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CONTROL OF HEAVY-DUTY DIESEL PARTICULATE EMISSIONS USING CATALYZED CERAMIC TRAPS

EXECUTIVE SUMMARY

Prepared for

California Air Resources Board
P.O. Box 2815
Sacramento, CA 95812

Under Contract No.
A4-132-32

June 1987

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By
Terry L. Ullman

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ARB Contract Officer: Robert Grant
ARB Technical Representative: Michael Carter

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Approved:

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Charles T. Hare, Director
Department of Emissions Research
Automotive Products and Emissions
Research Division

Heavy-duty diesel vehicles are a major contributor to NO_x and particulate matter air pollution. California's most severe air pollution problems occur in the South Coast Air Basin (Los Angeles area), where heavy-duty diesel vehicles are estimated to account for 23 percent of total on-road vehicle NO_x emissions and 55 percent of total exhaust particulate emissions. Without further controls, these percentages are predicted to increase by the year 2000 to 36 percent of NO_x and 87 percent of particulates. In addition, visibility is predicted to further degrade in California due to the increased number of heavy-duty diesels. Bus emissions are of particular concern; because buses are typically operated exclusively in urban areas; over the busiest roadway corridors with highest population exposure; and with exhaust typically discharged at ground level, directly into the human breathing zone.

The objective of the work reported here was to equip a transit bus with a particulate control system based on current light-duty diesel particulate control technology used on diesel Mercedes-Benz automobiles sold in California. The particulate control system was to eliminate "visible smoke," and reduce exhaust particulates from the bus by 70 percent. If the particulate control system was developed for the bus, the bus would undergo transit service in California to demonstrate system durability for one year.

The Mercedes-Benz diesel particulate control system consists of a ceramic filter placed in the exhaust stream to filter out, or trap, the particulate as it is exhausted from the engine. This ceramic filter has been coated with a catalyst to assist in the cleaning of accumulations "trapped" on the surface of the exhaust gas filter. Periodic or continuous cleaning of accumulations (regeneration) on the filter are necessary to prevent plugging the filter and consequently raising the engine exhaust backpressure beyond engine design limits. High temperatures, near 600°C (1112°F), are typically needed to clean these accumulations; however, it is claimed that use of proprietary catalyst coatings can promote the cleaning of accumulations at lower temperatures approaching 400°C (750°F).

Cleaning of the accumulation from the filter at lower temperatures is advantageous because exhaust gases may often reach (or can easily be made to reach) these lower temperature ranges during normal vehicle operation, resulting in a periodic or continuous regeneration of the trap. To favor continuous regeneration, the catalyzed ceramic trap used on the Mercedes-Benz light-duty diesel vehicle is located between the engine exhaust manifold and the exhaust inlet of the turbocharger. Positioning the trap "before" the turbocharger takes advantage of higher-temperature exhaust gases than those present "after" the turbocharger. In addition, some specific tuning of the engine can be used to further increase exhaust gas temperatures, favoring frequent trap regeneration.

The bus supplied to SwRI by Southern California Rapid Transit District (SCRTD), on behalf of the California Air Resources Board, was a 1980 GMC RTS II 04 transit coach, 40 feet in length. Bus No. 8296, shown in Figure 1, had accumulated approximately 100,000 miles on a 1980 DDAD 6V-92TAC engine/power-pack installed in the bus chassis in 1983. The bus was taken from service and evaluated for performance and smoke on a chassis dynamometer at SCRTD. During that evaluation, it was apparent that full power performance was poor.

FIGURE 1. GMC RTS II 04 SUPPLIED BY THE SCRTD TO EVALUATE THREE CATALYZED CERAMIC PARTICULATE TRAPS

Injector timing and throttle delay were checked and set to manufacturer's specifications, but the bus still had low power. The problem was discovered to be a defective accelerator pedal assembly which was not allowing the engine throttle mechanism to go to full power position. After these repairs and adjustments were completed, the bus was approved for delivery to SwRI for use in the project. There was some concern that this "tuned" bus may not represent the California smoke, or particulate, problem to be addressed during this trap demonstration project.

The ARB approved the use of this bus for this program, but requested that preliminary emissions data be collected on the bus "as-received" by SwRI. Based on these preliminary emissions results on low-sulfur test fuel used in this program, the ARB decided that the bus was not "smokey" enough to make meaningful evaluations of the ceramic trap media. On this basis, the ARB directed that the injection timing be retarded and the throttle delay shortened. Based on the higher smoke opacities obtained after adjustment of the engine, approval to proceed with the program was given.

Based on the bus selected and the resulting constraints on space available for placement of a ceramic trap assembly, the existing muffler location was chosen. A preliminary trap design was established by SwRI on the basis of projected exhaust flows, material availability, and space limitations for the application of a ceramic filter within the engine compartment of the bus. The design allowed the exhaust gases to enter a common plenum formed between two pieces of ceramic trap substrate, and held in place by a wall of a common container. The exhaust gases passed through the ceramic substrates, to an outer container, and around, to the outlet. The inlet and outlet of the trap assembly were planned so that the exhaust piping could be changed to accommodate experimentation with the trap in the before and after turbocharger positions without actually relocating the trap assembly. The completed ceramic trap assembly is shown in Figure 2.

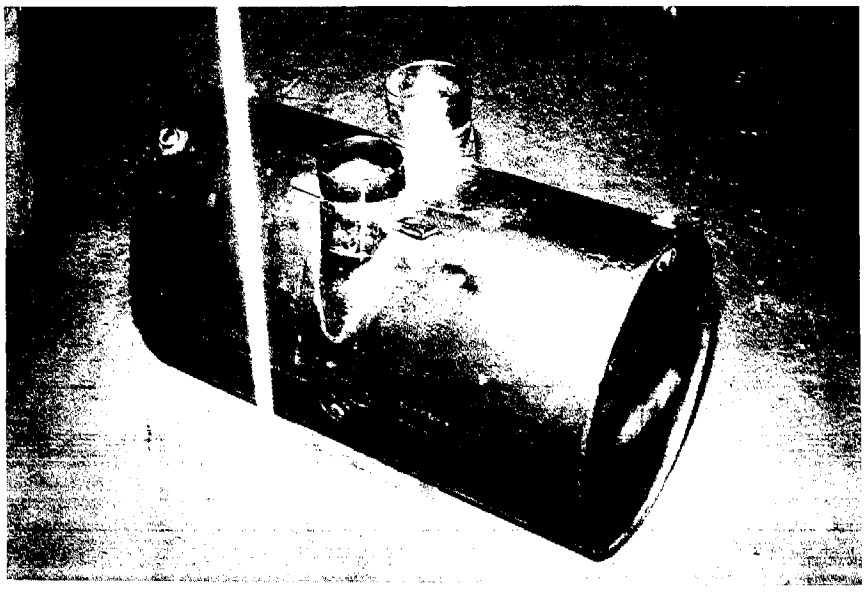

FIGURE 2. CERAMIC TRAP ASSEMBLY FOR THE HEAVY-DUTY DIESEL TRANSIT BUS

Several porosities of Corning ceramic diesel exhaust filter material were used on the basis of filter efficiency, backpressure characteristics, and potential interaction with various catalyst coating. After proving the design concept using the first assembly, Trap No. 1, three additional ceramic trap units were assembled using ceramic filter elements of varying porosity, with different catalyst coatings. The four trap assemblies tested in this program were as follows:

Trap No.	Corning Substrate	Particulate Trapping Eff., %	Catalyst Coating
1	EX-47	85-95	None
2	EX-66	25-68	"A"
3	Ex-54	65-80	"B"
4	EX-47	85-95	"C"

The bus was tested on the heavy-duty chassis dynamometer for comparison of emissions and acceleration performance, and to study trap regeneration scenarios. It was also tested on a defined road route for comparison of noise level and performance along with temperature and pressure data. The bus was tested on the chassis dynamometer with a simulation of 31,000 lb inertia. Total road load for the bus was 79 hp at 50 mph. The bus was tested over three chassis cycles, which included hot idle, a central business district cycle, and a bus cycle. The bus cycle served as the reference cycle to compare regulated emission levels of HC, CO, NO_x, and particulate. Additional operating conditions were run to evaluate changes to smoke emissions.

Aside from establishing emission levels for comparison purposes, most other test work carried out under this program was designed to evaluate the catalyzed ceramic traps, identify problems, and establish methodologies to obtain reliable regeneration of the trap over normal operation of a city bus.

Reliable regeneration must be accomplished periodically to assure that the trap does not become too burdened with diesel soot. Too much particulate loading results in large exotherms and high temperatures during regeneration that can damage or melt the trap. It is important, in evaluating a particulate trap, to approximate the quantity of soot accumulated in the trap. The pressure drop across the trap (Δp) increased as particulate is accumulated in the trap. During this work it was noted that the relative change in Δp or its square root ($\sqrt{\Delta p}$) indicates the relative soot loading in the trap. Use of this information was planned to provide signals to sense the need for regeneration.

Bus cycle emissions of HC, CO, and particulate for baseline and with all four trap assemblies are shown in Figures 3, 4, and 5, respectively. Changes to NO_x emissions were minor. Periodic testing of the bus without a muffler or trap assembly in place indicated that baseline emissions (determined with the muffler in place) of HC, CO and particulate increased during the conduct of this program as indicated in Figures 3, 4, 5, and 6. For perspective, heavy-duty diesel particulate standards of 0.60 g/hp-hr for 1987 and 0.10 g/hp-hr for 1991 correspond to bus particulate emissions of 2.1 and 0.36 g/mile (assuming an engine brake specific fuel consumption of 0.500 lb fuel/hp-hr and a vehicle fuel economy of 4.0 miles/gallon). Smoke and total particulate are related in that the relative level of smoke opacity indicates the relative level of particulate. The absence of smoke, however, does not indicate the absence of particulate. Smoke levels measured during simulation of the bus pulling away from a stop are given in Figure 6. Trap assembly Nos. 1, 2, and 3 were evaluated before and after the turbocharger. Trap No. 4 was evaluated only before the turbocharger.

Particulate trapping efficiency of Trap No. 1 was good, such that no visible smoke ($\leq$5 percent opacity) was emitted during experimentation, and measured particulate was reduced by more than 70 percent. Regeneration of the first unit was accomplished using an acetylene torch to achieve exhaust gas temperatures of 550°C. Trap No. 2, built using EX-66 and a proprietary catalyst coating similar to that used on the Mercedes diesel car, showed good reduction of HC and CO, along with an average 90 percent reduction of particulates. Virtually no visible smoke was observed from the bus when this unit was used. No low-temperature regeneration of Trap No. 2 was apparent during test work conducted on the road or dynamometer.

Trap No. 2 was regenerated using engine upset to increase the exhaust temperature. Engine upset consisted of altering the engine air-to-fuel ratio by venting a portion of the air box pressure used to scavenge the 2-stroke engine. Noticeable regeneration took place when the trap substrate temperatures reached approximately 510 to 550°C. Unfortunately, this trap was damaged during road course experimentation using engine upset.

Trap No. 3 consisted of Corning EX-54 substrates coated with a different catalyst formulation. This unit did not reduce HC and CO emissions, but did provide greater than 80 percent reduction in total particulate emissions. No visible smoke was noted with this trap, whether located after or before the turbocharger. Noticeable regeneration took place only when the trap substrate temperatures reached 510 to 550°C. The maximum substrate temperature noted during test work with Trap No. 3 was 830°C. Damage to the substrate can occur near 1000°C.

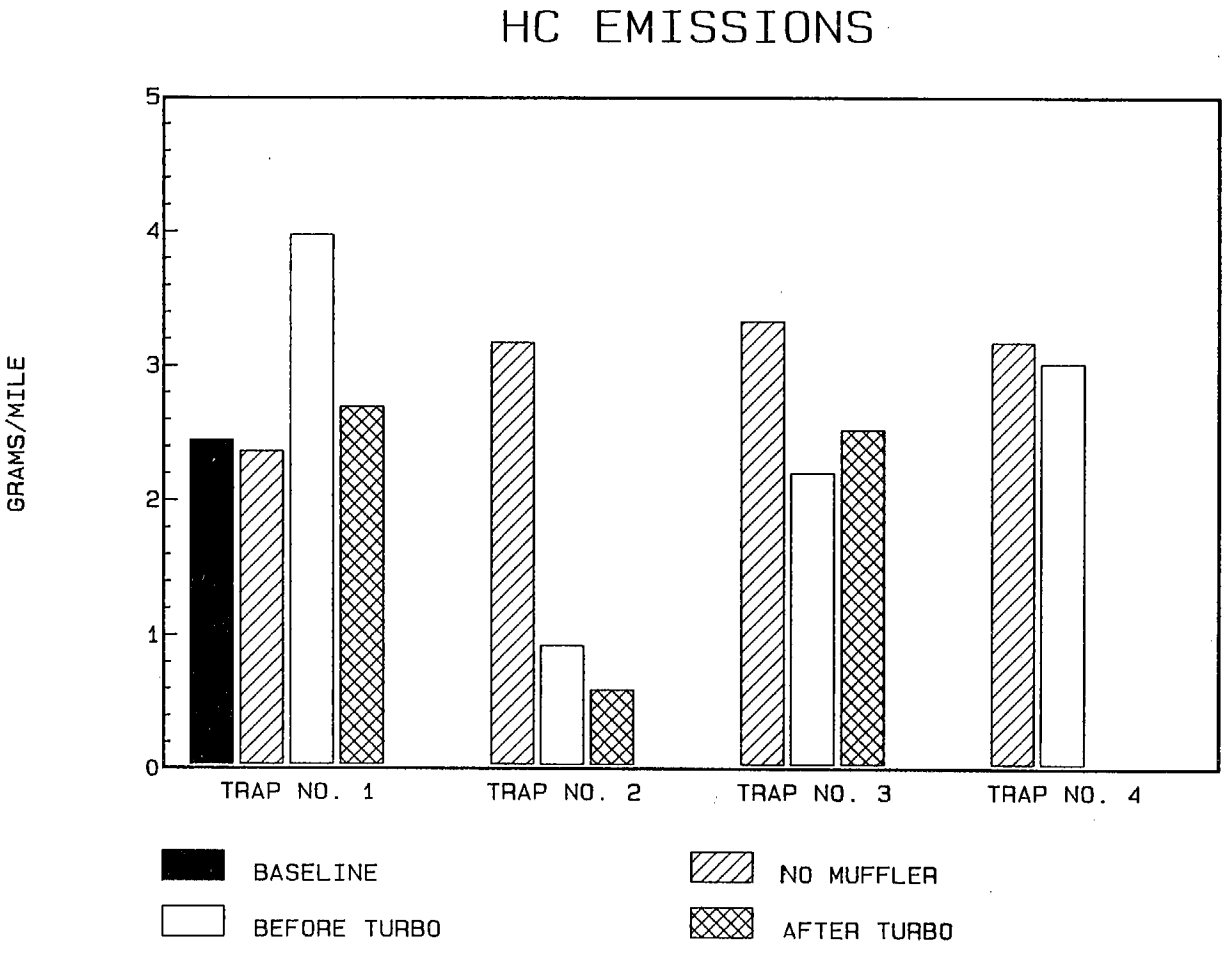

FIGURE 3. BUS CYCLE HC EMISSIONS

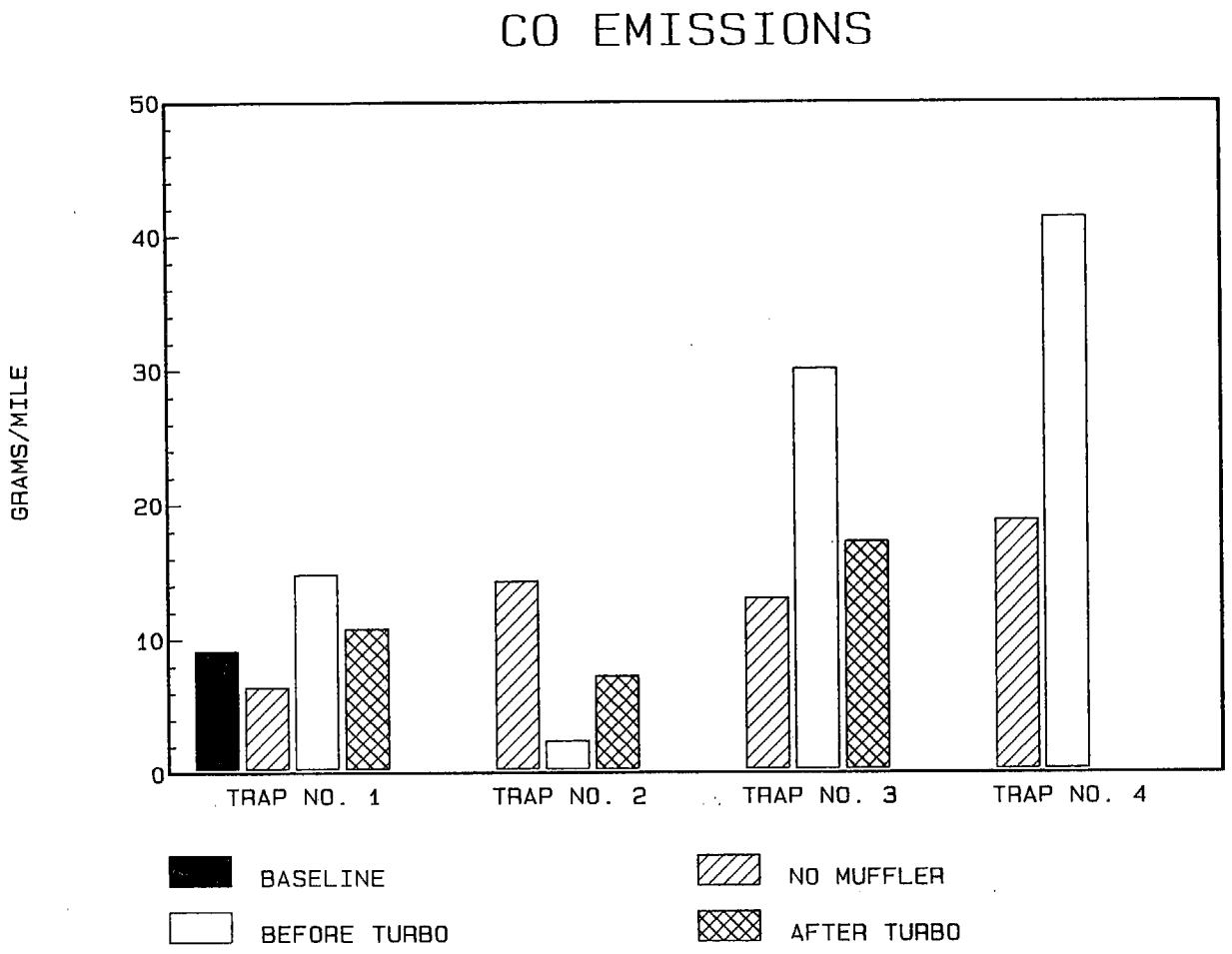

FIGURE 4. BUS CYCLE CO EMISSIONS

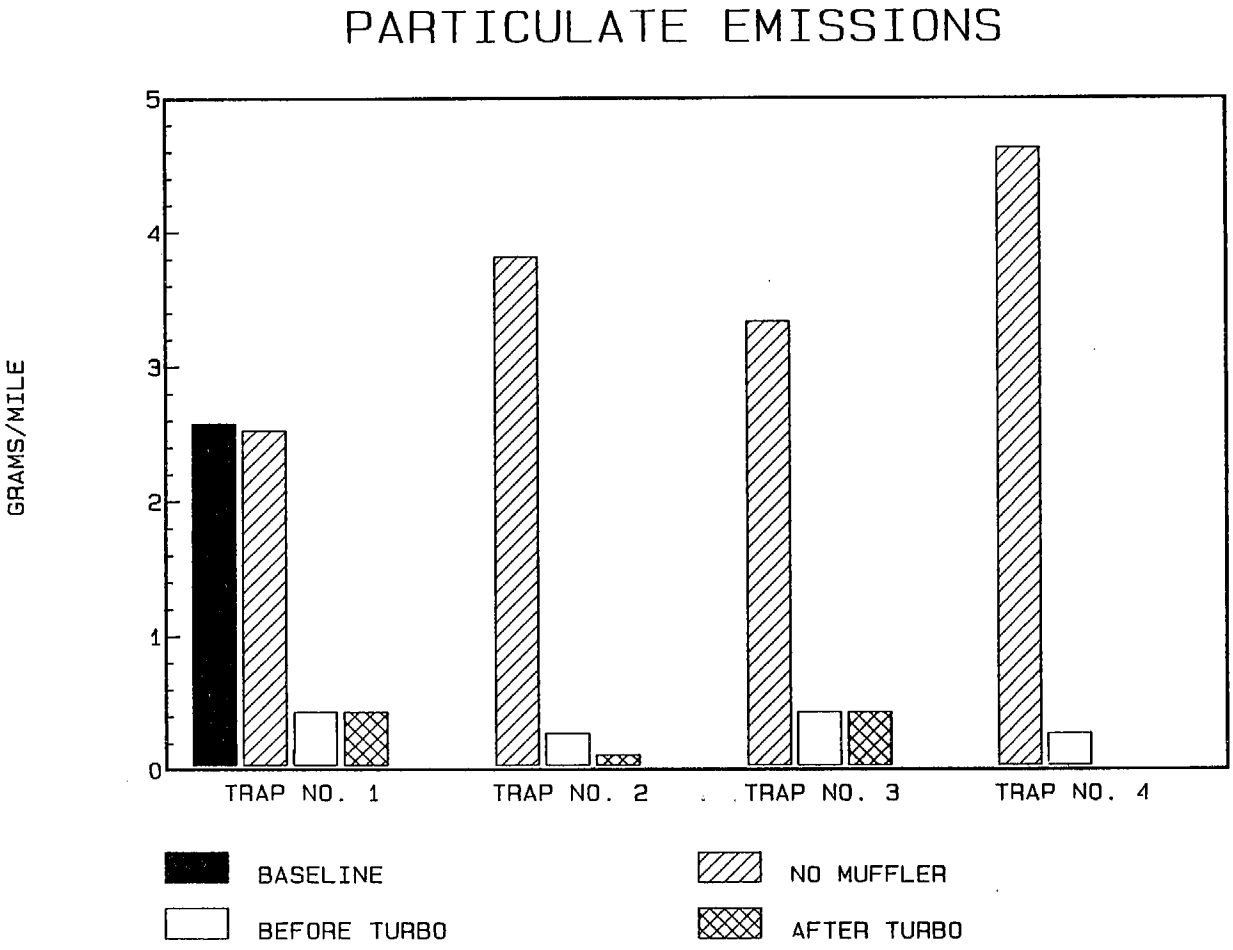

FIGURE 5. BUS CYCLE PARTICULATE EMISSIONS

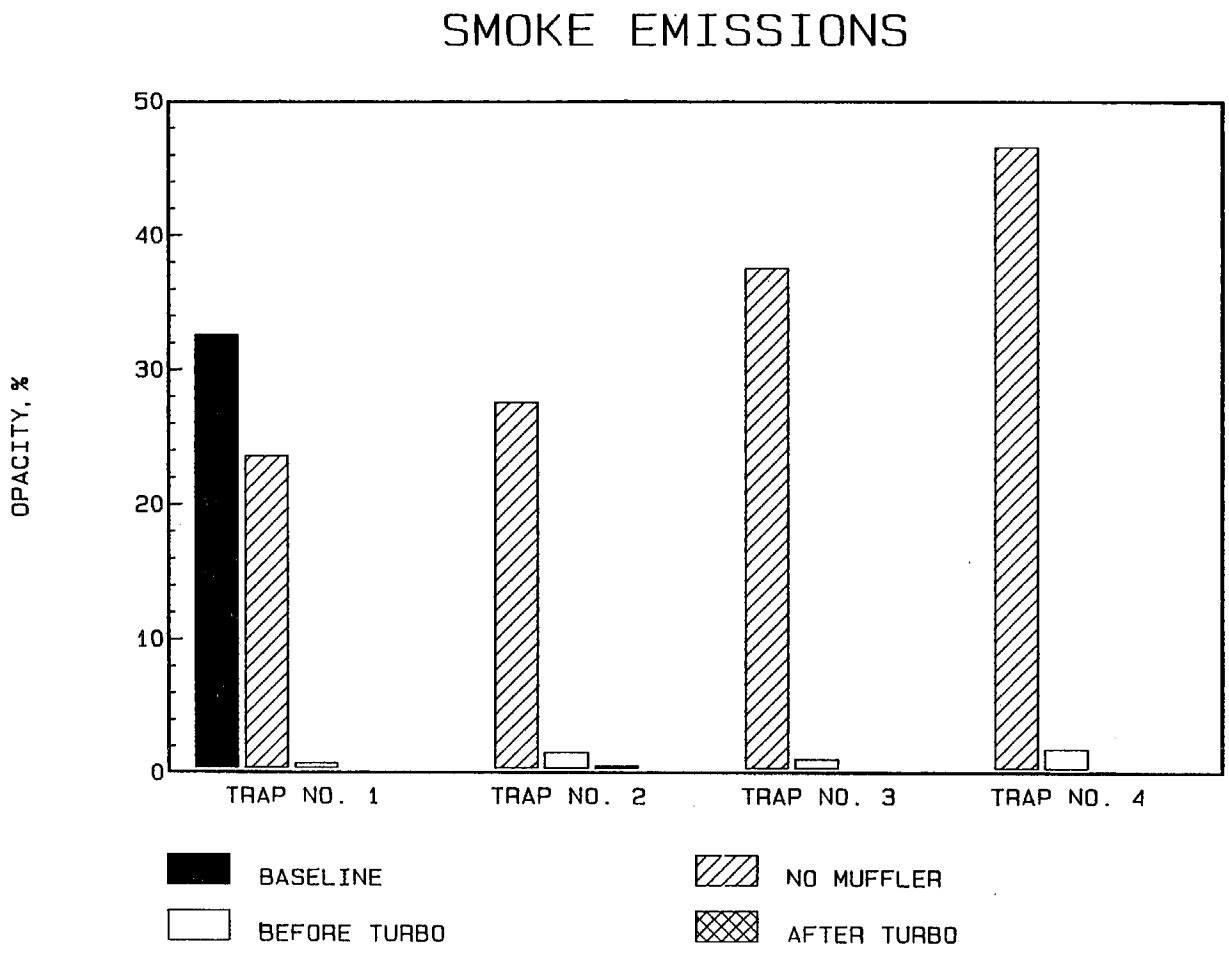

FIGURE 6. SMOKE EMISSIONS DURING SIMULATED PULL-AWAY OPERATION

Trap No. 4 was fabricated using Ex-47 ceramic substrates catalyzed with formulation "C." This fourth trap assembly reduced particulate emissions on the bus cycle by about 90 percent. No visible smoke was noted during any portion of the chassis dynamometer test work with the unit positioned before the turbocharger. Regeneration required substrate temperatures between 510 and 550°C (almost the same as the first uncatalyzed trap).

Plans to fit the bus with the best trap/regeneration system for demonstration purposes required the selection of the first choice. The criteria for selection of first choice were:

1. ≥70% reduction in total particulate
2. no visible smoke (≤5 percent opacity)
3. lowest regeneration temperature
4. least effect on engine performance
5. best reduction of CO and HC emission

All four trap assemblies functioned well as a muffler replacement. Changes to acceleration performance of the bus using the trap units before and after the turbocharger were minor. All three catalyzed trap assemblies were essentially equivalent based on the first four criteria listed above. Only trap No. 2 had the distinction of reducing CO and HC emissions. The most critical item, relative to pursuing a field demonstration, was criterion No. 3. No low temperature regenerations were noted for any of the three catalyzed ceramic units evaluated in the program. Locating the trap unit before the turbocharger was the most favorable position to obtain the high temperatures needed for regeneration.

The high exhaust temperatures required for regeneration (510 to 550°C) could be obtained with high engine loads or with engine upset in some cases. Because the catalyzed traps evaluated in this program lacked suitable low-temperature regeneration characteristics to permit general use of the bus in an in-service environment, a field demonstration was discouraged. Based on the information and alternatives presented, no in-service demonstration of the trap units was warranted, and further work with catalyzed ceramic traps developed for this program was terminated at the request of the ARB. The remaining effort, reserved for demonstration purposes, was redirected by the ARB to examine the impact of low-sulfur and low-aromatic diesel fuel on heavy-duty diesel emissions (to be reported in Volume II). The bus was restored to its original configuration and returned to SCRTD, October 23, 1986.

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16. Abstract (Limit: 200 words)

A ceramic particulate filter (trap) was designed as a muffler replacement for application to a GMC RTS II 04 city bus powered by a 2-stroke DDAD 6V-92TAC heavy-duty diesel engine. Preliminary testing indicated that the design was of adequate capacity and filtering efficiency to reduce total particulate by more than 70 percent and eliminate visible smoke emissions. Three different catalyst formulations were applied to three trap units to enhance on-board trap regeneration. Although some balancing of accumulated particulate was obtained below 500 C, notable regeneration was not obtained until the catalyzed substrates reached a temperature range of 510 to 550 C. The trap units were located before the turbocharger, where high exhaust temperatures, promoted by creating periodic engine upset, could best be utilized for regeneration. Even though low-temperature regeneration was not observed with any of the three catalyzed traps, all three were able to eliminate visible smoke and reduce total particulate by 80 percent; however, on-board regeneration could only be accomplished through periodic high-load operation of the bus. The durability of these catalyzed traps has yet to be established in a field demonstration because they lack suitable low-temperature regeneration characteristics to permit general use of the bus.

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