 3	2 6	4 6	5 69	16 5	5 1	1 0	1 1	5 1	4 16
2-METHYL-1-PENTENE	1 9	0 7	0 3	0 1	0 1	0 35	0 8	0 2	0 0	0 0	0 1	0 11
1-HEXENE	1 9	0 7	0 3	0 1	0 1	0 35	0 8	0 2	0 0	0 0	0 0	0 10
HEXANE	22 2	9 9	9 2	3 3	6 1	7 36	25 7	7 0	1 3	1 6	7 2	5 99
UNIDENTIFIED C6 OLEFINS	11 5	9 9	5 7	2 2	1 9	4 24	8 6	3 2	0 0	0 0	0 7	1 24
TRANS-3-HEXENE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
CIS-3-HEXENE	0 2	0 8	0 1	0 0	0 0	0 17	0 2	0 0	0 0	0 0	0 0	0 03
DI-ISOPROPYL ETHER	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
TRANS-2-HEXENE	0 7	0 6	0 2	0 1	0 1	0 23	0 5	0 2	0 0	0 0	0 1	0 08
3-METHYL-TRANS-2-PENTENE	1 1	0 0	0 7	0 3	0 3	0 36	1 0	0 4	0 1	0 0	0 2	0 20
2-METHYL-2-PENTENE	0 0	0 0	0 0	0 0	0 0	0 00	1 2	0 5	0 1	0 0	0 1	0 22
3-METHYLCYCLOPENTENE	0 0	0 0	0 0	0 0	0 0	0 00	0 3	0 1	0 0	0 0	0 0	0 04
CIS-2-HEXENE	0 3	0 0	0 1	0 0	0 0	0 05	0 1	0 0	0 0	0 0	0 0	0 02
ETBE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
3-METHYL-CIS-2-PENTENE	0 4	0 0	0 3	0 2	0 3	0 23	1 0	0 4	0 0	0 0	0 1	0 17
2,2-DIMETHYLPENTANE, NOTE A	9 6	7 4	7 0	2 6	2 4	4 29	11 9	3 1	0 5	0 7	2 9	2 56
METHYLCYCLOPENTANE, NOTE A	9 4	1 0	0 9	0 2	2 3	1 84	11 6	3 0	0 5	0 7	2 8	2 51
2,4-DIMETHYLPENTANE	16 5	8 3	7 4	2 9	4 8	5 89	16 4	5 1	1 0	1 1	4 8	4 04
2,2,3-TRIMETHYLBUTANE	2 1	1 6	0 9	0 4	0 5	0 79	3 0	1 6	0 3	0 1	0 5	0 68
3,4-DIMETHYL-1-PENTENE	0 6	0 0	0 4	0 1	0 0	0 12	0 7	0 1	0 0	0 0	0 1	0 08
1-METHYLCYCLOPENTENE	0 0	0 0	0 4	0 0	0 2	0 14	0 8	0 3	0 1	0 1	0 3	0 23
BENZENE	396 4	188 1	112 1	65 6	58 8	106 87	277 7	52 2	9 5	39 4	36 7	49 92

TABLE A-6. HYDROCARBON SPECIATION RESULTS

ISO E4 MODE	BASELINE OPEN-LOOP ENGINE CONFIGURATION						CLOSED-LOOP ENGINE CONFIGURATION WITH CATALYSTS					
	1	2	3	4	5	Weighted Composite	1	3	3	4	5	Weighted Composite
Weight Factor	0 06	0 14	0 15	0 25	0 4	1 0	0 06	0 14	0 15	0 25	0 4	1 0
Emission Rate	mg/min											
3-METHYL-1-HEXENE	0 4	0 0	0 2	0 0	0 0	0 05	0 0	0 0	0 0	0 0	0 0	0 00
3,3-DIMETHYLPENTANE	0 0	0 0	1 6	0 0	0 0	0 25	1 1	0 0	0 0	0 1	0 3	0 22
CYCLOHEXANE	13 7	5 3	5 4	1 9	3 2	4 14	13 6	3 5	0 7	0 8	3 5	2 99
2-METHYLHEXANE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
2,3-DIMETHYLPENTANE	16 1	7 9	7 5	2 5	4 5	5 62	10 2	5 5	1 2	1 4	6 2	4 37
1,1-DIMETHYLCYCLOPENTANE	1 0	0 4	0 4	0 1	0 2	0 30	1 3	0 3	0 0	0 1	0 2	0 24
TERT-AMYL METHYL ETHER	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
CYCLOHEXENE	1 6	1 1	0 8	0 2	0 3	0 54	1 1	0 4	0 1	0 1	0 1	0 20
3-METHYLHEXANE	4 9	2 2	2 1	0 7	1 3	1 61	8 0	2 2	0 5	0 5	2 4	1 94
CIS-1,3-DIMETHYLCYCLOPENTANE	1 5	0 5	0 5	0 2	0 4	0 43	1 7	0 4	0 1	0 1	0 4	0 34
3-ETHYLPENTANE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
TRANS-1,2-DIMETHYLCYCLOPENTANE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
TRANS-1,3-DIMETHYLCYCLOPENTANE	1 5	0 7	0 5	0 2	0 3	0 45	1 6	0 4	0 1	0 1	0 4	0 33
1-HEPTENE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
2,2,4-TRIMETHYLPENTANE	124 9	65 2	66 9	21 8	39 5	47 90	127 2	43 3	12 1	11 6	53 3	39 71
2-METHYL-1-HEXENE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
TRANS-3-HEPTENE	0 0	0 4	0 0	0 0	0 0	0 06	0 0	0 0	0 0	0 0	0 0	0 00
HEPTANE	6 4	2 6	2 5	0 9	1 8	2 08	8 8	2 1	0 4	0 5	2 3	1 94
CIS-3-HEPTENE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
UNIDENTIFIED C7	5 6	5 3	1 7	1 2	1 0	2 02	17 0	3 6	0 5	0 2	0 3	1 77
2-METHYL-2-HEXENE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
3-METHYL-TRANS-3-HEXENE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
TRANS-2-HEPTENE	0 3	0 2	0 1	0 0	0 0	0 08	0 3	0 0	0 0	0 0	0 0	0 03
3-ETHYL-CIS-2-PENTENE	0 1	0 0	0 1	0 0	0 0	0 04	0 0	0 0	0 0	0 0	0 0	0 00
2,4,4-TRIMETHYL-1-PENTENE	0 1	0 0	0 1	0 0	0 0	0 05	0 2	0 0	0 0	0 0	0 1	0 06
2,3-DIMETHYL-2-PENTENE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
CIS-2-HEPTENE	0 6	0 5	0 3	0 2	0 2	0 28	0 6	0 3	0 0	0 0	0 1	0 15
METHYLCYCLOHEXANE	15 0	5 3	5 2	1 9	3 6	4 33	11 3	2 5	0 5	0 6	2 8	2 36
CIS-1,2-DIMETHYLCYCLOPENTANE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
2,2-DIMETHYLHEXANE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
1,1,3-TRIMETHYLCYCLOPENTANE	1 0	0 3	0 3	0 2	0 2	0 27	0 5	0 2	0 0	0 0	0 1	0 12

TABLE A-6. HYDROCARBON SPECIATION RESULTS

ISO E4 MODE	BASELINE OPEN-LOOP ENGINE CONFIGURATION						CLOSED-LOOP ENGINE CONFIGURATION WITH CATALYSTS					
	1	2	3	4	5	Weighted Composite	1	3	3	4	5	Weighted Composite
Weight Factor	0 06	0 14	0 15	0 25	0 4	1 0	0 06	0 14	0 15	0 25	0 4	1 0
Emission Rate	mg/min											
2,4,4-TRIMETHYL-2-PENTENE	0 1	1 0	0 0	0 0	0 0	0 16	0 4	0 2	0 0	0 0	0 1	0 08
2,2,3-TRIMETHYLPENTANE	20 7	9 2	9 8	3 4	6 9	7 63	17 9	4 9	1 2	1 2	6 1	4 69
2,5-DIMETHYLHEXANE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
ETHYLCYCLOPENTANE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
2,4-DIMETHYLHEXANE	17 2	8 7	9 3	3 0	5 5	6 60	18 1	5 3	1 5	1 4	6 3	4 93
1-TRANS-2-CIS-4-TRIMETHYLCYCLOPENTANE	0 5	0 2	0 2	0 1	0 0	0 11	0 7	0 2	0 0	0 1	0 1	0 14
3,3-DIMETHYLHEXANE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
1-TRANS-2-CIS-3-TRIMETHYLCYCLOPENTANE	0 5	0 4	0 2	0 1	0 0	0 12	0 1	0 0	0 0	0 0	0 1	0 04
2,3,4-TRIMETHYLPENTANE	30 7	17 9	20 7	6 3	13 0	14 23	41 3	12 1	4 3	3 9	21 4	14 35
2,3,3-TRIMETHYLPENTANE	36 8	26 3	30 5	8 9	16 8	19 41	28 1	8 8	4 2	3 8	16 9	11 28
TOLUENE	820 0	272 8	280 6	131 1	111 3	206 76	830 1	195 7	31 8	25 4	102 0	129 14
2,3-DIMETHYLHEXANE	682 4	375 0	147 5	73 1	131 7	186 51	0 0	0 0	1 5	1 4	0 0	0 56
1,1,2-TRIMETHYLCYCLOPENTANE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
2-METHYLHEPTANE	0 0	0 0	0 0	0 3	0 0	0 08	0 0	0 0	0 0	0 0	0 0	0 00
3,4-DIMETHYLHEXANE, NOTE B	6 4	2 1	2 5	0 9	1 0	1 67	7 2	1 2	0 5	0 5	1 0	1 21
4-METHYLHEPTANE	9 4	3 6	3 1	0 7	0 9	2 06	8 8	1 6	0 3	0 5	0 8	1 24
3-METHYLHEPTANE	4 7	2 4	0 0	0 7	0 6	1 02	5 3	0 6	0 1	0 2	0 6	0 74
1-CIS,2-TRANS,3-TRIMETHYLCYCLOPENTANE	4 8	0 0	1 4	0 5	0 0	0 63	4 0	0 2	0 0	0 1	0 2	0 38
CIS-1,3-DIMETHYLCYCLOHEXANE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
TRANS-1,4-DIMETHYLCYCLOHEXANE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
3-ETHYLHEXANE	4 4	1 8	1 3	0 6	0 3	0 99	3 6	0 0	0 0	0 2	0 4	0 43
2,2,5-TRIMETHYLHEXANE	29 8	13 0	14 7	5 0	8 1	10 29	16 7	4 0	1 2	1 2	4 4	3 81
TRANS-1-METHYL-3-ETHYLCYCLOPENTANE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
CIS-1-METHYL-3-ETHYLCYCLOPENTANE	2 9	0 9	1 3	0 5	0 2	0 70	0 0	0 2	0 0	0 0	0 0	0 03
1,1-DIMETHYLCYCLOHEXANE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
TRANS-1-METHYL-2-ETHYLCYCLOPENTANE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00

TABLE A-6. HYDROCARBON SPECIATION RESULTS

ISO E4 MODE	BASELINE OPEN-LOOP ENGINE CONFIGURATION						CLOSED-LOOP ENGINE CONFIGURATION WITH CATALYSTS					
	1	2	3	4	5	Weighted Composite	1	3	3	4	5	Weighted Composite
Weight Factor	0 06	0 14	0 15	0 25	0 4	1 0	0 06	0 14	0 15	0 25	0 4	1 0
Emission Rate	mg/min											
1-METHYL-1-ETHYL-CYCLOPENTANE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
2,4,4-TRIMETHYLHEXANE	2 1	0 0	0 6	0 3	0 1	0 32	0 0	0 0	0 0	0 0	0 0	0 00
2,2,4-TRIMETHYLHEXANE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
TRANS-1,2-DIMETHYLCYCLOHEXANE	3 0	0 6	0 8	0 5	0 7	0 77	2 0	0 1	0 0	0 0	0 2	0 22
1-OCTENE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
TRANS-4-OCTENE	0 0	1 6	0 9	0 3	0 3	0 57	3 4	0 0	0 0	0 0	0 2	0 30
OCTANE	4 3	1 1	1 6	0 7	0 2	0 88	3 8	0 5	0 1	0 1	0 6	0 57
UNIDENTIFIED C8	8 1	3 9	1 4	0 9	0 9	1 83	0 0	0 0	0 0	0 0	0 4	0 15
TRANS-2-OCTENE	2 2	0 4	0 7	0 3	0 2	0 45	1 0	0 1	0 0	0 0	0 0	0 08
TRANS-1,3-DIMETHYLCYCLOHEXANE, NOTE C	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
CIS-2-OCTENE	1 6	0 0	0 4	0 3	0 0	0 23	2 7	0 1	0 1	0 0	0 2	0 26
ISOPROPYLCYCLOPENTANE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
2,2-DIMETHYLHEPTANE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
2,3,5-TRIMETHYLHEXANE	5 1	1 9	2 1	0 8	0 1	1 12	3 1	0 6	0 2	0 1	0 6	0 58
CIS-1-METHYL-2-ETHYLCYCLOPENTANE	0 9	0 0	0 2	0 2	0 2	0 22	0 0	0 0	0 0	0 0	0 0	0 00
2,4-DIMETHYLHEPTANE	2 4	0 4	0 8	0 3	0 0	0 42	1 5	0 1	0 0	0 0	0 1	0 16
4,4-DIMETHYLHEPTANE	0 9	0 0	0 1	0 1	0 3	0 24	0 3	0 0	0 0	0 0	0 0	0 03
CIS-1,2-DIMETHYLCYCLOHEXANE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
ETHYLCYCLOHEXANE	2 1	0 5	0 3	0 2	0 6	0 53	0 5	0 0	0 0	0 0	0 0	0 03
2,6-DIMETHYLHEPTANE, NOTE D	3 1	0 6	0 8	0 4	0 1	0 54	0 9	0 1	0 0	0 0	0 2	0 14
1,1,3-TRIMETHYLCYCLOHEXANE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
2,5-DIMETHYLHEPTANE, NOTE E	3 5	1 2	1 1	0 6	0 0	0 70	1 1	0 3	0 1	0 1	0 3	0 24
3,3-DIMETHYLHEPTANE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
3,5-DIMETHYLHEPTANE, NOTE E	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
ETHYLBENZENE	78 9	39 8	26 3	12 6	13 4	22 74	56 9	18 0	2 7	1 7	7 8	9 88
2,3,4-TRIMETHYLHEXANE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
2,3-DIMETHYLHEPTANE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
m-& p-XYLENE	234 7	54 3	39 2	25 8	17 4	40 99	147 2	24 2	3 4	2 7	8 5	16 82
4-METHYLOCTANE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
3,4-DIMETHYLHEPTANE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00

TABLE A-6. HYDROCARBON SPECIATION RESULTS

ISO E4 MODE	BASELINE OPEN-LOOP ENGINE CONFIGURATION						CLOSED-LOOP ENGINE CONFIGURATION WITH CATALYSTS					
	1	2	3	4	5	Weighted Composite	1	3	3	4	5	Weighted Composite
Weight Factor	0 06	0 14	0 15	0 25	0 4	1 0	0 06	0 14	0 15	0 25	0 4	1 0
Emission Rate	mg/min											
4-ETHYLHEPTANE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
2-METHYLOCTANE	7 2	0 0	1 0	0 4	0 4	0 84	3 5	0 3	0 0	0 0	0 3	0 35
3-METHYLOCTANE	3 0	0 4	0 3	0 3	0 2	0 44	1 1	0 0	0 0	0 0	0 1	0 11
STYRENE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
o-XYLENE	76 0	20 1	15 5	8 7	7 0	14 67	54 4	9 4	1 6	1 2	4 2	6 82
1-NONENE	10 2	2 1	1 9	1 2	1 0	1 89	2 3	0 7	0 2	0 1	0 6	0 52
TRANS-3-NONENE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
CIS-3-NONENE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
NONANE	7 3	1 2	1 4	0 7	0 7	1 30	2 5	0 5	0 2	0 1	0 5	0 47
TRANS-2-NONENE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
ISOPROPYLBENZENE (CUMENE)	8 0	1 9	1 4	0 9	0 7	1 43	3 2	0 7	0 1	0 0	0 0	0 33
2,2-DIMETHYLOCTANE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
2,4-DIMETHYLOCTANE	17 1	14 1	7 0	3 4	1 2	5 39	25 4	12 1	1 5	0 3	0 8	3 82
n-PROPYLBENZENE	30 5	12 9	11 9	4 1	5 8	8 77	30 9	6 9	1 5	0 6	2 5	4 18
1-METHYL-3-ETHYLBENZENE	156 8	60 3	50 4	19 3	24 8	40 16	160 2	35 5	6 7	3 1	12 0	21 19
1-METHYL-4-ETHYLBENZENE	67 1	26 1	22 0	8 6	11 0	17 54	71 0	15 6	2 9	1 3	5 1	9 25
1,3,5-TRIMETHYLBENZENE	115 0	34 0	27 5	12 7	13 2	24 22	112 2	22 0	3 9	1 8	7 3	13 76
1-METHYL-2-ETHYLBENZENE	14 2	5 5	4 8	2 0	10 1	6 87	64 1	14 4	2 5	1 2	4 7	8 40
1,2,4-TRIMETHYLBENZENE	360 6	102 8	90 5	42 0	43 3	77 41	379 4	76 1	13 7	5 9	22 9	46 08
TERT-BUTYLBENZENE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
1-DECENE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
DECANE, NOTE F	2 9	1 0	1 2	0 4	0 4	0 73	2 2	0 4	0 1	0 0	0 2	0 27
ISOBUTYLBENZENE, NOTE F	2 8	0 9	1 1	0 4	0 3	0 69	2 0	0 4	0 1	0 0	0 1	0 25
1,3,-DIMETHYL-5-ETHYLBENZENE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
METHYLPROPYLBENZENE (sec butylbenzene)	4 3	1 4	1 7	0 6	0 0	0 86	0 0	0 0	0 0	0 0	0 0	0 00
1-METHYL-3-ISOPROPYLBENZENE	0 0	0 0	0 1	0 0	6 7	2 69	70 0	13 6	2 5	1 1	4 0	8 36
1,2,3-TRIMETHYLBENZENE	57 3	18 6	15 0	6 4	0 3	10 03	2 2	0 4	0 0	0 0	0 1	0 25
1-METHYL-4-ISOPROPYLBENZENE	2 4	0 4	0 8	0 3	0 2	0 49	1 7	0 2	0 1	0 0	0 2	0 23
INDAN	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
1-METHYL-2-ISOPROPYLBENZENE	6 8	2 8	2 7	0 9	3 3	2 76	29 2	6 8	1 0	0 3	0 4	3 09
1,3-DIETHYLBENZENE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
1,4-DIETHYLBENZENE	2 9	2 4	1 1	0 4	1 4	1 30	12 5	2 8	0 4	0 1	0 7	1 53

TABLE A-6. HYDROCARBON SPECIATION RESULTS

ISO E4 MODE	BASELINE OPEN-LOOP ENGINE CONFIGURATION						CLOSED-LOOP ENGINE CONFIGURATION WITH CATALYSTS					
	1	2	3	4	5	Weighted Composite	1	3	3	4	5	Weighted Composite
Weight Factor	0 06	0 14	0 15	0 25	0 4	1 0	0 06	0 14	0 15	0 25	0 4	1 0
Emission Rate	mg/min											
1-METHYL-3-N-PROPYLBENZENE	16 7	4 8	6 2	1 9	0 9	3 44	8 9	1 5	1 4	0 5	0 6	1 32
1-METHYL-4-N-PROPYLBENZENE, NOTE G	20 5	10 4	6 0	2 8	0 1	4 33	1 1	0 2	0 0	0 0	0 0	0 11
1,2 DIETHYLBENZENE	1 0	0 2	0 3	0 1	0 1	0 23	1 1	0 1	0 2	0 0	0 1	0 14
1-METHYL-2-N-PROPYLBENZENE	4 4	2 8	1 3	0 5	1 0	1 37	16 5	1 8	0 0	0 0	0 0	1 24
1,4-DIMETHYL-2-ETHYLBENZENE	9 3	6 7	3 0	1 6	0 5	2 55	12 3	3 2	0 5	0 2	0 8	1 63
1,3-DIMETHYL-4-ETHYLBENZENE	2 0	4 7	0 9	0 7	1 6	1 71	5 0	1 6	0 2	0 0	0 2	0 64
1,2-DIMETHYL-4-ETHYLBENZENE	12 4	5 6	3 6	1 7	1 5	3 11	16 5	3 7	0 6	0 2	0 9	2 03
1,3-DIMETHYL-2-ETHYLBENZENE	3 9	2 6	0 6	0 4	0 4	0 94	2 9	1 1	0 2	0 0	0 0	0 36
UNDECANE	2 5	1 2	0 3	0 2	0 2	0 51	3 7	0 3	0 1	0 0	0 1	0 33
1,2-DIMETHYL-3-ETHYLBENZENE	0 0	0 0	0 5	0 0	0 0	0 08	2 6	0 0	0 0	0 0	0 0	0 17
1,2,4,5-TETRAMETHYLBENZENE	2 6	0 5	0 7	0 6	0 3	0 59	7 4	1 4	0 1	0 0	0 3	0 77
2-METHYLBUTYLBENZENE (sec AMYLBENZENE)	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
3,4 DIMETHYLCUMENE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
1,2,3,5-TETRAMETHYLBENZENE	0 0	0 0	0 1	0 0	0 0	0 03	0 7	0 0	0 0	0 0	0 0	0 06
TERT-1-BUT-2-METHYLBENZENE	1 5	0 8	0 5	0 2	0 2	0 40	0 5	0 4	0 0	0 0	0 1	0 14
1,2,3,4-TETRAMETHYLBENZENE	0 0	0 0	0 0	0 0	0 0	0 00	2 5	0 3	0 0	0 0	0 0	0 19
N-PENT-BENZENE	3 1	1 7	0 2	0 1	0 1	0 52	3 1	0 0	0 0	0 0	0 1	0 21
TERT-1-BUT-3,5-DIMETHYLBENZENE	0 0	0 0	0 0	0 0	0 0	0 00	53 6	9 3	0 5	0 0	2 9	5 74
TERT-1-BUTYL-4-ETHYLBENZENE	21 8	10 1	4 4	3 8	1 2	4 83	0 0	0 0	0 0	0 0	0 0	0 00
NAPHTHALENE	0 0	0 2	0 1	0 1	0 0	0 07	0 9	0 0	0 0	0 0	0 0	0 06
DODECANE	0 3	0 2	0 1	0 1	0 0	0 11	1 4	0 1	0 0	0 0	0 0	0 12
1,3,5-TRIETHYLBENZENE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
1,2,4-TRIETHYLBENZENE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
HEXYLBENZENE	0 0	0 0	0 0	0 0	0 0	0 00	0 0	0 0	0 0	0 0	0 0	0 00
UNIDENTIFIED C9-C12+	279 0	57 6	86 2	50 2	38 8	65 83	332 2	69 5	10 0	4 6	23 6	41 75
FORMALDEHYDE	396 0	104 4	48 4	26 5	14 3	57 97	15 1	11 2	0 8	0 1	0 6	2 86
ACETALDEHYDE	29 0	23 6	12 7	3 5	2 8	8 96	11 0	4 7	0 5	0 2	0 4	1 61
ACROLEIN	13 5	14 1	5 7	1 5	1 9	4 79	5 0	2 0	0 2	0 0	0 2	0 69
ACETONE	4 1	6 7	5 9	1 7	0 5	2 71	4 3	2 3	0 4	0 4	0 2	0 81

TABLE A-6. HYDROCARBON SPECIATION RESULTS

ISO E4 MODE	BASELINE OPEN-LOOP ENGINE CONFIGURATION						CLOSED-LOOP ENGINE CONFIGURATION WITH CATALYSTS					
	1	2	3	4	5	Weighted Composite	1	3	3	4	5	Weighted Composite
Weight Factor	0 06	0 14	0 15	0 25	0 4	1 0	0 06	0 14	0 15	0 25	0 4	1 0
Emission Rate	mg/min											
PROPIONALDEHYDE	8 2	7 1	3 7	0 9	0 8	2 59	1 5	0 7	0 1	0 0	0 1	0 22
CROTONALDEHYDE	5 3	6 1	3 0	0 8	0 6	2 08	1 3	1 1	0 2	0 0	0 0	0 28
ISOBUTYRALDEHYDE, NOTE H	1 6	1 1	0 6	0 3	0 2	0 49	0 8	0 5	0 1	0 0	0 0	0 14
METHYL ETHYL KETONE, NOTE H	1 6	1 1	0 6	0 3	0 2	0 49	0 8	0 5	0 1	0 0	0 0	0 14
BENZALDEHYDE	94 1	48 3	23 4	7 0	5 0	19 68	25 6	12 5	1 9	0 3	1 0	4 04
ISOVALERALDEHYDE	1 8	1 1	0 6	0 2	0 1	0 46	0 2	0 0	0 0	0 0	0 0	0 02
VALERALDEHYDE	0 7	0 3	0 5	0 1	0 1	0 24	0 2	0 0	0 0	0 0	0 0	0 03
O-TOLUALDEHYDE	7 5	3 8	1 5	0 5	0 4	1 51	0 5	0 3	0 0	0 0	0 0	0 08
M/P-TOLUALDEHYDE	32 8	14 7	7 4	2 6	1 9	6 57	3 7	1 4	0 2	0 0	0 1	0 48
HEXANALDEHYDE	0 0	0 1	0 1	0 0	0 0	0 03	0 0	0 0	0 0	0 0	0 0	0 00
DIMETHYLBENZALDEHYDE	20 1	8 9	5 0	1 4	1 1	3 96	2 0	0 9	0 1	0 0	0 0	0 29
SUM OF ALL SPECIATED COMPONENTS, mg/min	8104	3383	2351	1108	1371	2138	5026	1214	206	206	686	828
POWER, kW	152 9	87 1	43 5	15 3	0 0	31 7	153 5	88 2	42 2	16 6	0 0	32 1
BRAKE-SPECIFIC EMISSIONS, mg/kw-hr	3181	2332	3245	4348	NA	4046	1964	826	293	743	NA	1550