ATTACHMENT C

ENGINE TESTING PROGRAM

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1. Summary of Emissions Tests

ARB staff has gathered E4 emission data from the U.S. EPA (who performed in-house tests) and Mercury Marine. The data are shown below in Table C-1. "BSO" calibration refers to the "*Bodensee Schiffahrts Ordnung*," the Swiss boat engine emission requirements. "Base" calibration refers to the factory air-fuel ratio programming or setting.

The table shows that carbureted uncontrolled (new) engines have emissions of about 8 g/kW-hr HC and 6 g/kW-hr NOx, and rich-calibration (open-loop) EFI engines have emissions of about 5 g/kW-hr HC and 10 g/kW-hr NOx. Since about 1997, the engine makers have been phasing out production of non-EFI engines. The population of existing inboard gasoline engines is largely composed of carbureted engines now. It is expected that all new marine engines will be electronic multi-point fuel-injected by 2005.

The manufacturers have been leaning the mixture of their engines in response to the European standards which take effect in 2002. They have indicated that they plan to sell these leaned engines in the United States even though they are not yet required to meet any emission levels. The average of the emission results for these engines is 3.5 g/kW-hr HC and 13.0 g/kW-hr NOx. The population this was based on was not extensive, and the calibrations were not optimized.

2. Engine Test Program

ARB and U.S. EPA have been testing a catalyst-controlled, oxygen-feedback electronically fuel-controlled marine engine. GM Powertrain and Mercury Marine each donated 454-CID V-8 engines, and Southwest Research Institute installed, optimized, and evaluated the performance of the various control schemes over a wide-range of test conditions as well as the E-4 recreational marine test cycle. Engelhard and DCL International have developed and donated candidate catalysts.

Table C-1

Baseline Engines Summary of E4 Emission-test Results

Engine CID[1]	Power hp	Fuel sys[3]	Calibra-tion[4]	HC g/kW-hr	NOx g/kW-hr	CO g/kW-hr
L-4 181	106	Carb	Base	11.3	8.1	282
NK[2]	115	Carb		5.8	4.8	207
NK	120	Carb		8.6	4.3	200
NK	150	Carb		6.2	5.5	208
302	162	Carb	Base	8.5	6.0	247
L-4 230	165	Carb	Base	15.4	6.8	184
NK	200	Carb		5.8	6.7	208
350	220	Carb	Base	4.7	4.2	262
350	224	Carb	Base	8.1	5.8	173
351	212	Carb	Base	7.2	6.0	229
351	263	Carb	Base	4.4	10.3	101
454	282	Carb	Base	4.6	12.2	131
351	248	EFI	Base	5.2	9.7	149
454	280	MPI		4.4	8.5	170
454	294	MPI		4.7	9.4	160
V-6 262	213	TBI	BSO	3.0	8.7	42
351	243	EFI	BSOa	5.8	11.7	48
351	256	EFI	BSOb	3.4	18.2	72
454	307	MPI	BSO	2.7	13.4	44
460	307	MPI	BSO	2.7	13.1	44

[1]CID means cubic inches displacement. The engines are V-8 configuration unless otherwise marked.
[2]NK means not known
[3]The abbreviations and acronyms are as follows
Carb means carbureted
EFI means electronic fuel injection, not otherwise specified
MPI mean multi-port fuel injection
TBI means throttle-body fuel injection
[4]Calibration refers to air-fuel mixture program for the engine.
Blank means factory calibration
Base means factory calibration
BSO means calibrated lean according the Swiss Bodensee standards
BSOa means 1st attempt at BSO lean calibration
BSOb means alternative attempt at BSO lean calibration

Following are the data on the engine used in the testing. A big-block 454 cubic-inch displacement engine was chosen becauseit is supplied from the factory with electronically controlled fuel-injection. The engine control module was ready to receive exhaust gas recirculation and oxygen feedback signals. The small-block 350 cubic-inch displacement V-8 is the most common engine as far as sales, but is not offered with this capability at this time. Some data on the test engine are shown in Table C-2.

Table C-2

Test Engine Description

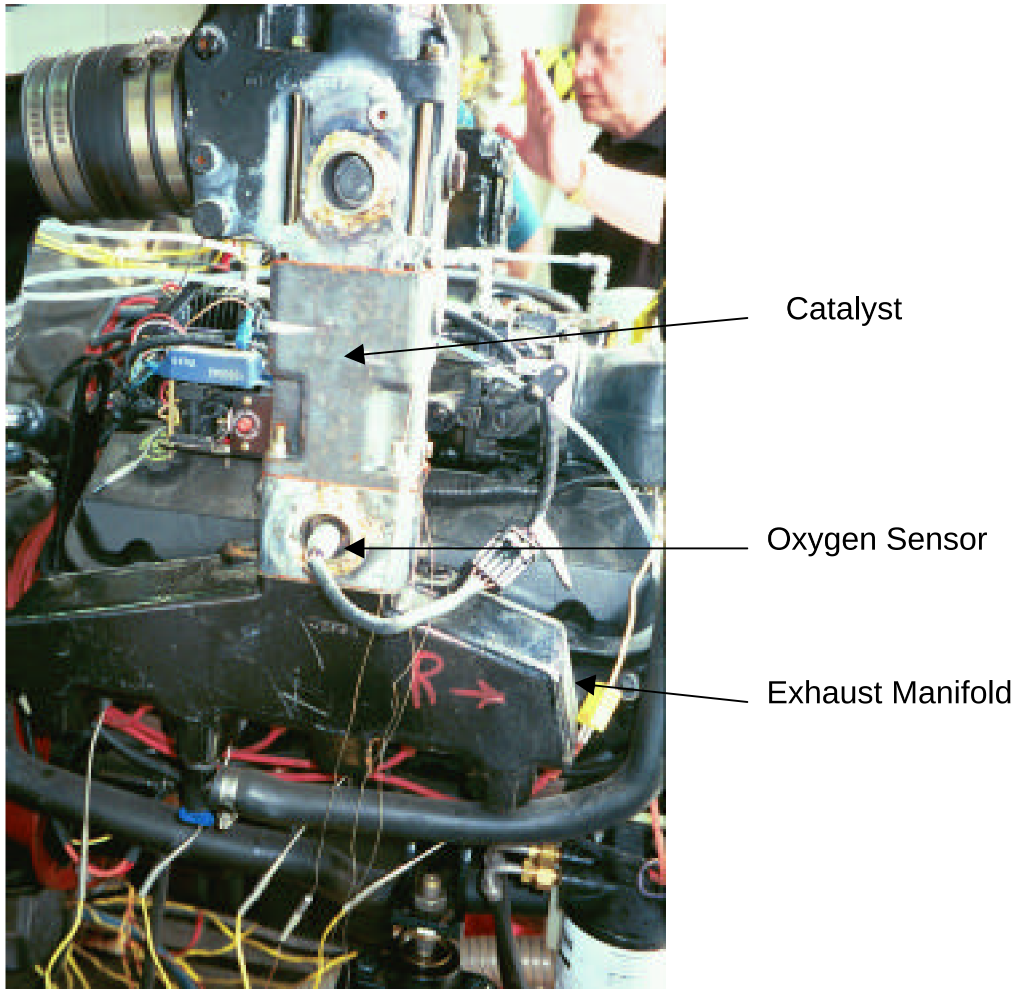
Engine Model	Mercury 7.4-liter MPI
Engine Supplier	General Motors (Marine Std)
Displacement	454 cubic inches
Power rating	310 hp at 4600 rpm
Exhaust Back pressure at 4600 rpm WOT	10 inches Hg (294 hp)
Material, valves	Cast-iron, overhead valve, push-rod operated, roller followers
Fuel System	Electronic multi-point fuel-injection
Cooling	Raw water jacket cooling, raw water exhaust manifold cooling. Engine jacket cooling modified later to be closed anti-freeze with water-to-water radiator.

Note: WOT is wide-open throttle.

SwRI outfitted the original factory engine with exhaust gas recirculation, oxygen-feedback air-fuel control, and exhaust catalysts. The exhaust gas recirculation modification consisted of an original factory (General Motors) exhaust gas recirculation valve to admit exhaust gases into the air intake manifold, a moisture knock-out drum, a small exhaust pipe from the exhaust manifold to the intake manifold, and an electrical connection to actuate and control the unit. The exhaust gas recirculation valve was linear in operation (gas flow is approximately linear with applied voltage or pulse-width), and fed its position back to the engine control module for fine-tuning and diagnostics.

The engine was outfitted with oxygen feedback air-fuel control. This included original factory General Motors parts: oxygen sensor and connection or wiring harness. The engine control module was programmed to accept these signals. The oxygen sensor was first installed near the dry exhaust gas sampling point, at the top of the exhaust elbow, about 3 to 6 inches upstream from the water-exhaust gas mixing point. But the oxygen sensors would be prone to shorting out or thermally cracking on exposure to inadvertent water contact at this location. So the oxygen sensor was moved another 6 to 12 inches upstream, near to the exhaust manifold joint to the riser (see figure C-1). In this position it has performed properly in over 100 hours of testing.

Figure C-1
View of Marine Engine Exhaust Manifold with Catalyst and Oxygen Sensor Visible



The engine was fitted with a succession of three-way catalysts. Three different catalyst substrates were installed in a stock Mercury Marine exhaust riser extension which has a rectangular cross-sectional flow area (see Figure C-2). This cast-iron water-jacketed piece is made to be placed in the exhaust pipe between the manifold and the elbow to raise the elbow above the water-line of the boat. Both Engelhard and DCL International supplied cut-to-fit 2” x 2” x 6” rectangular catalyst elements to fit in these risers. Specifications for these catalysts are listed in Table C-3. Substrates with varying densities were evaluated, including 400 cells-per-square-inch (cpsi), 200 cpsi, and 60 cpsi. The 400-cpsi catalyst had very high resistance-to-flow; consequently the engine was not run close to full-speed WOT with the catalysts. The 200 cpsi riser catalysts offered less resistance, but this still resulted in an unacceptably high power decrease (from 280 hp base-configuration down to less than 230 hp). The 200 cpsi substrates are the coarsest ones available for automobile service. However, 60 cpsi substrates were obtained through DCL International of Toronto, Ontario, in order to test a compact low-resistance candidate. These substrates are typically only used on two-stroke motorcycles in Asia.

Figure C-2
Riser Catalysts Installed in Factory Cast-iron Jacketed Exhaust Riser

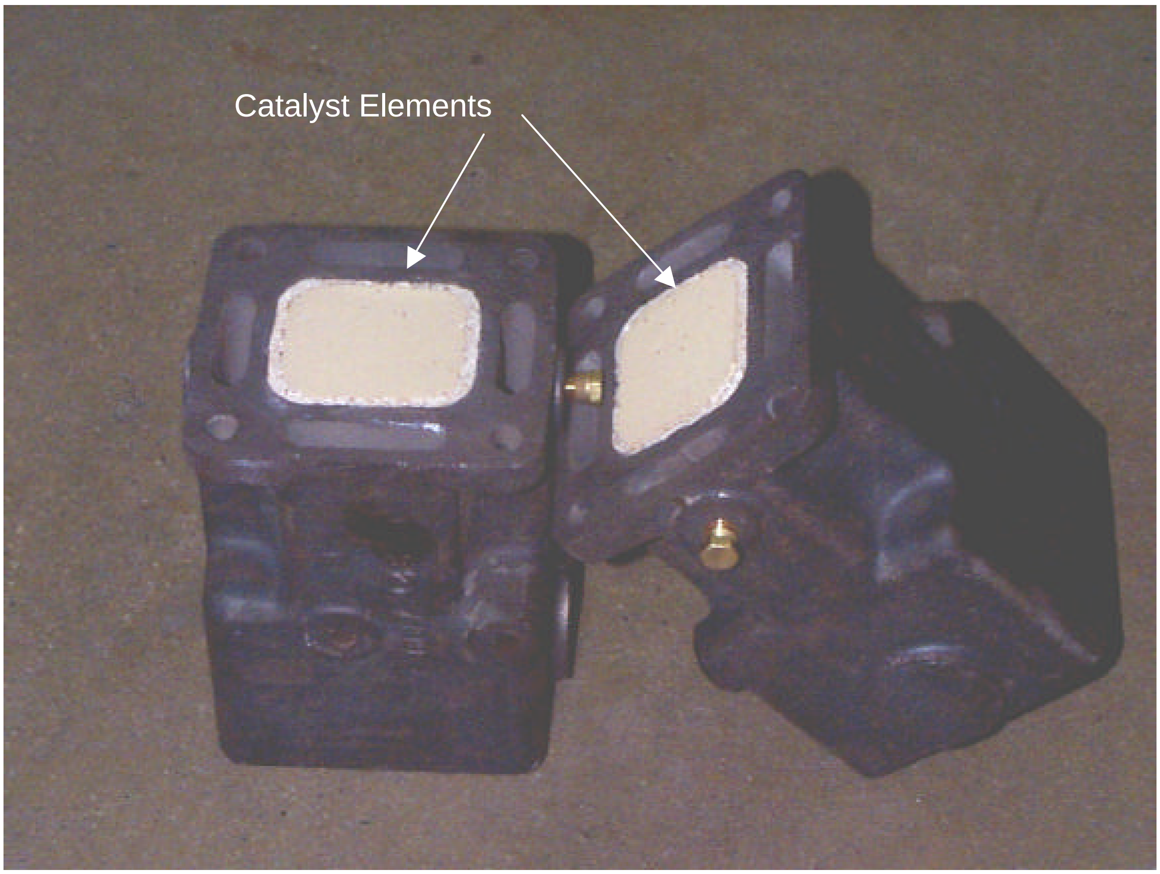


Table C-3 200 cpsi Compact Riser Catalyst Description	
Manufacturer	Engelhard Corporation
Volume	25 cubic inches (0.4 liters)
Number	2 required (left and right)
Substrate Density	200 cells per square inch. Ceramic. 8 mil wall thickness
Dimensions	2.25" x 1.88" x 6" long. Rectangular
Flow resistance at WOT, 4600 rpm	12 inches of mercury (catalyst only)
Cooling	Fully water-jacketed. (Installed in factory cast-iron exhaust riser).
Connections	Cast flange

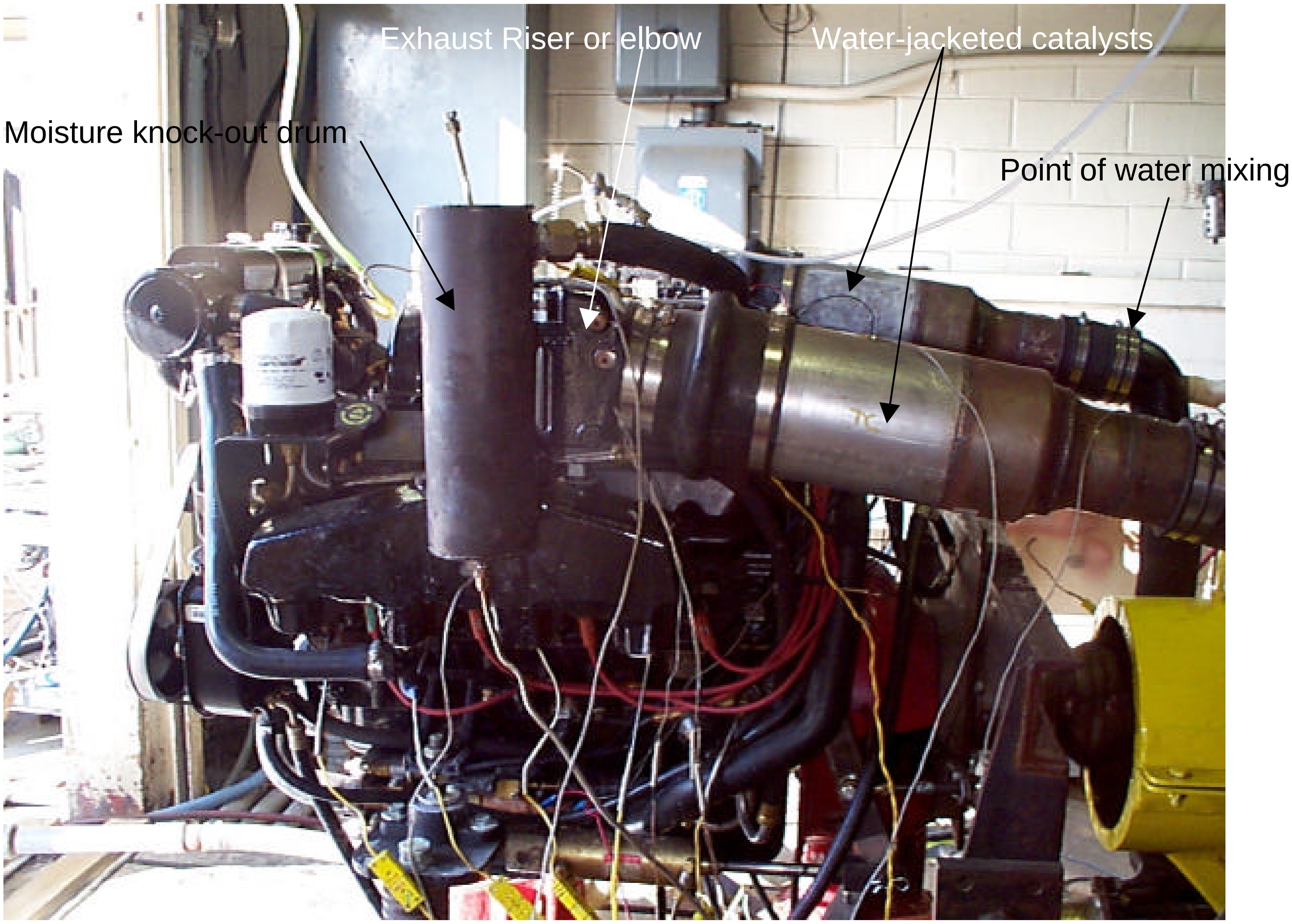
Note: cpsi is cells per square inch. WOT is wide-open throttle

An automotive-size cylindrical catalyst from Engelhard was also installed on the down-leg of the exhaust elbow, where there is more room (see Figure C-3). Specifications for this catalyst are listed in Table C-4. For a proper installation the point of injection of raw cooling water into the exhaust gases had to be moved downstream, past the catalyst. So the catalyst is quite near the water injection point. The advantage of this position, however, is that an element with a larger cross-sectional flow area may be used, which would offer lower resistance-to-flow.

Table C-4 Full-size Catalyst Description	
Manufacturer	Engelhard
Volume	102 cubic inches (1.7 liters)
Number	2 required (left and right)
Substrate Density	200 cell per square inch. Ceramic. 8 mil wall thickness
Dimensions	4.66" diameter by 3" long, 2 bricks in series. Cylindrical
Flow resistance at WOT, 4600 rpm	2 to 2.4 inches of mercury (catalyst only)
Cooling	Fully water-jacketed
Connections	Hose-clamped, butted

Note: WOT means wide-open throttle

Figure C-3
External Cylindrical Catalysts Installed on Engine



Six-inch-long catalysts were also installed in the riser position between the exhaust manifold and the exhaust elbow. They were cylindrical with a larger cross-sectional flow area than the factory riser extensions, to minimize resistance-to-flow and engine power loss (compare Figure C-4 below with Figure C-2). DCL International fabricated cylindrical catalysts for this position which allow for the maximum cross-sectional area that would clear the mounting bolts on the flanges (about 3-3/8" diameter, increased from 2" x 2" square). DCL provided a 300-cpsi candidate and a 60-cpsi candidate. Figure C-4 shows the cylindrical riser catalysts with the water-jacket installed. Table C-5 lists the specifications for the cylindrical riser catalysts.

Figure C-4
Cylindrical Riser Cat (Water-jacketed)

Table C-5 **Cylindrical Compact Riser Catalyst Description**	
Manufacturer	DCL International, Toronto
Volume	47 cubic inches (0.77 liters)
Number	2 required (left and right)
Substrate Density	300 cells per square inch. Ceramic. 10.5 mil wall thickness
Dimensions	3.38” diameter x 5.25” long. Cylindrical
Flow resistance at WOT, 4600 rpm	3.5 inches of mercury (catalyst only)
Cooling	Water-jacketed
Connections	Flanged

Note: WOT means wide-open throttle

3. Test Cycle

The engine was tested on a laboratory test stand using the International Organization for Standardization Standard ISO 8178-4 E4* (recreational marine gasoline) test-cycle. To simulate operation in a boat, the engine cooling system was connected to a raw water supply, and cooling water was injected into the exhaust manifolds downstream of the exhaust elbows.

The steady-state test points are specified as a function of the manufacturer's rated speed and the full-speed maximum torque. The torque percentages fall as a function of speed to the 1.5-power, mimicking the performance of a propeller in the water. The cycle is described in Table C-6 below. The five columns on the right are the mapped speed and power conditions for a General Motors 454 cubic-inch displacement engine during the E4 test. Also shown are the weighted contributions of power and fuel flow in each of the modes, to display the importance of the individual modes. For the E4 test cycle, mode 2 is the most important mode as far as fuel usage and power, and mode 1 is close behind in importance. Those two represent half the fuel usage. The idle mode, mode 5, in spite of its high weighting factor, only represents 5% of the fuel used over the cycle (0.25 gal/hr out of 5.55 gal/hr).

Table C-6

E4 Test Cycle

Stated Requirements				Calculated values for 7.4-liter engine example				
Mode No.	Percent Speed	Percent Torque	Weight factor	Speed rpm	Power hp	Weighted power, hp	Fuel flow gal/hr	Weighted fuel flow, gal/hr
1	100	100	0.06	4600	280	17	26.8	1.61
2	80	71.6	0.14	3680	162	23	13.5	1.89
3	60	46.5	0.15	2760	78	12	7.1	1.06
4	40	25.3	0.25	1840	28	7	3.0	0.75
5	Idle	--	0.40	590	0	0	0.6	0.25
						58		5.55

The importance of this comparison of the modes on the basis of weighted power or weighted fuel usage is that it is expected that the absolute emission rates (grams per hour) will be approximately proportional to the absolute fuel rates,

* International Standard ISO 8178-4. Reciprocating Internal Combustion Engines. Exhaust Emissions Measurement. Part 4: Test Cycles for Different Engine Applications. Test cycle E4—Spark-ignited pleasure-craft less than 24 m length. International Organization for Standardization. Geneva, Switzerland. The same test cycle, was adopted by U.S. EPA for marine outboard engines at 40 CFR 91.410(a), Subpart E Appendix Table 2. It was developed by the International Committee of Marine Industry Organizations (ICOMIA) and is also known by that name. (ICOMIA Standard 36, 1988)

thus the contribution to the composite results (weight factor times grams per hour divided by test-weighted power—the 58 hp in the bottom line of the table, 21% of the mode 1 rated power) will be approximately proportional to the contribution to weighted fuel rates.

Typically, the marine versions of automobile engines are rated for higher speeds than the automotive versions, and, at least in the case of the engine used in our testing, at a speed which is beyond the maximum power point of the engine and far beyond the maximum torque point. The full-speed points are rating points of marine engines, and the engines are expected to be able to operate there for many hours at a time. These engines are highly fuel-enriched at this condition, to keep cylinder temperatures low. This practice results in less efficient fuel usage and in greater carbon monoxide production than the optimum fuel-air condition. In automotive service, the engines rarely see wide-open throttle operation like this. Thus the automotive engines perform in marine service in conditions which they were not originally intended, and have to compensate at full load for this deficiency.

4. Results and Conclusions

Various combinations of stoichiometric air-fuel control were tested (performed with exhaust oxygen sensing, and feedback to the electronic engine control module), exhaust gas recirculation, and three-way exhaust catalysts. Below in Table C-7 is a summary of the results to date.

With the twin 1.7-liter catalysts installed on the engine with oxygen-feedback stoichiometric air-fuel control, a composite emission rate of 3.2 g/kW-hr of HC+NOx was achieved. This is compared to the baseline engine emission rate of 12.9 g/kW-hr HC+NOx. Adding exhaust gas recirculation to the catalyst-controlled engine, 2.6 g/kW-hr HC+NOx was achieved. The compact cylindrical 0.8-liter catalysts were tested in the exhaust manifold riser position, well upstream of the water mixing point. With these smaller catalyst units we achieved 3.6 g/kW-hr HC+NOx results, with a power degradation of 6 kW (from baseline power of 219 kW). Very compact (0.4-liter) catalysts stuffed in a stock riser extension were also tried. The results were 4.5 g/kW-hr HC+NOx without EGR, but the engine power was reduced to 172 kW (from 209 kW originally).

The conclusion is that regardless of the catalyst-system design, a catalyst near the exhaust-water mixing point, or a catalyst well upstream of the exhaust-water mixing point, the emission test results were below the proposed standard of 5 g/kW-hr. The compact-design catalyst resulted in a maximum-power decrease of the engine of 6 kW (about 3 percent). Exhaust gas recirculation improved the results for nitrogen oxides, but results without it also met the standards.

Table C-7
Emission Test Results
E4 Recreational Marine Steady-state Cycle

		HC	NOx	HC+NOx	CO	Weighted Air-fuel ratio	BSFC
	kW	g/kW-hr	g/kW-hr	g/kW-hr	g/kW-hr	kg/kg	g/kW-hr
Baseline	209	4.4	8.5	12.9	170	13.2	348
Baseline EGR	209	4.4	4.8	9.2	184	13.3	365
Stoich A/F-CL	209	3.5	11.7	15.2	117	13.7	338
Stoich A/F+EGR	209	3.2	6.8	10.0	105	14.0	345
CL A/F, TWC*	172	1.5	3.0	4.5	150	13.8	389
CL A/F, EGR, TWC*	172	1.3	1.9	3.2	143	13.9	389
Baseline Rebuilt	219	4.7	9.4	14.1	160	13.4	358
CL A/F, TWC**	221	2.0	1.2	3.2	83	13.8	341
CL A/F, EGR, TWC**	221	1.9	0.7	2.6	74	14.0	345
CL A/F, TWC***	213	1.7	1.9	3.6	87	13.9	345
CL A/F, EGR, TWC***	213	1.6	1.2	2.8	78	14.1	348

* 200 cpsi rectangular riser catalyst, 0.4 liters per side.
** 200 cpsi cylindrical external catalyst 1.7 liters per side.
*** 300 cpsi cylindrical riser catalyst, 0.8 liters per side.
EGR means exhaust gas recirculation
Stoich means stoichiometric
A/F means air-to-fuel ratio
CL means closed-loop
TWC means three-way catalyst
BSFC means brake-specific fuel consumption