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Catalytic Exhaust Emission Control of Small Internal Combustion Engines

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ABSTRACT

Gaseous emissions present in the engine exhaust of on-road motor vehicles are subject to stringent exhaust emission control standards for carbon monoxide (CO), hydrocarbons (HC), and oxides of nitrogen (NOx). All major automobile manufacturers utilize three-way catalytic converters to meet these standards.

There are millions of small engines in on-road and off-road applications whose exhaust emissions are currently not subjected to any form of regulations. This situation may change in the near future as the exhaust pollution control standards become more stringent. In many in-door applications where ventilation is not sufficient, small engine-powered equipment requires an exhaust pollution control system to meet carbon monoxide standards for a confined environment.

This paper illustrates the design of a new catalytic emission control system for application in small engine powered equipment. High exhaust purification, low exhaust gas restriction, low catalyst activation temperature and high mechanical / thermal catalyst durability are discussed.

Three catalytic exhaust emissions control systems consisting of various catalyst formulations and catalyst configurations are tested in a 3kW generator with a 242cc, 4-cycle gasoline engine and their performances are analyzed. It is shown that high exhaust purification of small internal combustion engines can be achieved in a simple and reliable manner.

1. INTRODUCTION

To control CO, HC and NOx emissions from automotive engines, a three-way catalyst with an air/fuel ratio electronic control unit is used.

The three-way catalyst simultaneously oxidizes HC and CO and reduces NOx if the exhaust air/fuel ratio is held close to a stoichiometric point. A lambda sensor located in the exhaust system measures the oxygen content of the exhaust gas entering the catalyst (Figure 1). A correction signal is sent from the lambda sensor to the electronic control unit to keep the air/fuel ratio near stoichiometry, i.e. within the catalyst window (Figure 2).

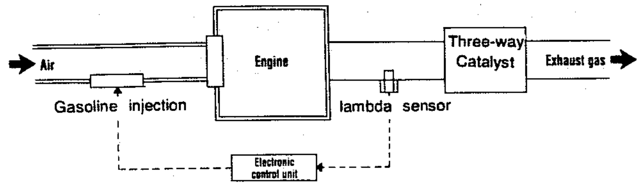

Fig. 1 Exhaust Emission Control System with a Three-way Catalyst.

A system consisting of a three-way catalyst and an air/fuel ratio controller seems too complex to be used for the control of exhaust emissions from small internal combustion engines.

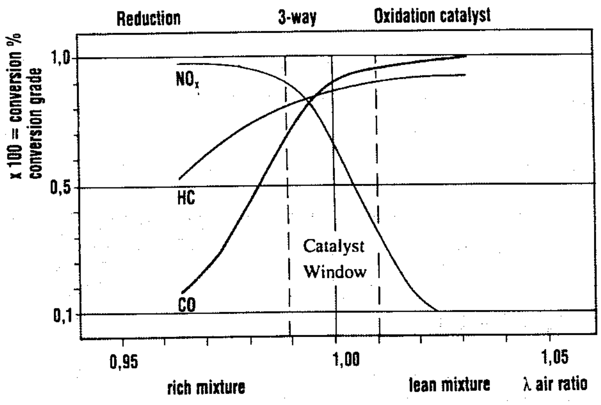

Fig. 2 The Effects of Air/Fuel Ratio on CO, HC, and NOx Conversions.

2. CATALYTIC EXHAUST GAS PURIFICATION

The catalytic exhaust purification system should convert CO, HC and NOx to H_2O, CO_2 and N_2 (Figure 3).

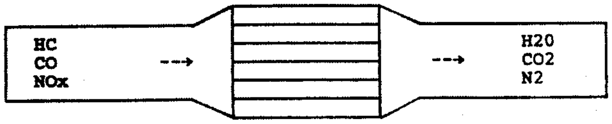

Fig. 3 Catalytic Exhaust Gas Purification. (1)

CO and HC are oxidized and NOx is reduced in a three-way catalytic converter according to the following stoichiometric equations (2):

$$(1)\quad CO + \frac{1}{2}O_2 \rightarrow CO_2$$

$$(2)\quad \text{Hydrocarbons} + O_2 \rightarrow H_2O + CO_2$$

$$(3)\quad NO + CO \rightarrow \frac{1}{2}N_2 + CO_2$$

$$(4)\quad NO + H_2 \rightarrow \frac{1}{2}N_2 + H_2O$$

$$(5)\quad NO + \text{hydrocarbons} \rightarrow N_2 + H_2O + CO_2$$

The catalytic coverter consists of ametallic or ceramic honeycomb (catalyst support) with various cell configurations. An intermediate layer (washcoat) is deposited on the honeycomb walls (Figure 4) to increase the specific surface area and to provide more oxygen storage capacity. This active washcoat allow fine and even distribution of nobel metals (catalyst) on the honeycomb walls as well as assuring high thermal stability of the catalyst.

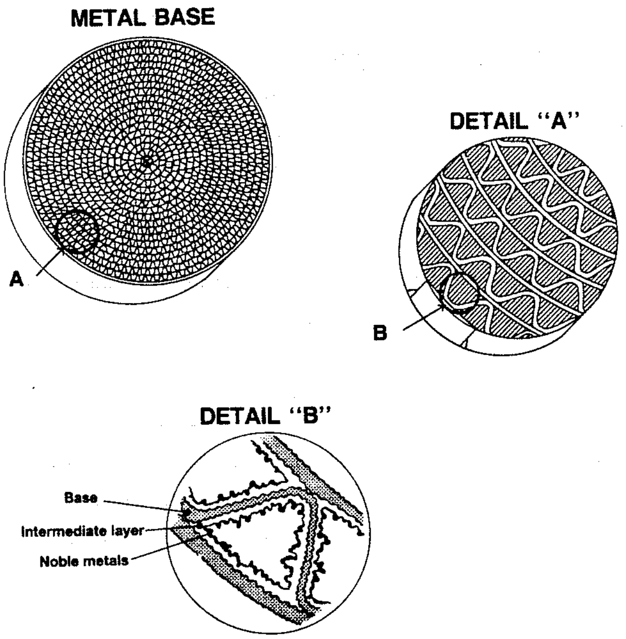

Fig. 4 Catalyst Construction

3. SYSTEM DESIGN CRITERIA

The design criteria for the exhaust emission control system for small engines were as follows:

I. High CO and HC reduction

II. NOx reduction, if the cost of the system is not prohibitive and if the system is not too complex.

III. No engine power loss

IV. High mechanical and thermal durability

V. No increase in noise emissions

VI. Low maintenance

VII. Simple installation in new engines as well as easy retrofitting of existing equipment.

Metallic catalyst support was chosen as opposed to the ceramic support due to its low exhaust back pressure (Figure 5).

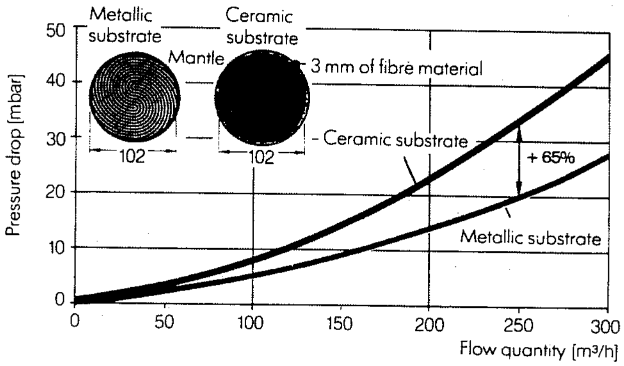

Fig. 5 Exhaust Back Pressure of a Metallic Versus a Ceramic Catalyst Support of the Same Size.

Low back pressure is an important design feature which eliminates any possible engine power loss.

Geometrical data	Metallic substrate	Ceramic substrate
Wall thickness (mm, uncoated)	0.04	0.2–0.15
Cell density (cpsi)	400 (25–600)	400
Clear cross section (%) (uncoated)	91.6	67.1 76,0
Specific surface area (m^2/l)	3.2	2.4. 2.8

Physical data	Metallic substrate	Ceramic substrate
Thermal conductivity ($W/m \cdot K$)	14–22	1–0.8
Heat capacity ($kJ/kg \cdot K$)	0.5	1.05
Density (g/cm^3)	7.4	2.2–2.7
Thermal expansion ($\Delta L/L \cdot 10^{-6}/K$)	15	1
Max. short-duration operating temperature (°C)	1500	1200

Fig. 6 Comparison Data on Metallic Versus Ceramic Catalyst Support

Low heat capacity and high thermal conductivity (Figure 6) provide fast catalyst start-up so that exhaust purification can be achieved even during the engine cold-start phase. A high percentage of clear cross section, small geometrical size and high mechanical and thermal durability make the metallic catalyst support very suitable for the application in small engine-powered equipment. The metallic support versus the ceramic support is shown in Figure 7.

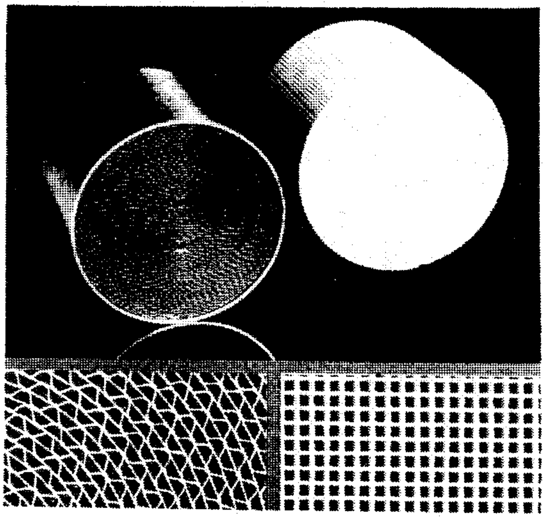

Fig. 7 Metallic Support Versus Ceramic Support

4. SYSTEM DESIGN

The main component of the system is an S-shaped metallic catalyst support. S-shaped supports are made of flat and corrugated metallic foils with thicknesses ranging from 0.04mm to 0.05mm (Figure 8). The dimensions of the corrugations are designed in accordance with the required cell geometry and cell density.

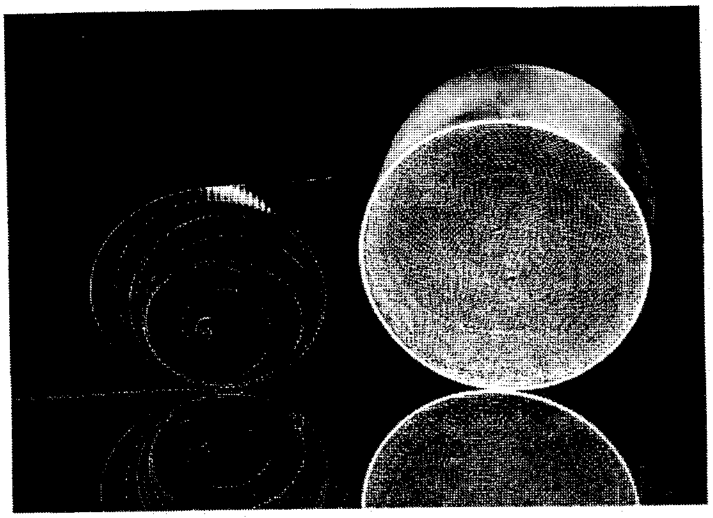

Fig. 8 Design and Production of S-Shape Support

A flat foil is placed on top of the corrugated foil resulting in a trapezoidal cell configuration. The flat and corrugated foils are coiled up into the required diameter and the coil is coated with a special brazing material. The coil is then slid into a steel housing and the whole unit is high-temperature-vacuum-brazed. The brazing process will connect the support and its housing firmly together into one single support-housing unit (3).

After brazing, the support-housing unit is degreased and ready for the washcoat and catalyst coating. The metallic support used in the system is shown in Figure 9.

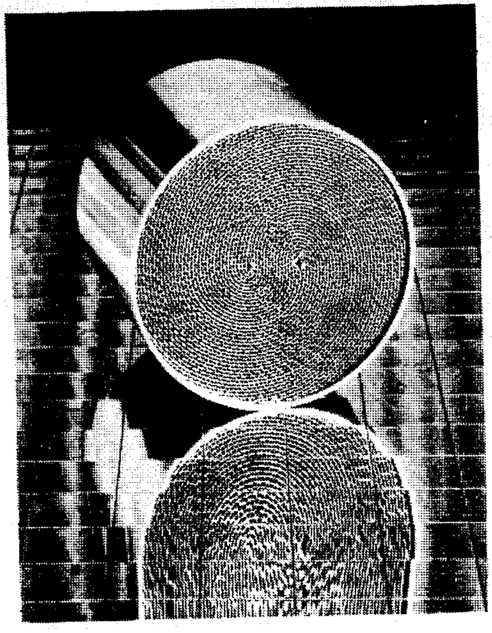

Fig. 9 S-Shape Metallic Support

The support is coated with a platinum-based catalyst and then welded into the exhaust system between the engine and the exhaust muffler. The piping of the exhaust system designed to achieve the lowest possible exhaust flow restriction. A stock muffler, installed at the end of the exhaust piping and downstream of the catalyst, provides high noise attenuation. Secondary air is injected upstream of the main catalyst. The distance from the secondary air injection port to the catalyst inlet is carefully selected to provide enough time for the mixing of the exhaust gas with the secondary air before the air/gas mixture enters the catalyst. A secondary air injection system is currently under development. For testing purposes, secondary air was delivered to the exhaust system from the air compressor.

5. TEST PROCEDURE AND RESULTS

5.1 Test Procedure

For all the tests, a commercially available Honda 3 kW generator was used. The engine that powered the generator was a single cylinder unit which operated on unleaded gasoline. The genset was tested in four configurations. The setups included the following:

-- stock condition (with muffler but no catalysts).

-- with catalyst A1

-- with catalyst B

-- with catalyst A2 and B.

In all cases, the exhaust was drawn from the lab under a vacuum of approximately one inch of water column or less. The electrical load was two 1500 W (240 V) rod heaters immersed in water. Both heaters were used for the 3 kW load testing while only one was used for the 1.5 kW testing. For the no load (idle) testing, the circuit breaker on the genset was shut off. Secondary air was provided by a shop air outlet regulated down to 28 psi and controlled with a needle valve. The typical experimental test set-up (for catalysts A2 and B) is shown schematically in Figure 10.

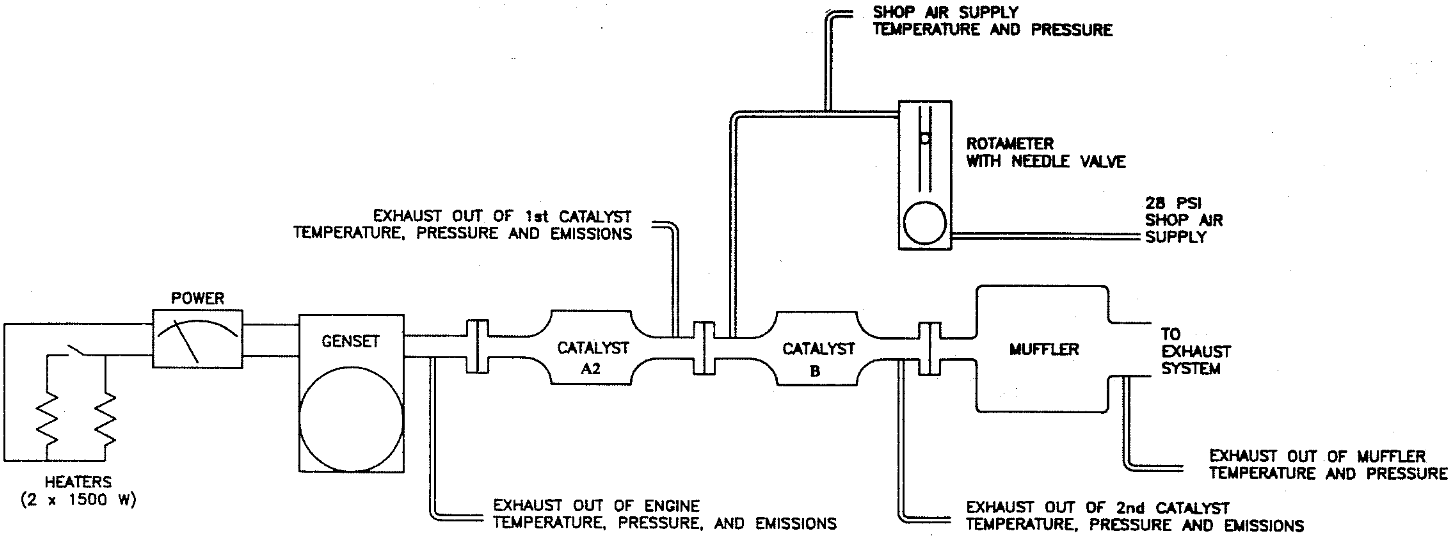

Fig. 10 Test Configurations For Two Catalysts.

The secondary airflow was measured with a 0 - 40 1/min (at 19 degrees Celsius and 760 mm Hg) rotameter. The secondary air pressure was monitored with a mercury manometer while the exhaust gas pressures were monitored with a water manometer. All temperatures were monitored with type K thermocouples and measured with a Fluke digital thermocouple reader. The exhaust gas composition was measured with several Beckman exhaust gas analyzers:

-- 951A NO/NOx chemiluminescent analyzer.

-- 865 CO nondispersive infrared analyzer.

-- 865 CO_2 nondispersive infrared analyzer.

-- 400 HC flame ionization detection analyzer.

To reduce testing cost and duration, these analyzers were left on the same ranges throughout the test:

-- NO/NOx 0-1000 ppm NOx (by volume)

-- CO 0-10% CO (by volume)

-- CO_2 0-20% CO_2 (by volume)

-- HC 0-8000 ppm HC (by volume)

When the genset was started for a given set of tests, the exhaust temperatures, pressures and composition were allowed to stabilize at the first test condition before being recorded. All of the tests were conducted for a given catalyst setup without stopping the generator. First the 3 kW points were performed in decreasing airflow. Then the 1.5 kW points were done (again, in decreasing secondary airflow); and lastly, the idle test point. The exhaust system was allowed to cool down to the point where it could be handled and the catalyst setup was changed to the next required test configuration. The above procedure was then repeated.

5.2 Test Results

The experimental results were analyzed and the data has been summarized in graphical form (see Appendix "A"). The emission of oxides of nitrogen is shown as a function of secondary airflow in Figures 11, 12 and 13 for the case of genset loads of 0, 1.5 and 3.0 kW respectively. In each diagram the results are presented for the three different catalysts used in the test program. For each diagram reference is made to the baseline emissions which refers to the data without any catalyst attached to the engine exhaust. It is clear from these results that NOx emissions are significantly reduced by all of the catalysts.

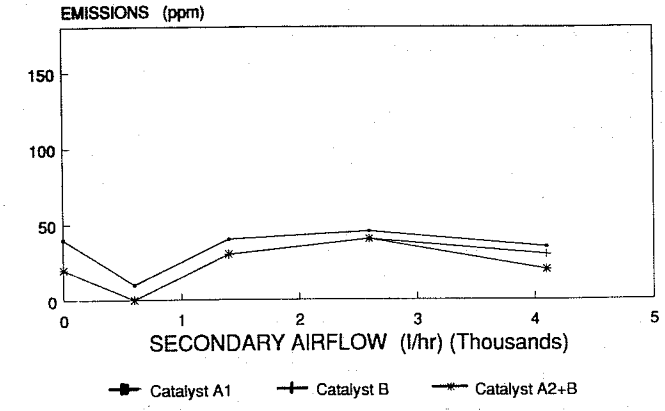

Fig. 11 NOx Emissions Versus Secondary Airflow
Load = 0kW, Baseline = 90 ppm

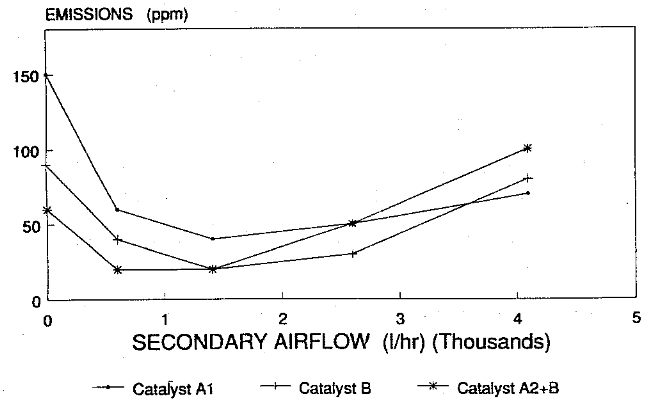

Fig. 12 NOx Emissions Versus Secondary Airflow
Load = 1.5kW, Baseline = 200 ppm

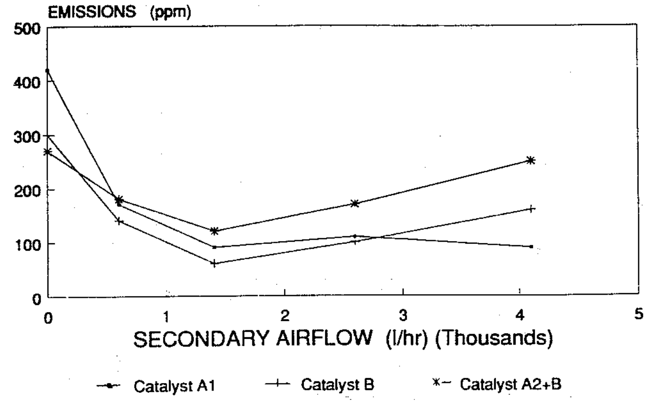

Fig. 13 NOx Emissions Versus Secondary Airflow
Load = 3kW, Baseline = 720 ppm

From the experimental data the catalyst efficiency has been calculated as a function of secondary airflow. Catalyst efficiency is defined as follows:

$$E_C = 100\ [(C_b - C_a)/C_b]$$

where

E_c = catalyst efficiency (%)

C_b = exhaust species concentration before the catalyst

C_a = exhaust species concentration after the catalyst

For NOx emissions typical results are shown in Figures 14 and 15. For catalysts B and A2+B efficiency exceeds 80% for flows in the range of 1000-2000 1/hr. The latter catalyst displays these efficiency levels at much lower flow rates than catalyst B. However, for a 3 kW load, the efficiency of catalyst B is superior to A2+B.

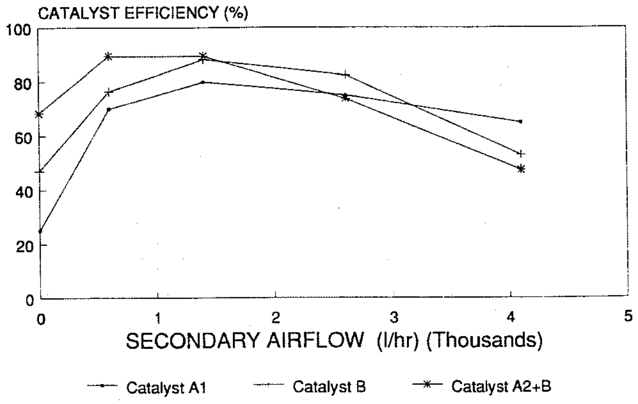

Fig. 14 NOx Catalyst Efficiency Versus Airflow
Load = 1.5kW

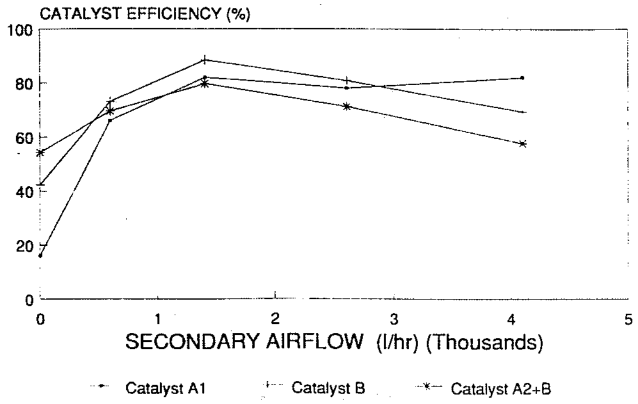

Fig. 15 NOx Catalyst Efficiency Versus Airflow
Load = 3kW

Hydrocarbon emissions are shown in Figures 16, 17 and 18 as a function of secondary airflow. For the latter two cases (1.5 kW and 3.0 kW), the HC emissions are higher than the baseline for zero secondary airflow. It is not clear why this occurred. One possible explanation is that the catalyst increased the backpressure in the exhaust system and altered the air fuel ratio of the engine. Since exhaust emissions are strongly dependent on air fuel ratio, any change in this ratio could be responsible for the higher HC emissions when the catalyst is added. It is clear from the results that the HC emissions decrease dramatically as soon a the secondary airflow is introduced.

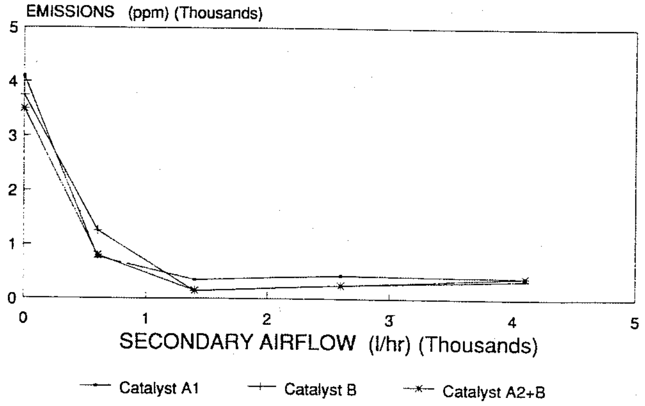

Fig. 16 HC Emissions Versus Secondary Airflow Load = 0kW, Baseline = 4500 ppm

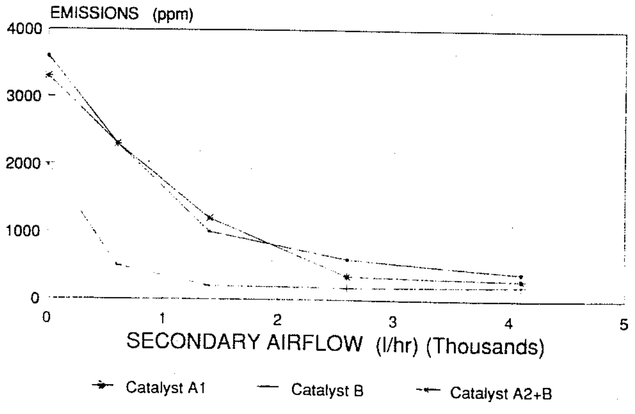

Fig. 17 HC Emissions Versus Secondary Airflow Load = 1.5kW, Baseline = 2900 ppm

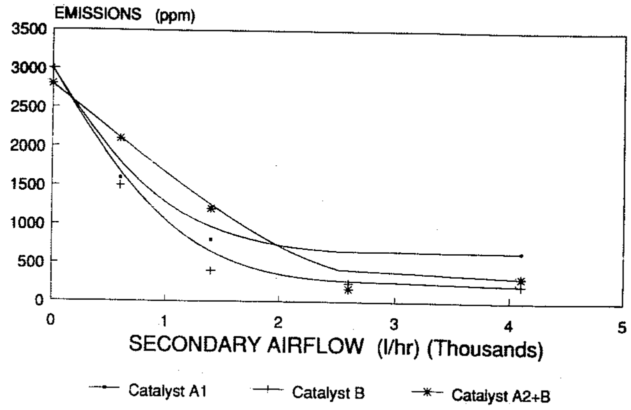

Fig. 18 HC Emissions Versus Secondary Airflow Load = 3kW, Baseline = 2300 ppm

Catalyst efficiency for HC has been calculated for the two load levels considered in the test program. The results are shown in Figures 19 and 20. From these diagrams it is clear that catalyst B is the most effective in reducing HC emissions. For airflows above 1000 1/hr catalyst B exhibits conversion efficiencies of greater that 90% for 1.5 kW load and greater than 80% for 3.0kW load. Catalyst A2+B has comparable conversion efficiencies, however much higher secondary airflows are required to accomplish these levels.

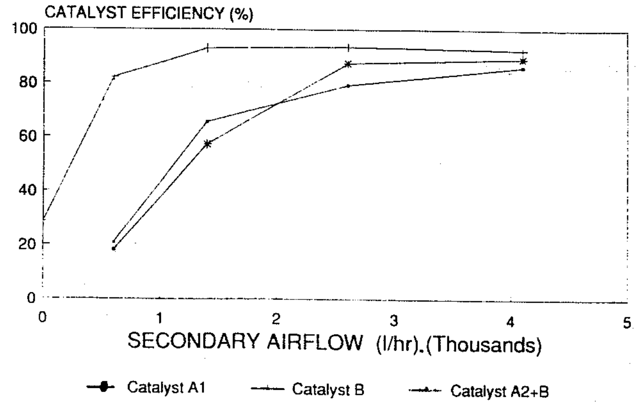

Fig. 19 HC Catalyst Efficiency Versus Airflow Load = 1.5kW

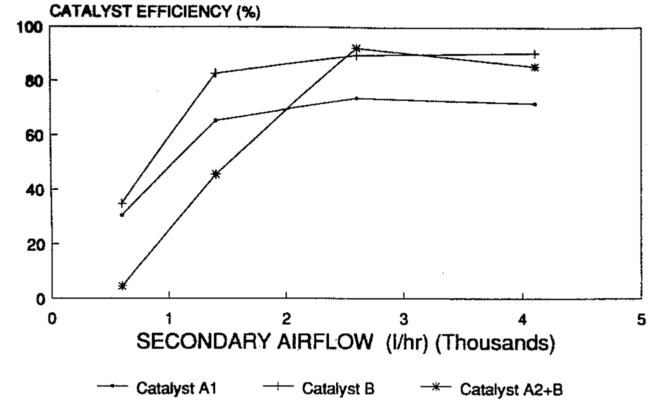

Fig . 20 HC Catalyst Efficiency Versus Airflow
Load = 3kW

CO emissions are shown in Figures 21, 22 and 23 as a function of secondary airflow. It is clear from these results that CO emissions decrease monotonically with increasing secondary airflow for all three catalyst tested.

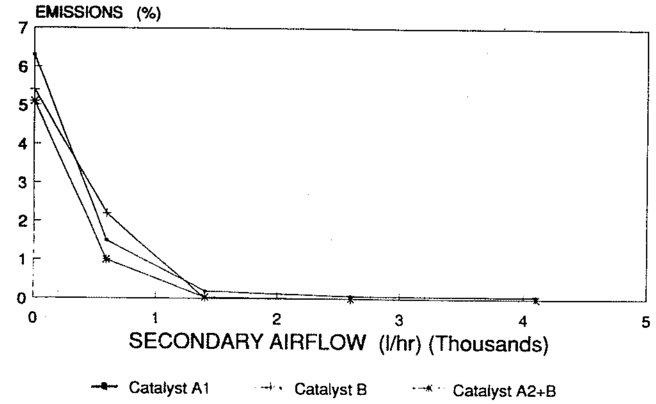

Fig. 21 CO Emissions Versus Secondary Airflow
Load = 0kW, Baseline = 6.5%

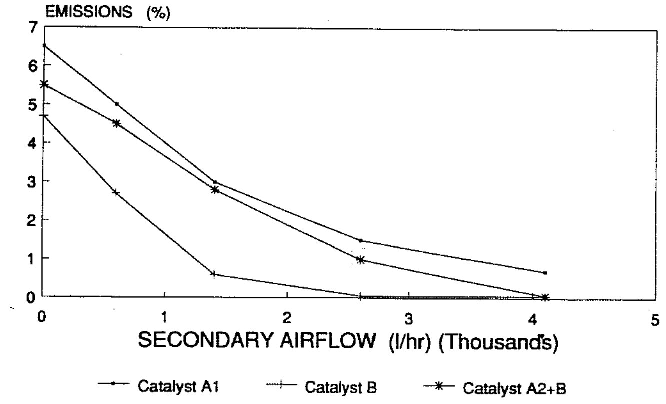

Fig. 22 CO Emissions Versus Secondary Airflow
Load = 1.5kW, Baseline = 6.6%

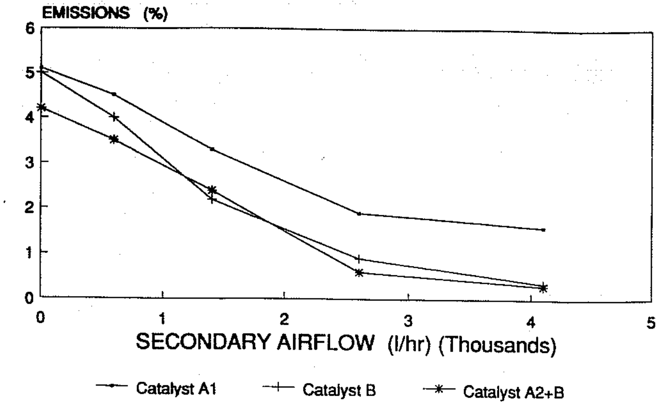

Fig. 23 CO Emissions Versus Secondary Airflow
Load = 3kW, Baseline = 4.5%

CO catalyst efficiency has been calculated for the two load levels used in the test program. The results are shown in Figures 24 and 25. For operation at a 1.5 kW load, catalyst B is clearly superior in performance to the two other catalysts tested. For 3 kW loads, the efficiency of catalyst B and A2 + B are comparable with the latter marginally greater.

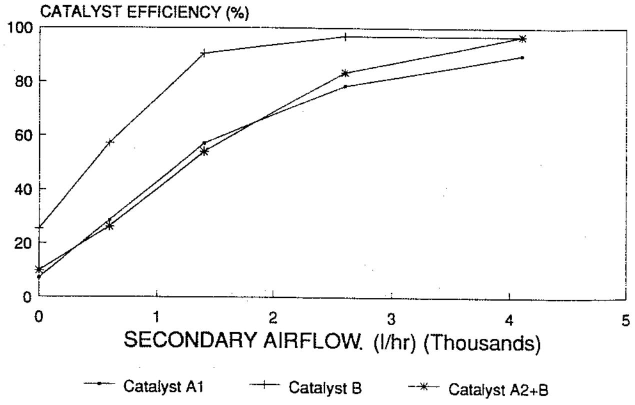

Fig. 24 CO Catalyst Efficiency Versus Airflow
Load = 1.5kW

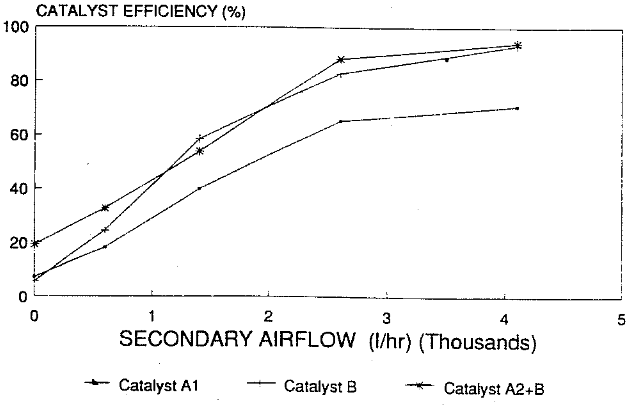

Fig. 25 CO Catalyst Efficiency Versus Airflow
Load = 3kW

5.3 Discussion of Results

Based on the results presented in Section 5.2 a ranking of the catalysts in terms of performance can be made. This has been done and the results summarized below. For each load the most effective catalyst in reducing exhaust emissions has been selected and is shown in the table.

Engine Load	Exhaust Species		
kW	NOx	HC	CO
1.5	A2+B	B	B
3.0	B	B	B or A2+B

Table 1. Summary of Best Performing Exhaust Catalyst

Based on the assessment provided in Table 1, it is clear that catalyst B offers the best performance in reducing exhaust emissions. In addition to the high conversion efficiency demonstrated by catalyst B, it is also important to note that it is a lower cost than catalyst A2+B. Thus, based on the criteria of performance and cost, catalyst B is clearly the best performing unit tested.

ACKNOWLEDGEMENTS

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Appendix

Catalyst comparison for Honda 3500 generator
Note that these points are in the order that they were taken
Analyzer rangesNOx 0-1000 ppm
HC 0-8000 ppm
CO 0-10 %
CO2 0-20 %

Load	Secondary Air				Exhaust Temperatures (Deg C)				Exhaust Pressures ("H2O)				Emissions Out of Engine				Emissions Out of 1st Catalyst				Emissions Out of 2nd Catalyst			
kW	Airflow scale	Press psi	Temp Deg C	Airflow S l/hr	Out of Engine	Out of 1st Catalyst	Out of 2nd Catalyst	Out of Muffler	Out of Engine	Out of 1st Catalyst	Out of 2nd Catalyst	Out of Muffler	NOx ppm	HC ppm	CO ppm	CO2 %	NOx ppm	HC ppm	CO ppm	CO2 %	NOx ppm	HC ppm	CO ppm	CO2 %
					NO CATALYST INSTALLED																			
0	0			0	370			97	0			-0.6	90	4500	6.5	11.9								
3	0			0	650			230	4.2			-0.7	720	2300	4.5	13.1								
1.5	0			0	590			240	2			-0.7	200	2900	6.6	11.8								
					CATALYST A1 INSTALLED																			
3	60	11.5	20	4100	650	650		350	6.8	0		-1.1	500	2300	5.5	12.6	90	650	1.6	14.2				
3	45	7.4	20	2600	630	640		350									110	610	1.9	14.5				
3	30	3.05	20	1400													90	800	3.3	14				
3	15	1.8	20	600													170	1600	4.5	13.1				
3	0			0													420	3000	5.1	12.8				
1.5	60	11.5	20	4100	590	660		370	4	0		-0.2	200	2900	7	11.6	70	400	0.7	13.7				
1.5	45	7.4	20	2600													50	600	1.5	14.2				
1.5	30	3.05	20	1400													40	1000	3	14				
1.5	15	1.8	20	600													60	2300	5	12.5				
1.5	0			0													150	3600	6.5	12				
1.5	0			0									200	2900	6.5	12								
0	60	11.5	20	4100	360	435		230	0.8	-0.1		-0.5	80	4300	6.3	11.6	35	400	0.06	8.9				
0	45	7.4	20	2600													45	430	0.07	11.7				
0	30	3.05	20	1400	350	470		175									40	350	0.19	13.7				
0	15	1.8	20	600													10	770	1.5	14.5				
0	0			0	360	370		150									40	4100	6.2	11.6				
					CATALYST B INSTALLED																			
3	60	11.5	20	4100	650	790		390	4.9	4.8		-1	520	2300	5.3	12.6	160	220	0.35	14.8				
3	45	7.4	20	2600													100	240	0.9	15.1				
3	30	3.05	20	1400													60	400	2.2	14.5				
3	15	1.8	20	600													140	1500	4	13.5				
3	0			0													300	3000	5	12.9				
3	>65		20	>5000													180	260	0.3	14.5				
1.5	>65		20	>5000	590	725		360	2.7	2.8		-0.7	170	2800	6.3	12	80	210	0.05	13.7				
1.5	60	11.5	20	4100													80	180	0.05	14				
1.5	45	7.4	20	2600	590	750		350									30	200	0.6	15.1				
1.5	30	3.05	20	1400													20	500	2.7	14.4				
1.5	15	1.8-	20	600													40	2000	4.7	12.9				
1.5	0			0													90	3500	6	13.1				

0	60	11.5	20	4100	370	450		220	0.5	0.5		-0.1	80	3800	5.7	12.1	30	350	0	10.6				
0	45	7.4	20	2600													40	250	0	12.7				
0	30	3.05	20	1400	375	480		175									30	140	0	14.9				
0	15	1.8	20	600	370	500		160									0	1260	2.2	14.5				
0	0			0													20	2750	5.4	12.6				
					CATALYST A2 AND B INSTALLED (SEC AIR INTO B)																			
3	60	11.5	22	4000	650	580	730	360	6.4	6.2	5.5	-1.1	590	2200	5.2	13	290	3000	4.4	12.8	250	320	0.3	15.1
3	45	7.4	22	2500	650	570	710	370									300	3100	4.7	13.1	170	170	0.6	15.2
3	30	3.05	22	1400	650	570	680	370									300	3300	4.6	13.2	120	1200	2.4	13.3
3	15	1.8	22	600	650	570	630	350													180	2100	3.5	13.9
3	0			0	650	570	580	340													270	2800	4.2	13.5
1.5	60	11.5	22	4000	600	515	645	265	3.9	3.6	3.3	-1.3	190	2800	6.1	12.5	100	3100	5.5	12	100	300	0.06	14.1
1.5	45	7.4	22	2600	600	500	690	280													50	350	1	15
1.5	30	3.05	22	1400	600	500	670	270													20	1200	2.8	14.3
1.5	15	1.8	22	600	600	500	620	260													20	2300	4.5	13.5
1.5	0			0	600	500	500	245													60	3300	5.5	12.9
0	60	11.5	22	ERR	380	370	425	180	1.1	1.1	1	-1.1	90	2900	5.9	12.6	10	2450	3.8	11.9	20	400	0	10.1
0	45	7.4	22	- 3000	385	340	440	150													40	250	0	12.2
0	30	3.05	22	1700	385	320	440	140													30	150	0.03	14
0	15	1.8	22	700	380	310	470	130													0	800	1	15.1
0	0			0	380	300	300	120													20	3500	5.1	12.5