EPA/AA/CTAB/88-08

Technical Report

Evaluation of a Resistively Heated Metal Monolith Catalytic Converter On An M100 Neat Methanol-Fueled Vehicle

by

David M. Blair and
Gregory K. Piotrowski

August 1988

NOTICE

Technical Reports do not necessarily represent final EPA decisions or positions. They are intended to present technical analysis of issues using data which are currently available. The purpose in the release of such reports is to facilitate the exchange of technical information and to inform the public of technical developments which may form the basis for a final EPA decision, position or regulatory action.

U. S. Environmental Protection Agency
Office of Air and Radiation
Office of Mobile Sources
Emission Control Technology Division
Control Technology and Applications Branch
2565 Plymouth Road
Ann Arbor, Michigan 48105

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

ANN ARBOR, MICHIGAN 48105

OFFICE OF
AIR AND RADIATION

August 31, 1988

MEMORANDUM

SUBJECT: Exemption From Peer and Administrative Review

FROM: Karl H. Hellman, Chief KH
Control Technology and Applications Branch

TO: Charles L. Gray, Jr., Director
Emission Control Technology Division

The attached report entitled "Evaluation of a Resistively Heated Metal Monolith Catalytic Converter On An M100 Neat Methanol-Fueled Vehicle," (EPA/AA/CTAB/88-08) describes emission tests results obtained from testing a resistively heated catalytic converter on a methanol-fueled 1981 Volkswagen Rabbit.

Since this report is concerned only with the presentation of data and its analysis and does not involve matters of policy or regulations, your concurrence is requested to waive administrative review according to the policy outlined in your directive of April 22, 1982.

Concurrence: Charles L. Gray, Jr. Date: 8-31
Charles L. Gray, Jr., Dir., ECTD

Nonconcurrence: _____ Date: _____
Charles L. Gray, Jr., Dir., ECTD

cc: E. Burger, ECTD

EPA/AA/CTAB/88-08

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I. Summary

A prototype metal monolith catalytic converter, which may be resistively heated, was emission-tested on a M100 neat methanol-fueled vehicle. This catalytic converter, when tested as a 3-way catalyst without resistive heating, controlled emissions over the Federal test procedure (FTP) [1] to levels previously obtained by ceramic substrate converters coated with noble metal catalyst formulations. Resistively heating the catalyst substantially lowered emissions of hydrocarbons (HC) and formaldehyde (HCHO) compared to those from the unheated tests.

II. Introduction

The major portion of HC and HCHO emissions measured from a catalyst-equipped methanol-fueled vehicle over the FTP cycle are generated during cold start and warmup of the catalyst.[2] These emissions are difficult to control because engine-out emissions are high and catalytic converters have low conversion efficiency during their warm-up phase of operation.

A prototype resistively heated metal monolith catalyst has also been tested by EPA; that converter was a predecessor design to the subject of this report. Results from this previous testing indicated the feasibility of the concept of a resistively heated metal monolithic substrate as a quick light-off catalyst support.[3] The time it took to warm up the resistively heated catalyst to operating temperature was considered to be a drawback of the initial prototype tested. An improved configuration, the subject of the present report, was designed to achieve light-off temperature in a substantially shorter period of heating time than the initial prototype.

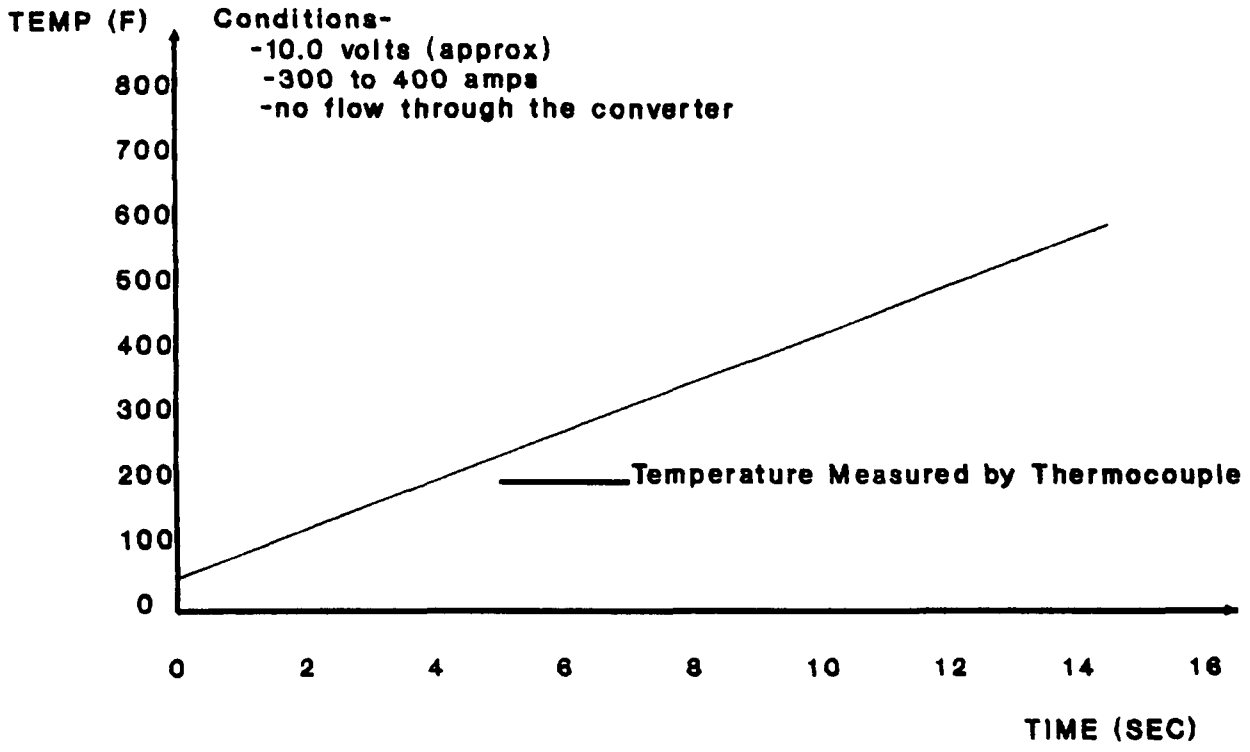
III. Catalytic Converter Description

The catalytic converter evaluated here was a dual-bed configuration consisting of an unheated metal monolith catalyst and a smaller resistively heated metal monolith catalyst. Detailed specifications are provided in Appendix A.

The dimensions of the converter are similar to those of typical underfloor catalysts on late model compact automobiles. The amperage draw was comparable to that required by an automotive starter motor cranking in cold weather. The rise in mid-bed gas temperature from 70°F to 600°F during prestart heating as measured by a thermocouple located near the center of the converter was linear and is presented in Figure 1. The catalyst wall temperature was probably higher than the measured 600°F after 15 seconds of heating, since the thermocouple may not have responded fast enough to the quickly rising temperature and stagnant gas temperature was probably lower than the resistively heated wall prior to start.

Drawing 300 to 400 amps at 10 volts is 3 to 4 kilowatts. Assuming that the use per start is 30 seconds, the energy required is 0.03 kw/hr, so this device is like a starter motor: high power drain but low energy consumption due to the short time it is used.

FIGURE 1
SUBSTRATE TEMPERATURE VERSUS TIME



IV. Vehicle Description

The test vehicle was a 1981 Volkswagen Rabbit 4-door sedan, equipped with automatic transmission, air conditioning, and radial tires. The 1.6-liter engine had a rated maximum power output of 88 horsepower at 5,600 rpm, when using neat methanol fuel. The vehicle was tested at 2,500 lbs inertia weight and 7.7 actual dynamometer horsepower.

A detailed description of the vehicle and special methanol modifications is provided in Appendix B.

V. Test Facilities and Analytical Methods

Emissions testing was conducted on a Clayton Model ECE-50 double-roll chassis dynamometer, using a direct-drive variable inertia flywheel unit and road load power control unit. The Philco-Ford CVS has a nominal capacity of 350 CFM. Exhaust HC emissions were measured with a Beckman Model 400 flame ionization detector (FID). CO was measured using a Bendix Model 8501-5CA infrared CO analyzer. NOx emissions were determined by a Beckman Model 951A chemiluminescent NOx analyzer.

Exhaust formaldehyde was measured using a dinitrophenylhydrazine (DNPH) technique.[4] Exhaust carbonyls including formaldehyde are reacted with DNPH solution forming hydrazine derivatives; these derivatives are separated from the DNPH solution by means of high performance liquid chromatography (HPLC), and quantization is accomplished by spectrophotometric analysis of the LC effluent stream.

HC test results in the text and in Appendices C and E are presented without accounting for FID response to methanol or the difference in HC composition because of the use of methanol fuel. The emission values presented in this report were also calculated using proposed methanol-fueled vehicle test procedures.[5] Modifications to the proposed test procedures were required as methanol emissions were not specifically measured. These modifications are discussed in Appendix D.

VI. Test Procedure

The evaluation program had three separate goals:

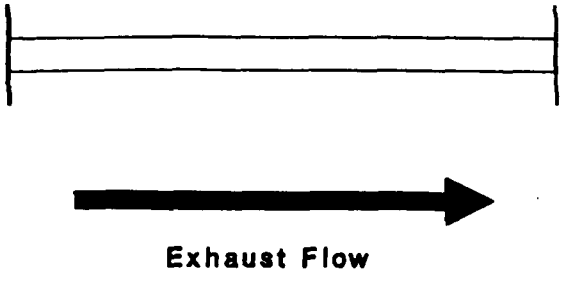
1. To evaluate different resistive heating strategies for the catalyst over the FTP cycle, with emphasis on elimination of HC and HCHO emissions;

2. To determine the effect of resistive heating on exhaust gas temperature; and

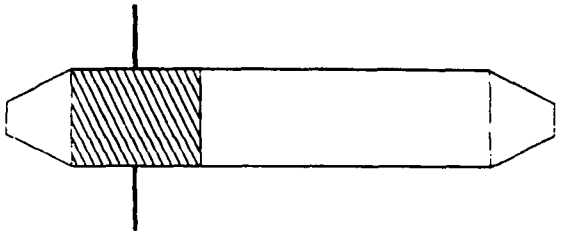
3. To evaluate the emissions performance of the vehicle using a specific heating mode, with emphasis on elimination of HC and HCHO emissions.

Different heating strategies were determined by first conducting a series of tests consisting of the Bag 1 portion (first 505 seconds) of the FTP cycle. Emissions of all regulated pollutants, as well as formaldehyde and methane, were sampled and measured. The better orientation in the exhaust train of the catalyst was selected, and a series of tests over the complete FTP cycle were then conducted to further define the heating strategy. The various configurations in which the converter was tested are explained in Figure 2.

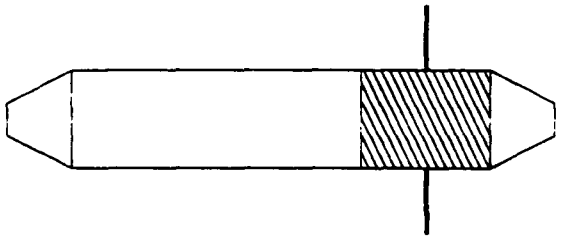
FIGURE 2
TESTED CONFIGURATIONS



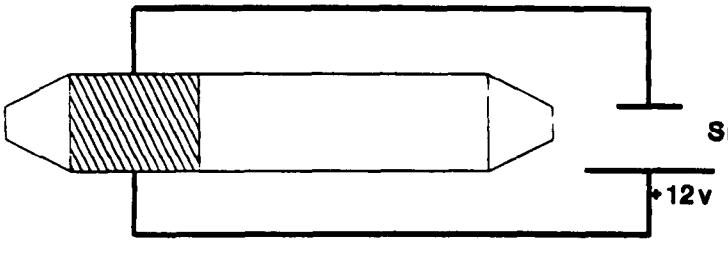
Baseline
No Converter Installed
Engine Out Emissions



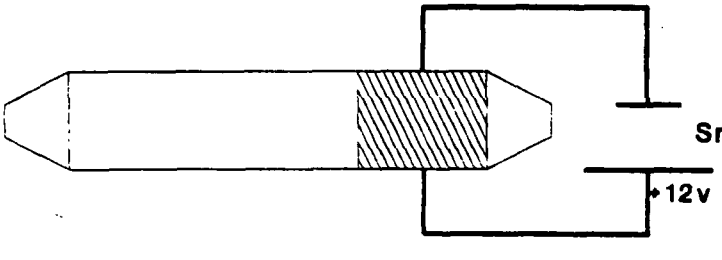
Configuration A
Converter Installed
Small Catalyst Brick Upstream
(Unheated)



Configuration B
Converter Installed
Small Catalyst Brick Downstream
(Unheated)



Configuration C
Converter Installed
Small Catalyst Brick Upstream
(Heated)



Configuration D
Converter Installed
Small Catalyst Brick Downstream
(Heated)

The catalyst can was fitted with thermocouples to measure inlet and outlet exhaust gas temperatures. A thermocouple was also installed in the middle of the heated catalyst brick so that the gas temperature in the middle of the substrate could be measured. Data from these thermocouples was translated to temperature data and recorded on a stripchart recorder during the heating strategy optimization testing. This temperature data is presented in the Discussion section.

The catalyst's emissions reduction performance was evaluated by testing it several times over the FTP cycle; the configurations tested no resistive heating as well as the optimized heating strategy determined in the first phase of the project. The results from this testing are also presented in the Discussion section.

VII. Discussion

A. Different Heating Strategy Evaluation

Two orientations, Configurations C and D of Figure 2, were possible with the heated converter in the exhaust train. Configuration C might be considered the more logical alternative as much of the energy generated during resistive heating and any exothermic chemical reactions could be transferred to the relatively cool exhaust gas passing through the converter immediately after a cold start. This energy would aid the catalytic processes downstream by warming the surface of the larger catalyzed but unheated monolith. Configuration D could not be ignored, however. The upstream catalyst eventually could be coated with a reducing or 3-way catalyst and the heated downstream monolith coated with an oxidizing formulation.

Several emission tests were conducted over the first 505 seconds of the FTP cycle to determine the preferred orientation. The results are presented in Figures 3 and 4; emissions of greatest interest were HCHO and HC. Detailed test results are given in Table C-1 of Appendix C.

The tests of Configuration D, which required heating of the catalyst for 15 seconds following cold start, produced substantially lower masses of both HC and HCHO than the tests which ceased resistive heating upon start. Configuration C, which placed the heated unit upstream, was almost 20 percent more efficient in both emission categories than Configuration D given similar heating strategies. Though the amount of testing was limited, the results indicated a slightly greater efficiency for Configuration C over Configuration D, with some resistive heating after cold start preferred.

FIGURE 3
INITIAL CONFIGURATION DETERMINATION

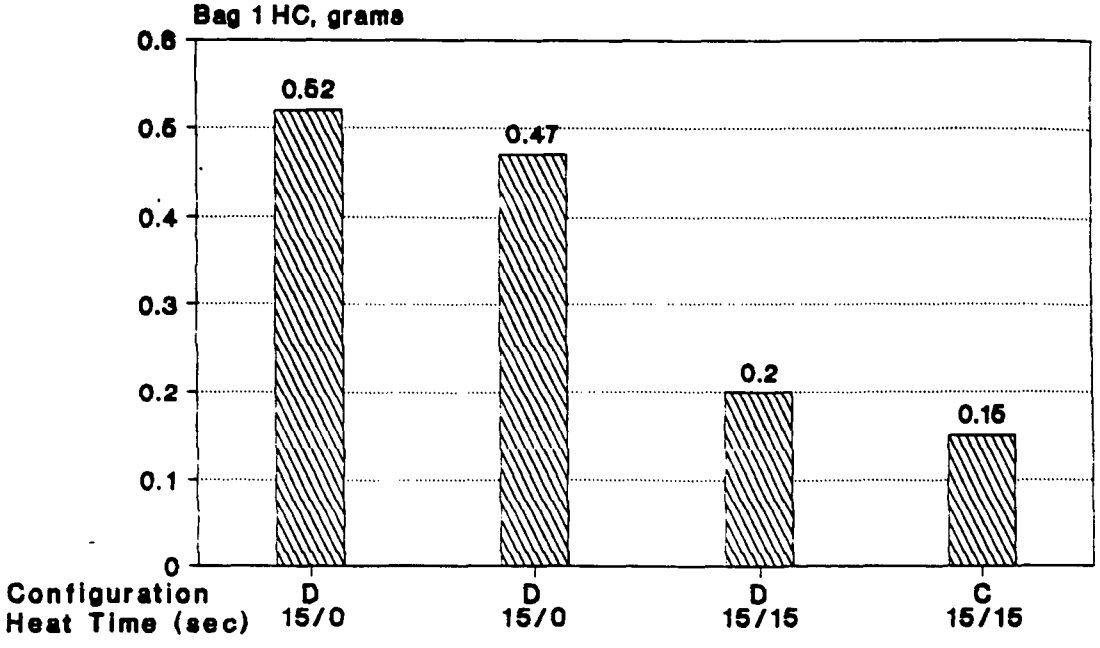
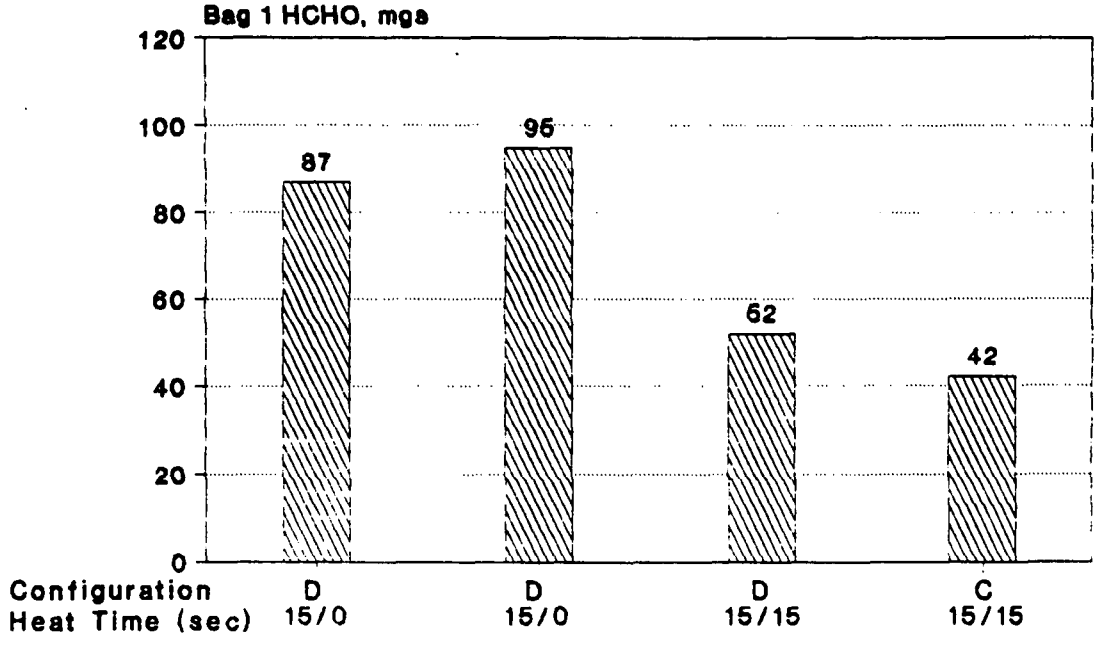


FIGURE 4
INITIAL CONFIGURATION DETERMINATION



Figures 5 and 6 present graphically the results of several tests over the FTP cycle utilizing different strategies for resistive heating of the catalyst during the early part of Bags 1 and 3 (first 505 seconds and final 505 seconds respectively of the test cycle). Figures 5 and 6 present grams of HC produced during Bags 1 and 3. Complete emission results are given in Table C-2 of Appendix C. Figure 6 shows the trends in Bag 1 emissions as a function of pre-start heating time for the data for which the post-start heating time was constant at 15 seconds.

FIGURE 5
REFINEMENT OF HEATING STRATEGY

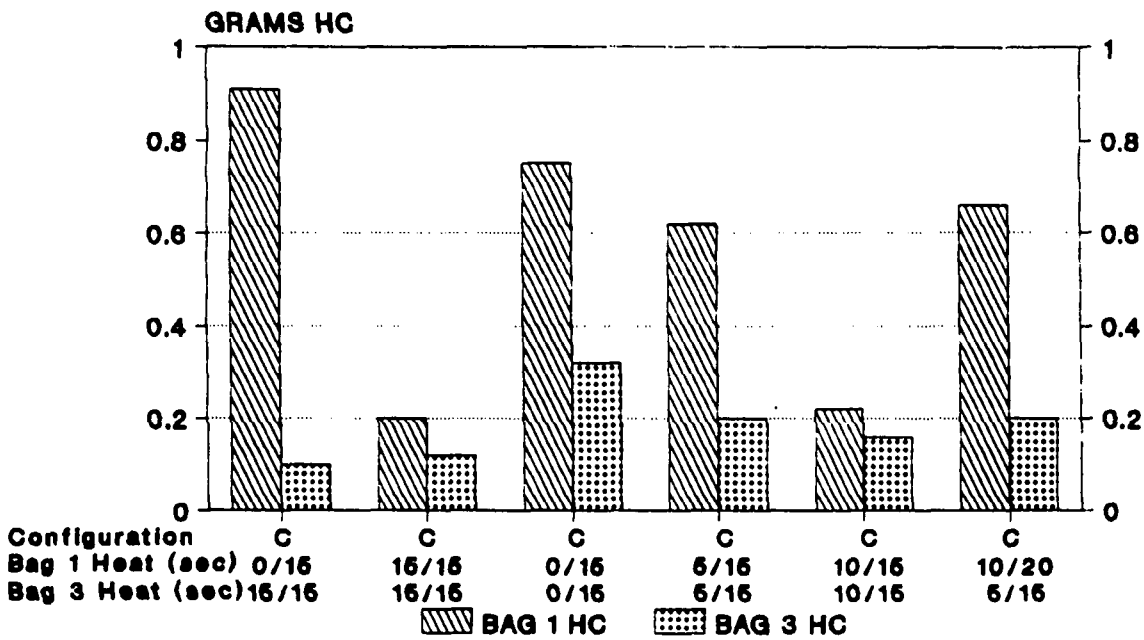
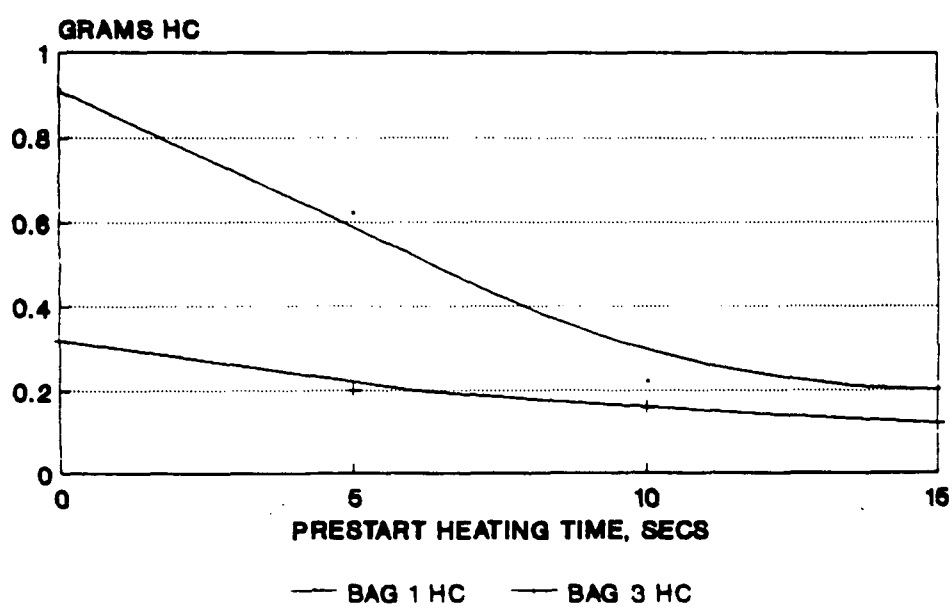


FIGURE 6
REFINEMENT OF HEATING STRATEGY

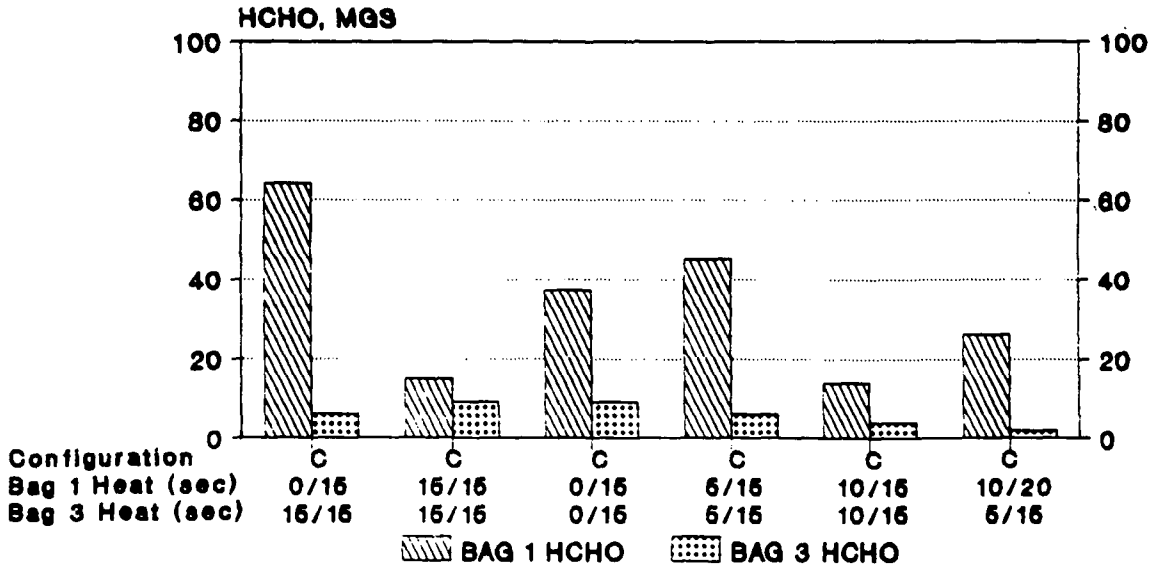


Lengthening the period of heating time prior to start generally reduced HC emission levels as shown in Figure 6. The two highest masses of HC produced during Bag 1, .91 and .75 grams respectively, occurred during tests when resistive heating commenced with the cold start. The lowest mass produced during Bag 1, .20 grams, occurred when the catalyst was resistively heated for 15 seconds prior to start. All tests included at least a 15-second period of heating following engine start to ensure that the catalyst experienced a rapid transition to a stabilized, warm temperature.

Bag 3 results followed Bag 1; generally, extending heating times prior to engine start produced lower masses of HC emissions. The lowest masses, .10 and .12 grams respectively, were produced after 15 seconds of heating prior to engine start. A 15-second heating period following start was included on each test.

Figure 7 present levels of HCHO measured under the same heating schemes as given in Figure 5. Generally, Bag 1 levels of formaldehyde decreased with increasing periods of resistive heating prior to start. Because of the lower mass of HCHO involved under hot start conditions of Bag 3, it is difficult to determine an optimum heating scheme. Some heating prior to hot start appears preferable though; 9 milligrams of HCHO were measured during the 0/15 Configuration C test, compared to 6, 4, and 2 milligrams measured during the three following tests which utilized short periods of resistive heating prior to the hot start.

FIGURE 7
REFINEMENT OF HEATING STRATEGY



B. Exhaust Gas Temperature Behavior During Resistive Heating

The catalytic converter was modified to accept three K-type thermocouples. These thermocouples measured inlet and outlet exhaust gas temperatures as well as gas temperature near the middle of the heated monolith. Temperature data from these thermocouples was collected during the tests previously described.

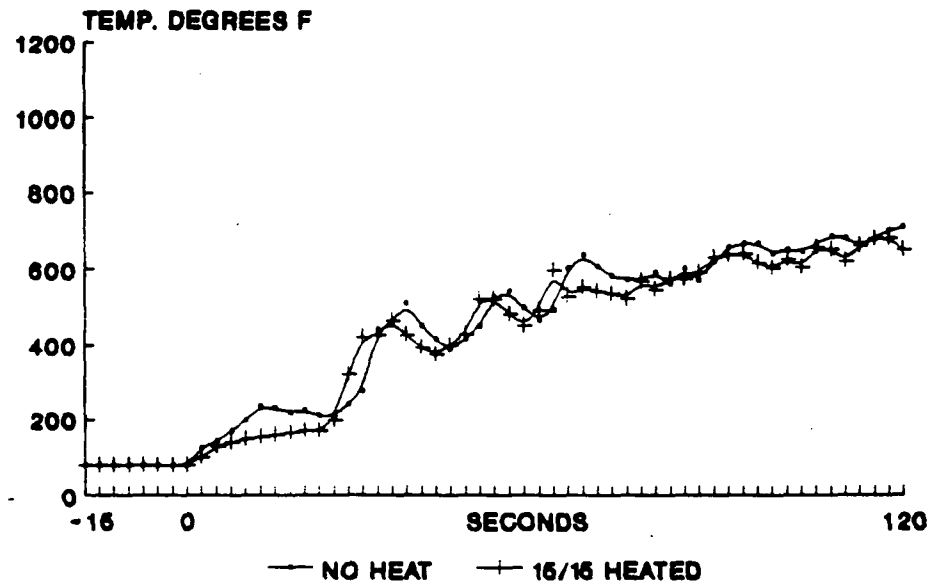
Figure 8 presents inlet exhaust gas temperature data over a portion of the FTP commencing at 15 seconds prior to start and ending with the completion of 120 seconds of this test. Two modes of catalyst operation are considered here:

1. No resistive heating of the catalyst; and

2. Resistive heating of the catalyst for 15 seconds prior to and 15 seconds following start, using Configuration C.

Inlet temperatures follow a similar pattern for both heating modes; resistively heating the catalyst did not appreciably affect inlet exhaust temperatures. Inlet temperatures appeared to stabilize at about 650-700°F after 120 seconds of engine operation over the FTP.

FIGURE 8
INLET GAS TEMPERATURES



Outlet exhaust gas temperatures for the conditions described in the previous paragraphs are given in Figure 9. Very different temperature patterns are evident here for the two heating schemes.

Outlet gas temperature rose very slowly for the first 40-50 seconds following engine start with the unheated catalyst. The next 30 seconds was characterized by a greatly increased rate of temperature change; during this time period, exhaust gas temperature rose from less than 200°F to approximately 650°F. A stabilizing of the exhaust temperature occurred after that, the temperature reaching a stabilized value of approximately 650-700°F.

A gradual rise in outlet exhaust gas temperature, from 75 to approximately 110°F, occurred during the 25 seconds following engine start with the heated catalyst. A very large change in temperature, from 100° to 800°F, occurred during the next 20-25 seconds of engine operation. Outlet exhaust gas temperature appeared to stabilize after approximately 1 minute of engine operation and the stabilized value was 750°F, or almost 50°F higher than the stabilized temperature from the unheated catalyst mode testing.

FIGURE 9
OUTLET GAS TEMPERATURES

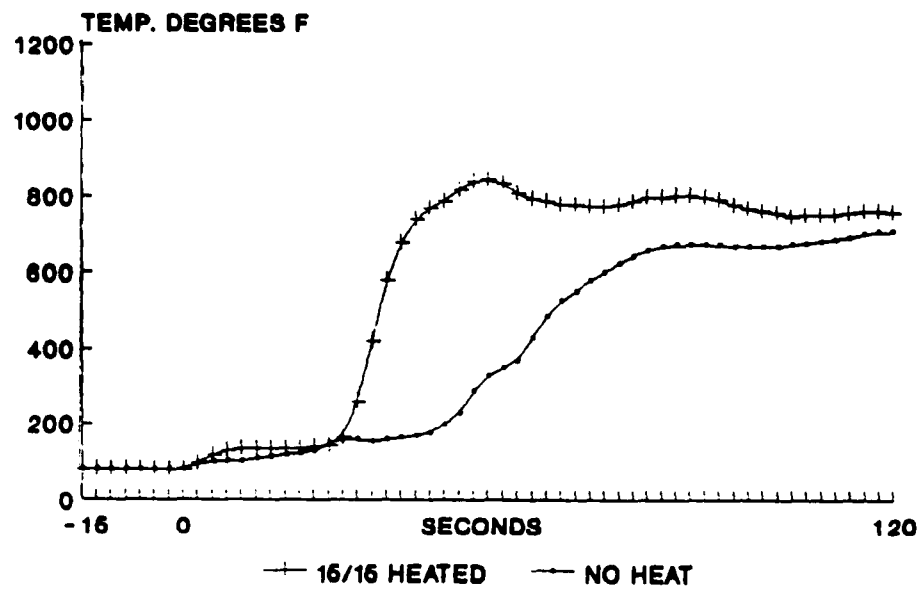
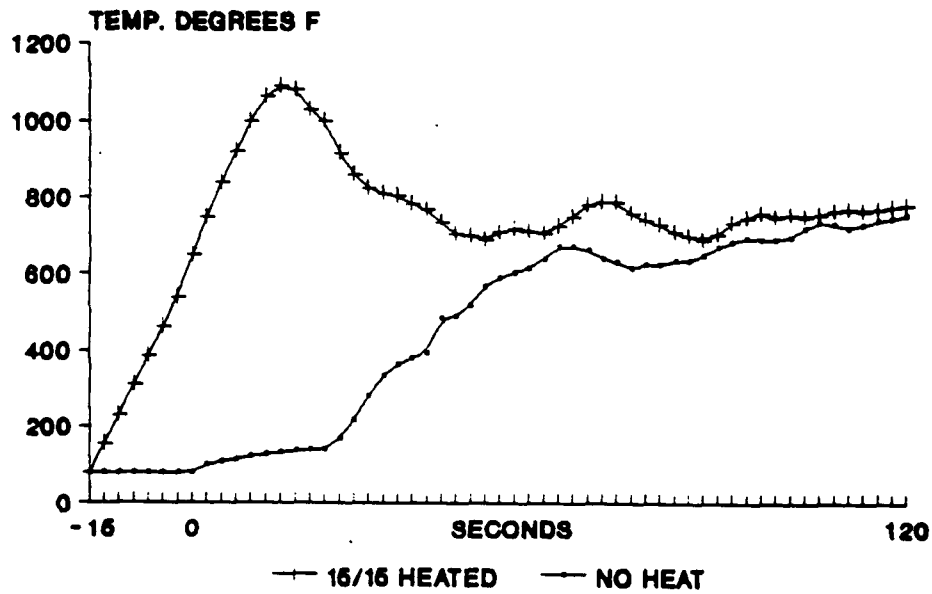


Figure 10 presents gas temperature at the middle of the catalyst bed for the heating modes and the time periods mentioned above.

In the unheated mode, the catalyst gas temperature gradually warmed to 100°F during the first 25 seconds of engine operation. A 35-40 second period of increased temperature change then occurred with the catalyst finally warming to 650°F after a total of 1 minute of engine operation. The mid-bed temperature then warmed to approximately 750°F after an additional minute of engine operation.

The heated catalyst attained a mid-bed gas temperature of approximately 650°F immediately before engine start through the 15-second preheat period. This rate of temperature increase continued after engine start until a maximum temperature of approximately 1100°F was attained 15 seconds after engine start. This gas temperature dropped steadily for the next 25 seconds; the decrease in temperature coincided with the cessation of resistive heating. During the remainder of the 120-second period following engine start the mid-bed gas temperature moved toward a stabilized value of approximately 750°F.

FIGURE 10
MIDBED GAS TEMPERATURE



The primary significance of the data in Figure 10 is that the gas at the mid-bed point of the converter reaches light-off temperature at vehicle start. This temperature is defined here to be greater than 600°F; a near stabilized exhaust gas temperature of 600°F was obtained with the unheated configuration only after 1 minute of engine operation. After start, the gas temperature measured by the mid-bed thermocouple did not drop below 600°F. Further, at no time during the first 120 seconds of engine operation did the temperature of the resistively heated catalyst drop below the temperature of the unheated configuration for the same point in time. If a light-off temperature of 600°F is all that is necessary, then the substrate temperature characteristics of the resistively heated catalyst tested here may be difficult to improve upon.

Configuration C was determined to be the better orientation of the catalyst in the exhaust. A period of resistive heating prior to and following cold start was determined to be necessary. Generally, more extended periods of heating prior to cold start generated lower emission levels

of HC and HCHO than shorter heating periods. A heating strategy of 10 seconds prior to cold start was chosen as a guess at a compromise; shorter heating periods may not have generated the light-off temperatures desired, whereas a longer period (15 or more seconds) might be considered by some unacceptable from a vehicle operator's standpoint. This resistive heating continued for 20 seconds following cold start to ensure a stabilized catalyst temperature. A 5/15 heating strategy for Bag 3 was chosen because catalyst light-off is considerably easier to achieve from hot start conditions.

C. Evaluation of Resistively Heated Catalyst

The resistive heating strategy for further evaluation of the catalyst was chosen to be:

1. Heating for 10 seconds prior to cold start and 20 seconds following cold start over the Bag 1 (first 505 seconds) portion of the FTP; and

2. Heating for 5 seconds prior to and 15 seconds following the hot start of the Bag 3 (final 505 seconds) portion of the FTP.

This strategy was chosen with a 10-second preheat time to achieve a timing that might be customer acceptable. The first diesel engines had glow plug preheat times of up to one minute. As they were improved, this time was reduced to 10 seconds or less. Since this time seemed to be acceptable to customers, we chose it as a maximum preheating time for this test phase.

Four complete FTP tests were conducted using this heating strategy. Several FTP tests were also conducted utilizing the unheated catalyst Configurations A and B referred to in Figure 2. Test results are summarized and compared in Tables 1 through 6. Details of individual test results are given in Appendix E.

Table 1 presents the average mass of emissions over the Bag 1 (first 505 seconds) portion of the FTP. The results are given in grams per test phase except for HCHO, which is presented in milligrams per test phase. Catalyst efficiencies over baseline in percent are provided in Table 2; a figure for percent improvement in emissions reduction by the heated catalyst over an average of the unheated catalyst configuration by emissions category is also provided in Table 2.

Unheated catalyst Configurations A and B showed substantial and similar reductions in mass of emissions produced for each pollutant category. The two pollutant categories of particular interest, HC and HCHO, were reduced to levels of 1.74 grams and 162 milligrams per phase respectively, when a simple average composite of the unheated configuration is considered. These levels equate to efficiencies of 74 and 88 percent respectively for these pollutant categories.

The resistively heated catalyst configuration reduced emission levels in almost every pollutant category from unheated catalyst levels. The heated catalyst reduced Bag 1 HC mass to 0.50 grams for a 92 percent efficiency; HCHO efficiency rose to 96 percent over baseline levels. The improvement in emission levels by the resistively heated catalyst over the unheated composite configuration was 71 and 67 percent for HC and HCHO respectively. Reduction of NOx levels was slightly improved (9 percent) by heating the catalyst versus the unheated composite.

CO increased to 11.6 grams over Bag 1 when the catalyst was heated from 8.5 grams with the unheated composite configuration. The reason for this increase is unknown. The testing over Bag 1 conducted as part of the heating strategy optimization indicated that 5.8 to 10.9 grams of CO might be expected given similar heating strategies. Additional testing may be necessary to determine the cause of this increase in emissions.

Table 3 presents the average mass of emissions produced over the Bag 3 (final 505 seconds) portion of the FTP. Test results are presented in the same format as that in Table 1. Table 4 presents catalyst efficiencies over Bag 3 in the same format as that in Table 2.

Again, the unheated Configurations A and B provided substantial and similar reductions in emissions from baseline levels over each pollutant category. HC and HCHO levels were reduced to .35 grams and 10 milligrams respectively over Bag 3, when the composite of Configuration A and B emission levels is considered. Composite unheated converter efficiencies exceeded 90 percent for each pollutant category with the exception of NOx. HCHO efficiency in particular was 99 percent for both unheated configurations.

The heated configuration substantially lowered emissions below levels from unheated catalyst testing in almost every pollutant category. HC and CO were reduced 29 and 40 percent respectively from unheated catalyst levels. HCHO mass emissions increased to 19 milligrams from 10 milligrams over the composite unheated configuration. The 19 milligram HCHO emission level corresponds to a greater than 98 percent decrease in emissions from baseline levels, however.

Table 5 presents FTP results for the catalyst configurations referred to in Tables 1 through 4. Catalyst efficiencies are presented in Table 6.

Table 1

Average Mass of Emissions

Bag 1 of FTP Cycle

Catalyst Configuration	HC (g)	NMHC* (g)	HC** (g)	OMHCE** (g)	CH3OH** (g)	CO (g)	NOx (g)	HCHO (mg)
Baseline (no catalyst)	6.63	6.58	0.78	9.19	18.01	33.03	8.36	1324
Configuration A	1.85	1.80	0.22	2.45	4.99	9.33	4.56	157
Configuration B	1.62	1.58	0.20	2.18	4.40	7.66	4.10	166
Average of A and B	1.74	1.69	0.21	2.32	4.70	8.50	4.33	162
Configuration C-Heated 10/20***	0.50	0.44	0.06	0.67	1.35	11.56	3.92	54

Table 2

Catalyst Efficiencies Over Bag 1 of FTP

Catalyst Configuration	HC (%)	NMHC (%)	HC** (%)	OMHCE** (%)	CH3OH** (%)	CO (%)	NOx (%)	HCHO (%)
Configuration A	72	73	72	73	72	72	45	88
Configuration B	76	76	74	76	76	77	51	87
Average of A and B	74	74	73	75	74	74	48	88
Heated configuration versus baseline	92	93	92	93	93	65	53	96
Heated configuration versus unheated composite	71	74	71	71	71	(36)	9	67

* Non-methane hydrocarbons.

** Calculated values per proposed rulemaking.

*** Catalyst preheated 10 seconds prior to cold start and 20 seconds following start.

Table 3

Average Mass of Emissions

Bag 3 of FTP Cycle

Catalyst Configuration	HC (g)	NMHC (g)	HC* (g)	OMHCE* (g)	CH3OH* (g)	CO (g)	NOx (g)	HCHO (mg)
Baseline (no catalyst)	3.71	3.69	0.44	5.31	10.09	21.12	8.26	1095
Configuration A	0.36	0.34	0.02	0.47	0.97	1.26	3.60	8
Configuration B	0.34	0.31	0.04	0.45	0.92	2.96	3.47	12
Average of A and B	0.35	0.33	0.03	0.46	0.95	2.11	3.54	10
Configuration C-Heated 5/15**	0.25	0.21	0.03	0.33	0.67	1.27	3.42	19

Table 4

Catalyst Efficiencies Over Bag 3 of FTP

Catalyst Configuration	HC (%)	NMHC (%)	HC* (%)	OMHCE* (%)	CH3OH* (%)	CO (%)	NOx (%)	HCHO (%)
Configuration A	90	91	95	91	90	94	56	99
Configuration B	91	92	91	92	91	86	58	99
Average of A and B	91	91	93	91	91	90	57	99
Heated configuration versus baseline	93	94	93	94	93	94	59	98
Heated configuration versus unheated composite	29	36	--	28	29	40	3	(90)

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* Calculated values per proposed rulemaking.

** Catalyst preheated 5 seconds prior to hot start and 15 seconds following start.

Table 5

Emission Levels Over The FTP Cycle

Catalyst Configuration	HC g/mi	NMHC g/mi	HC* g/mi	OMHCE* g/mi	CH3OH* g/mi	CO g/mi	NOx g/mi	HCHO mg/mi
Baseline (no catalyst)	1.11	1.10	0.13	1.58	3.00	6.62	1.74	337
Unheated Configuration A	0.14	0.13	0.02	0.19	0.38	0.73	0.85	10
Unheated Configuration B	0.13	0.12	0.02	0.17	0.36	0.92	0.75	12
Average of A and B	0.14	0.13	0.02	0.18	0.37	0.83	0.80	11
Configuration C-Heated 10/20 Bag 1, 5/15 Bag 3	0.05	0.04	0.01	0.07	0.14	0.77	0.83	5

Table 6

Catalyst Efficiencies Over The FTP Cycle

Catalyst Configuration	HC (%)	NMHC (%)	HC* (%)	OMHCE* (%)	CH3OH* (%)	CO (%)	NOx (%)	HCHO (%)
Unheated Configuration A	89	90	86	90	89	89	55	97
Unheated Configuration B	89	90	86	90	89	86	57	96
Average of A and B	89	90	86	90	89	87	56	97
Heated configuration versus baseline	95	96	92	96	95	88	52	99
Heated configuration versus unheated composite	64	69	50	61	62	7	(4)	55

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* Calculated values per proposed rulemaking.

The unheated composite configuration produced HC and HCHO levels of .14 g/mi and 11 mg/mi respectively over the FTP. These levels were reduced to .05 g/mi and 5 mg/mi respectively by resistively heating the catalyst. CO and NOx levels were relatively unchanged by heating the catalyst versus the unheated configurations.

Individual FTP HCHO levels in Table E-3 vary from 4 to 7 mg/mi for this heated catalyst testing; Bag 1 levels vary from 42 to 60 mg. These levels substantially exceed those from testing conducted during the prior phase, reported in Table C-2. For example, the three tests of Configuration C presented in Table C-2 that involve preheating the catalyst for 10 seconds or longer prior to Bag 1 cold start produced HCHO Bag 1 levels of 15, 14, and 26 mg. These same tests produced weighted FTP levels of 3, 1, and 2 mg/mi.

The reason for this increase in HCHO levels between test sets is unknown. The baseline levels presented in Table E-1 are high when compared to the resistively heated catalyst levels from either Table C-2 or E-3. Resolution of chromatograph test results may be difficult at the low emission levels considered here. Higher levels of HCHO from the later tests under the same conditions could also mean that deterioration of the catalyst's activity was occurring. Additional car and bench testing of the catalyst and of background levels in the test cell may be necessary to explain this difference.

VIII. Conclusions

1. Best results were obtained when the resistively heated portion of the catalyst was located upstream.

2. Generally, lower emissions levels of HC and HCHO over Bag 1 of the FTP resulted when resistive heating time of the catalyst prior to cold start was increased. Preheating periods in excess of 15 seconds were not evaluated.

3. Extending the resistive preheating time prior to the hot start generally lowered emission levels of HC and HCHO from Bag 3 of the FTP. Preheating periods in excess of 15 seconds were not evaluated.

4. A 12-volt DC power source was able to increase gas temperature in the center of the catalyst from 75° to 650°F. This temperature rise occurred during 15 seconds of catalyst preheat prior to engine cold start. Fifteen seconds of additional heating following cold start raised mid-bed gas temperature to 1100°F at the end of this period.

5. Resistively heating the catalyst for 10 seconds prior to and 20 seconds following cold start lowered Bag 1 emissions of HC and HCHO to 0.50 grams and 54 milligrams respectively. The levels were a 71 and 67 percent improvement respectively over HC and HCHO levels from a composite of two unheated configurations of the same catalyst.

6. Resistively heating the catalyst for 5 seconds prior to and 15 seconds following start lowered Bag 3 emission levels of HC and HCHO to 0.25 grams and 19 milligrams, respectively. These figures represent a 93 and 98 percent reduction in HC and HCHO emissions from baseline levels over the Bag 3 portion of the FTP.

7. Weighted FTP emission level averages from testing the catalyst with the heating strategy utilized were 0.05 g/mi and 5 mg/mi for HC and HCHO, respectively. These figures represent a 95 and 99 percent efficiency from baseline HC and HCHO levels, respectively.

IX. Future Effort

The test vehicle is equipped with an air pump; modifications to the exhaust system permit testing of converters as simulated oxidation catalysts. This converter will be tested as a simulated oxidation catalyst utilizing the final heating strategy.

A gasoline-powered 1987 Volkswagen Golf has been procured by CTAB to be used as a test vehicle for this converter. The catalyst will be emission tested on the vehicle using the final heating strategy. Emission results from resistively heated catalyst testing will be compared to engine-out emission levels and emission levels from the vehicle equipped with a stock catalytic converter. Because the unburned fuel from this car will not contain oxygen, in contrast to methanol, we estimate that some air injection may be necessary for good results.

The success of this effort has prompted us to begin looking at the background levels of HCHO in our test cell more closely. We are considering running background tests for each test in the future and accounting for background in a manner similar to that done for other pollutants. No allowance for background levels was made in the results reported in this report, even though one test (which is being repeated) indicated that the background levels were roughly equivalent to 1 mg/mi.

At the low levels of HCHO measured (below 5 mg/mi) we sometimes see results in the DNPH cartridges that are difficult to understand. For example, the backup cartridge maybe measured as containing more HCHO than the primary cartridge. This "shouldn't happen." As a result, we are reexamining the sampling approach and procedure. We may have to improve the procedure at the low levels of HCHO measured in each bag of the test.

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XI. References

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APPENDIX A

CAMET RESISTIVELY HEATED CATALYTIC CONVERTER SPECIFICATIONS AND POWER REQUIREMENTS

Construction	Dual-bed element composed of two metal monolith catalysts, a smaller resistively heatable one and a larger one with no provisions for resistive heating
Catalyst material/loadings	Proprietary
Shape	Rectangular
Overall outer dimensions (excluding mounting flanges)	10-3/4" x 4-1/4" x 2-3/4"
Length: flange to flange	14-3/4"
Heated brick dimensions	3" x 4-1/4" x 2-3/4" (approx)
Unheated brick dimensions	4" x 4-1/4" x 2-3/4" (approx)
Power supply	12-volt automotive battery
Power delivered	300-400 amps at 10-11 volts
Heatup time to 600°F with no gas flow through the converter	Less than 20 seconds from 70°F

APPENDIX B

TEST VEHICLE SPECIFICATIONS

Vehicle type	1980-81 Volkswagen Rabbit
Fuel	M100 (neat methanol)
Engine	
Displacement	1.6 liter
Bore	7.95 cm
Stroke	8.00 cm
Compression ratio	12.5 to 1
Fuel System	Type Bosch CIS fuel injection with Lambda feedback control, calibrated for methanol operation
Cold start injectors	Two injectors, valve pulse for 8 seconds after start when coolant temperature below 0° C.
Transmission	
Type	Production 1981 automatic three-speed
Torque converter ratio	2.44
Stall speed	2000-2200 rpm
Gear ratios	
1	2.55
2	1.45
3	1.00
Axle	3.57
Curb weight	2822 lbs
Equivalent test weight	2500 lbs
Actual dynamometer horsepower	7.7 hp

APPENDIX C

HEATING STRATEGY TESTS

Table C-1

Heating Strategy Tests

Cold Start Bag 1 Portion of FTP

Test Number	Configuration Heat Strategy	NMHC* (g)	HC (g)	HC** (g)	OMHCE** (g)	CH3OH** (g)	CO (g)	NOx (g)	HCHO (mg)
883951	Configuration D 15/0***	.48	.52	.06	.72	1.43	5.83	4.48	87
883952	Configuration D 15/0	.43	.47	.06	.66	1.29	5.50	4.08	95
883953	Configuration D 15/15	.16	.20	.02	.28	0.55	5.30	4.18	52
883956	Configuration C 15/15	.11	.15	.02	.22	0.42	5.80	4.40	42

* Non-methane hydrocarbons.

** Calculated values per proposed rulemaking.

*** Notation indicates time of preheating catalyst in seconds prior to start/time of heating in seconds immediately following start.

Table C-2

Heating Strategy Tests

FTP Cycle

Test Number/Type Heating Strategy	NMHC	HC	CO	NOx	HCHO*	HC**	OMHCE**	CH3OH**
883955/Configuration D Bag 1--15/15***								
Bag 1(g)	.68	.73	8.70	3.93	79	.09	.98	1.98
Bag 2(g)	.02	.07	3.33	1.82	11	.01	.10	0.21
Bag 3(g)	.32	.35	3.80	3.48	12	.04	.46	0.96
Composite(g/mi)	.07	.08	1.23	0.73	7	.01	.11	0.21
883958/Configuration C Bag 1--0/15 Bag 3--15/15								
Bag 1(g)	.88	.91	8.18	4.71	64	.11	1.21	2.48
Bag 2(g)	.02	.08	3.32	2.35	4	.01	0.11	0.23
Bag 3(g)	.05	.10	3.91	4.23	6	.01	0.14	0.28
Composite(g/mi)	.06	.07	1.21	0.90	5	.01	0.10	0.20
883959/Configuration C Bag 1--15/15 Bag 3--15/15								
Bag 1(g)	.16	.20	9.13	4.78	15	.02	.27	.55
Bag 2(g)	.02	.07	2.51	2.33	7	.01	.10	.20
Bag 3(g)	.06	.12	4.25	4.39	9	.01	.16	.32
Composite (g/mi)	.02	.03	1.18	0.92	3	.01	.04	.08
884263/Configuration C Bag 1--0/15 Bag 3--0/15								
Bag 1(g)	.71	.75	8.34	4.94	37	.09	.99	2.03
Bag 2(g)	.02	.07	4.60	2.28	6	.01	.10	0.20
Bag 3(g)	.29	.32	3.62	4.63	9	.04	.43	0.89
Composite(g/mi)	.07	.08	1.37	0.94	4	.01	.10	0.21

* HCHO is given in mg for bag data and mg/mi for composite data.

** Calculated values per proposed rulemaking.

*** Notation indicates preheating catalyst 15 seconds prior to start of vehicle and 15 seconds into test.

Table C-2 (cont'd)

Heating Strategy Tests

FTP Cycle

Test Number/Type Heating Strategy	NMHC	HC	CO	NOx	HCHO*	HC**	OMHCE**	CH3OH**
884418/Configuration C Bag 1--5/15 Bag 3--5/15								
Bag 1(g)	.58	.62	8.54	5.12	45	.07	.82	1.67
Bag 2(g)	.05	.10	5.07	2.44	7	.01	.14	0.28
Bag 3(g)	.15	.20	4.97	4.69	6	.02	.26	0.54
Composite(g/mi)	.05	.06	1.54	0.98	4	.01	.09	0.18
884440/Configuration C Bag 1--10/15 Bag 3--10/15								
Bag 1(g)	.16	.22	8.68	4.89	14	.03	.29	0.59
Bag 2(g)	.04	.09	7.88	2.16	3	.01	.12	0.25
Bag 3(g)	.03	.16	4.76	4.55	4	.02	.21	0.43
Composite(g/mi)	.02	.04	1.91	0.91	1	.01	.05	0.10
884419/Configuration C Bag 1--10/20 Bag 3--5/15								
Bag 1(g)	.62	.66	10.97	4.52	26	.08	.87	1.81
Bag 2(g)	.63	.08	4.85	2.48	3	.01	.11	0.23
Bag 3(g)	.15	.20	6.10	4.09	2	.02	.26	0.54
Composite(g/mi)	.05	.06	1.74	0.90	2	.01	.08	0.17

* HCHO is given in mg for bag data and mg/mi for composite data.

** Calculated values per proposed rulemaking.

APPENDIX D

MODIFICATION OF THE PROPOSED METHANOL-FUELED VEHICLE TEST PROCEDURES

As proposed, the regulations in reference 5 require the measurement of methanol (CH_3OH) and formaldehyde (HCHO). Methanol emissions are especially important since the dilution factor equation includes CH_3OH emissions. At the time the testing reported on here was conducted, the EPA test cell in which this program was run was not equipped to measure CH_3OH. Therefore, the results shown here were computed with a FID response factor of 0.75 and an assumed HC ppm to methanol ppm factor of xx/.85, where xx is the fraction of methanol in a methanol gasoline blend. HC results were then computed using the procedures specified in the draft regulations.[5]

APPENDIX E

CATALYST EVALUATION - DETAILED FTP RESULTS

Table E-1

Individual FTP Test Results

Baseline Testing

Test Number/Type	HC	NMHC	HC*	OMHCE*	CH3OH*	CO	NOx	HCHO**
883229/Baseline								
Bag 1 (g)	7.60	7.56	0.90	10.42	20.66	33.22	8.47	1256
Bag 2 (g)	3.38	3.36	0.40	5.08	9.19	23.06	4.62	1525
Bag 3 (g)	3.90	3.88	0.46	5.61	10.60	19.81	8.16	1205
Composite (g/mi)	1.19	1.18	0.14	1.71	3.23	6.52	1.73	369
883231/Baseline								
Bag 1 (g)	7.23	7.19	0.85	9.86	19.66	31.08	8.55	1065
Bag 2 (g)	3.45	3.42	0.41	5.08	9.38	21.94	4.80	1323
Bag 3 (g)	4.05	4.02	0.48	5.75	11.01	20.69	8.52	1097
FTP (g/mi)	1.19	1.18	0.14	1.68	3.22	6.29	1.78	322
884422/Baseline								
Bag 1 (g)	5.46	5.42	0.64	7.78	14.83	32.47	8.15	1543
Bag 2 (g)	3.09	3.06	0.36	4.56	8.41	25.06	4.54	1200
Bag 3 (g)	3.36	3.34	0.40	4.83	9.14	22.79	8.10	1038
Composite (g/mi)	0.98	0.97	0.12	1.42	2.67	6.93	1.69	327
884423/Baseline								
Bag 1 (g)	6.22	6.16	0.73	8.71	16.90	35.33	8.27	1433
Bag 2 (g)	3.23	3.20	0.38	4.78	8.79	23.33	4.90	1275
Bag 3 (g)	3.54	3.51	0.42	5.06	9.61	21.18	8.27	1038
Composite (g/mi)	1.06	1.05	0.12	1.52	2.87	6.75	1.76	331

* Calculated values per proposed rulemaking.

** HCHO given in mg and mg/mi.

Table E-2

Individual FTP Test Results

Unheated Catalyst Mode

Test Number/Type	HC	NMHC	HC*	OMHCE*	CH3OH*	CO	NOx	HCHO**
883239/Configuration A								
Bag 1 (g)	1.53	1.50	0.18	2.04	4.16	5.40	4.35	121
Bag 2 (g)	0.07	0.03	0.01	0.10	0.20	1.16	1.81	8
Bag 3 (g)	0.19	0.17	0.02	0.26	0.53	1.80	3.75	8
Composite (g/mi)	0.11	0.10	0.01	0.15	0.31	0.60	0.78	9
883240/Configuration A								
Bag 1 (g)	1.81	1.77	0.21	2.42	4.93	7.09	4.95	157
Bag 2 (g)	0.10	0.05	0.01	0.14	0.28	1.71	1.99	5
Bag 3 (g)	0.29	0.26	0.03	0.38	0.79	1.99	3.51	17
Composite (g/mi)	0.14	0.13	0.02	0.19	0.38	0.78	0.81	11
884121/Configuration A								
Bag 1 (g)	2.10	2.06	0.25	2.80	5.71	13.22	4.69	169
Bag 2 (g)	0.01	0.01	0.01	0.02	0.04	0.02	2.88	3
Bag 3 (g)	0.48	0.46	0.06	0.62	1.31	0.62	3.66	2
Composite (g/mi)	0.16	0.15	0.02	0.21	0.43	0.81	0.93	10
884441/Configuration A								
Bag 1 (g)	1.90	1.86	0.22	2.54	5.15	11.60	4.25	180
Bag 2 (g)	0.04	0.01	0.01	0.06	0.11	0.01	2.76	1
Bag 3 (g)	0.46	0.45	0.06	0.61	1.26	0.61	3.48	4
Composite (g/mi)	0.15	0.14	0.02	0.20	0.41	0.71	0.88	11
883242/Configuration B								
Bag 1 (g)	1.66	1.61	0.20	2.23	4.51	7.50	4.04	165
Bag 2 (g)	0.07	0.02	0.01	0.10	0.20	1.94	1.76	5
Bag 3 (g)	0.33	0.30	0.04	0.43	0.89	3.03	3.51	3
Composite (g/mi)	0.13	0.12	0.02	0.17	0.36	0.92	0.74	10
883950/Configuration B								
Bag 1 (g)	1.58	1.54	0.19	2.12	4.29	7.83	4.16	166
Bag 2 (g)	0.07	0.02	0.01	0.10	0.20	1.89	1.94	10
Bag 3 (g)	0.35	0.32	0.04	0.46	0.95	2.88	3.42	22
Composite (g/mi)	0.13	0.12	0.02	0.17	0.35	0.92	0.76	13

* Calculated values per proposed rulemaking.

** HCHO given in mg and mg/mi.

Table E-3

Individual FTP Test Results - Configuration C

Catalyst Heated 10/20 Bag 1, 5/15 Bag 3

Test Number	HC	NMHC	HC*	OMHCE*	CH3OH*	CO	NOx	HCHO**
884442								
Bag 1 (g)	0.82	0.76	0.10	1.09	2.24	15.48	4.17	42
Bag 2 (g)	0.02	0.01	0.01	0.03	0.05	0.02	2.60	15
Bag 3 (g)	0.25	0.21	0.03	0.33	0.67	1.43	3.33	17
Composite (g/mi)	0.07	0.06	0.01	0.09	0.19	1.00	0.84	6
884443								
Bag 1 (g)	0.32	0.28	0.04	0.44	0.87	7.81	3.92	60
Bag 2 (g)	0.03	0.01	0.01	0.04	0.09	0.02	2.58	1
Bag 3 (g)	0.22	0.19	0.03	0.29	0.60	1.21	3.35	2
Composite (g/mi)	0.04	0.03	0.01	0.05	0.11	0.54	0.82	4
884444								
Bag 1 (g)	0.30	0.24	0.04	0.42	0.82	10.53	3.73	57
Bag 2 (g)	0.03	0.01	0.01	0.04	0.07	0.06	2.75	32
Bag 3 (g)	0.25	0.23	0.03	0.35	0.69	1.12	3.66	50
Composite (g/mi)	0.04	0.03	0.01	0.06	0.11	0.70	0.86	7
884445								
Bag 1 (g)	0.54	0.46	0.06	0.73	1.47	12.40	3.86	59
Bag 2 (g)	0.03	0.01	0.01	0.04	0.07	0.04	2.51	2
Bag 3 (g)	0.26	0.22	0.03	0.34	0.71	1.33	3.35	7
Composite (g/mi)	0.05	0.04	0.01	0.07	0.15	0.82	0.81	4

* Calculated values per proposed rulemaking.

** HCHO given in mg and mg/mi.