EPA/AA/CTAB/88-12

Technical Report

Evaluation Of A Resistively Heated Metal Monolith Catalytic Converter On A Gasoline-Fueled Vehicle

by

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AIR AND RADIATION

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MEMORANDUM

SUBJECT: Exemption From Peer and Administrative Review

FROM: Karl H. Hellman, Chief
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 A Gasoline-Fueled Vehicle," (EPA/AA/CTAB/88-12) concerns an emissions testing program conducted on a gasoline-fueled Volkswagen Golf vehicle. The emissions control technology tested was a resistively heated metal monolith catalytic converter provided by Camet, a subsidiary of W. R. Grace. The vehicle was evaluated at two different test cell temperatures, 72-74°F and 20°F.

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: ______________________ Date: __________
Charles L. Gray, Jr., Dir., ECTD

Nonconcurrence: ______________________ Date: __________
Charles L. Gray, Jr., Dir., ECTD

cc: E. Burger, ECTD

Table of Contents

Page Number

I. Summary

A prototype metal monolith catalytic converter, which may be resistively heated, was emission tested on a gasoline-fueled vehicle. The vehicle was tested at 72-74°F ambient test cell conditions and at 20°F ambient "cold-room" conditions.

The testing reported here was conducted over the Federal test procedure (FTP) cycle.[1] The most efficient resistive heating/excess air addition strategy tested at 72-74°F ambient conditions is given below:

Bag 1: Preheat the catalyst for 20 seconds prior to cold start and heat for 20 seconds following cold start. Bottled air at 2.0 standard cubic feet per minute (SCFM) was added ahead of the catalyst at cold start until the cessation of resistive heating (the last 20 seconds).

Bag 2: No resistive heating or excess air addition employed.

Bag 3: Preheat the catalyst for 10 seconds prior to hot start and heat for 15 seconds following hot start. Bottled air at 2.0 SCFM was added at hot start until the cessation of resistive heating (the last 15 seconds).

Hydrocarbons (HC) and carbon monoxide (CO) were reduced to 0.043 and 0.57 grams per mile respectively with this strategy. No weighted FTP benefits for HC and CO were noted at 20°F ambient conditions with the heating/air addition strategies employed.

II. Introduction

The major portion of HC and CO emissions measured from a catalyst-equipped gasoline-fueled vehicle over the FTP cycle are generated during cold start and warmup of the catalyst. 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 resistively heated metal monolith catalyst has been evaluated by EPA on a methanol-fueled vehicle. Results from this previous testing indicated the feasibility of the concept of a resistively heated metal monolith substrate as a quick light-off catalyst support.[2] This catalytic converter, when tested as a three-way catalyst without resistive heating, controlled emissions over the Federal test procedure (FTP) to levels previously obtained by ceramic substrate converters coated with noble metal catalyst formulations. Resistively heating the catalyst substantially lowered HC and formaldehyde (HCHO) emission levels compared to those from the unheated tests.

The purpose of the testing reported on here was to evaluate this resistively heated catalyst technology on a gasoline-fueled vehicle. In order to facilitate qualitative comparisons in emissions results with the levels measured with the methanol vehicle, a gasoline-fueled Volkswagen Golf with a similar fuel injection system was a desirable choice as the test vehicle, and such a vehicle was loaned to EPA by Volkswagen for this test program.

We were interested in two separate ambient temperature ranges for this testing: 1) 72-74°F, and 2) 20°F. The first range refers to our usual laboratory test cell temperatures, within the boundaries (68-86°F) required for constant volume sampler (CVS) dilution air by the FTP.[3] The 20°F conditions were of interest because other researchers [4,5] have reported that HC and CO emissions rise as the ambient temperatures at which gasoline-fueled vehicles operate at are reduced.

The first part of this evaluation, referred to in the Discussion as "Testing at 72-74°F Conditions" was conducted in a chassis dynamometer test cell at those ambient temperatures. This testing was conducted over the FTP cycle. The second part of the Discussion refers to testing conducted in a temperature controlled chamber which housed a chassis dynamometer. Test cell temperatures could be varied over the range 20-70°F; 20°F was chosen for this cold temperature evaluation because it was the temperature at which many other test programs have been run.

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. This is the same converter that was evaluated on a methanol-fueled vehicle in [2].

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.

Detailed specifications are provided in Appendix A.

IV. Vehicle Description

The test vehicle was a 1987 Volkswagen Golf 4-door sedan, equipped with automatic transmission, continuous fuel injection (Bosch CIS) and radial tires. The 1.78-liter engine had a rated maximum power output of 85 horsepower at 5250 rpm. The vehicle was tested at 2,500 lbs inertia weight and 7.7 actual dynamometer horsepower.

A more detailed description of the vehicle is provided in Appendix B.

V. Test Facilities and Analytical Methods

Emissions testing at 72-74°F conditions 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. Methane was measured with a Bendix Model 8205 methane analyzer.

Exhaust formaldehyde was measured using a dinitrophenyl hydrazine (DNPH) technique.[6] 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.

Exhaust HC emissions at 20°F ambient conditions were measured with a Beckman Model 400 FID. CO was measured with a Horiba Model AIA 23 infrared detector, while NOx emissions at 20°F were determined by chemiluminescent technique using a Beckman Model 951A NOx analyzer.

VI. Test Procedure

The gasoline-fueled vehicle evaluation of this catalyst technology was conducted in two phases:

1. An evaluation at 72-74°F ambient conditions, and
2. Testing at 20°F ambient conditions.

The first phase of this evaluation was conducted to determine the catalysts' effectiveness at reducing pollutants in vehicle exhaust at 72-74°F ambient conditions. Of special interest was the determination of the catalysts' ability to oxidize HC and CO emissions. Although HCHO emissions from light-duty gasoline-fueled vehicles are not currently regulated, they were measured during this testing to determine if this catalyst reduced emissions below stock catalyst levels.

Testing during this phase was conducted over the FTP cycle. Of particular interest was the difference in HC and CO emission levels between the first and third bag portions (initial and final 505 seconds of the Urban Dynamometer Driving Schedule). These portions involve similar driving conditions; the first bag begins with a cold start however, compared to a hot start beginning the third bag. We wished to know if the resistively heated catalyst could lower Bag 1 emissions to Bag 3 levels by bringing the catalyst to light-off conditions prior to cold start.

A tap was placed in the exhaust line approximately eight inches upstream from the catalytic converter for the introduction of bottled air. Admission of air ahead of the catalyst simulates oxidation catalyst conditions over timeframes of interest. Controlling air pressure at the gas bottle regulator allowed the variation of airflow through the catalyst.

The second phase of this evaluation was conducted to determine the effectiveness of this catalyst system at a lower ambient temperature, 20°F. This testing was also conducted over the FTP cycle.

VII. Discussion

A. Testing At 72-74°F Conditions

The initial evaluation of the resistively heated converter was conducted over the FTP cycle only. The test cell temperature varied between 72° and 74°F during this testing.

The test vehicle was originally equipped with a stock underfloor noble metal monolith catalyst. The car was tested twice in this configuration; this is referred to below as stock catalyst testing. This catalyst was removed and replaced with a straight exhaust pipe; testing in this configuration is referred to below as baseline testing.

The Camet resistively heated metal monolith was evaluated in the same underfloor location that the stock catalyst occupied in the exhaust stream.

Two conditions were varied during the evaluation of the heated converter: the amount of time that resistive heating was applied to the catalyst and the amount of air flowed over the catalyst during heating.

The electrical circuit consisted of a 12-volt battery power source, a starter switch and relay, on/off power indicator, heavy gauge copper wiring and the catalytic converter. Resistive heating was confined to the cold-start/hot-start portions (Bags 1 and 3) of the FTP. The following scheme had been developed during the methanol-fueled vehicle evaluation of this technology:

1. Heating for 10 seconds prior to cold start and 20 seconds following cold start during the Bag 1; and

2. Heating for 5 seconds prior to and 15 seconds following the hot start in Bag 3.

This strategy was chosen with a 10-second cold start preheat time to achieve 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, it was chosen as a maximum preheating time for this test phase. This strategy was used during this gasoline-fueled vehicle testing; this scheme is referred to below as the 10/20, 5/15 heating scheme. A modification to the scheme also used was a 20-second preheat/20-second heating after cold start (Bag 1) and 10-second preheat/15-second heating after hot start (Bag 3).

The amount of air flowed over the catalyst during catalyst heating/vehicle operation was also varied. A tap into the exhaust stream was made approximately eight inches upstream of the converter for the introduction of bottled air. When used, bottled air was flowed over the catalyst only when the vehicle engine was operated and resistive heating was simultaneously applied to the catalyst. Air was not admitted prior to cold or hot start. The air pressures referred to in the discussion correspond to pressures at the secondary regulator on the gas bottle. A relationship between air flow rate and regulator pressure is given below.

30 psi: 2.4 SCFM
20 psi: 2.0 SCFM
12 psi: 1.0 SCFM
6 psi: 0.2 SCFM

A summary of the data from this phase of the evaluation is presented below in tabular and graphical form. Table 1 presents emission levels in grams (milligrams for HCHO) over Bag 1 of the FTP for the various catalyst configurations tested. Bag 3 results can be found in Appendix C. Table 2 presents weighted FTP averages for these emissions categories. Figures 1 and 2 present a summary of HC and CO bag data in grams for some catalyst configurations tested, while Figure 3 presents weighted FTP averages.

The levels in Table 2 are below the current light-duty gasoline vehicle standards for HC, CO and NOx. HCHO efficiency over the FTP was 88 percent with this catalyst. The stock catalyst is a good benchmark; the resistively heated metal monolith converter would have to reduce pollutant emissions to very low levels in order to compare favorably with this catalyst.

The configuration labeled Camet no-heat/no-air in Tables 1 and 2 is the metal monolith tested without heating in the three-way mode. HC and CO levels over the FTP were low for this configuration, lower even than those from the stock catalyst. NOx was substantially higher, yet lower than the level of the 1 gram per mile current vehicle standard. This could be due to the difference in the active catalysts used between the stock and Camet converters, rather than physical or volume differences between the substrates.

Table 1

Average Mass of Emissions
Bag 1 of FTP Cycle, 72-74°F Testing

Catalyst Configuration	HC (g)	NMHC* (g)	CO (g)	CO2 (g)	NOx (g)	Aldy. (mg)
Baseline (no catalyst)	5.33	5.01	88.36	1296.	14.14	165.
Stock catalyst	1.09	0.93	20.01	1437.	1.32	17.
Camet no heat, no air	0.92	0.81	16.08	1335.	2.34	11.
Camet heat 10/20, no air	0.85	0.75	16.07	1342.	1.82	7.
Camet no heat, 30 psi air	0.87	0.77	16.09	1335.	2.22	14.
Camet heat 10/20, 6 psi air	0.66	0.57	12.07	1318.	2.30	9.
Camet heat 10/20, 12 psi air	0.65	0.55	10.91	1331.	2.06	13.
Camet heat 20/20, 12 psi air	0.48	0.37	9.15	1321.	1.95	6.
Camet heat 20/20, 20 psi air	0.42	0.33	7.95	1316.	1.90	N/A
Camet heat 20/20, 30 psi air	0.52	N/A	7.58	1318.	2.01	7.

N/A Not available
* Non-methane hydrocarbons.

FIGURE 1
HC, CO, BAG 1 OF FTP

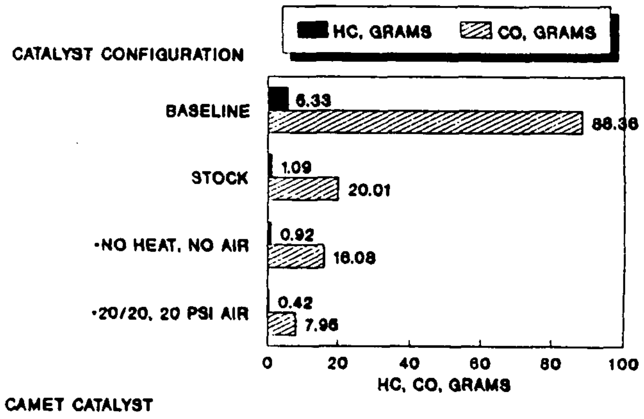


FIGURE 2
HC, CO, BAG 1 OF FTP
INCREASED HEATING, AIR FLOW SCHEMES

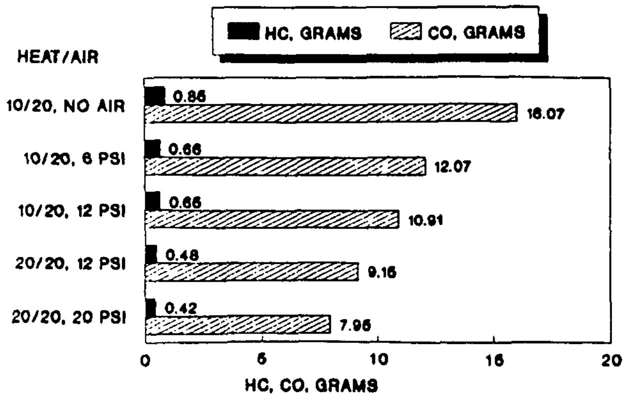


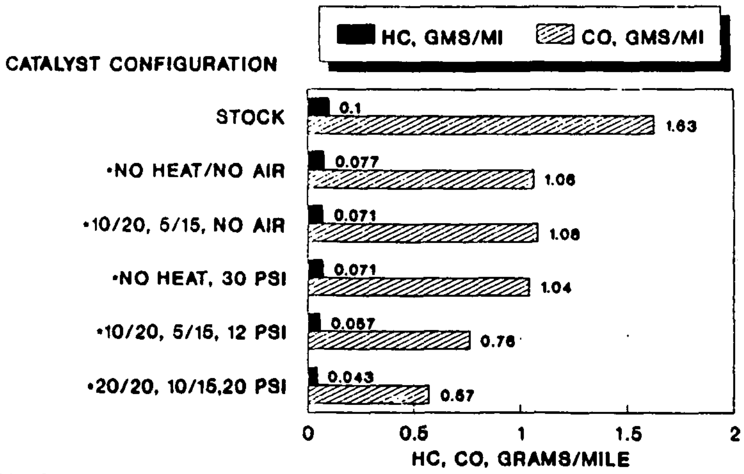
Table 2

Emission Levels Over the FTP Cycle, 72-74°F Testing

Catalyst Configuration	HC (g/mi)	NMHC (g/mi)	CO (g/mi)	CO2 (g/mi)	NOx (g/mi)	Aldy. (mg/mi)
Baseline (no catalyst)	1.030	0.99	12.33	348.	3.48	41.
Stock catalyst	0.100	0.08	1.63	376.	0.20	5.
Camet no heat, no air	0.077	0.063	1.06	354.	0.72	1.
Camet heat 10/20 Bag 1, 5/15 Bag 3, no air	0.071	0.058	1.08	356.	0.63	2.
Camet no heat 30 psi air	0.071	0.055	1.04	355.	0.70	N/A
Camet heat 10/20 Bag 1, 5/15 Bag 3, 6 psi air	0.058	0.044	0.83	349.	0.77	2.
Camet heat 10/20 Bag 1, 5/15 Bag 3, 12 psi air	0.057	0.043	0.76	351.	0.67	4.
Camet heat 20/20 Bag 1, 10/15 Bag 3, 12 psi air	0.048	0.033	0.65	346.	0.66	1.
Camet heat 20/20 Bag 1, 10/15 Bag 3, 20 psi air	0.043	0.029	0.57	343.	0.67	2.
Camet heat 20/20 Bag 1, 10/15 Bag 3, 30 psi air	0.049	N/A	0.56	346.	0.66	1.

N/A Not available.

FIGURE 3
HC, CO, FTP CYCLE



•CAMET CATALYST

The Camet catalyst was tested with two variable conditions: 1) air flow over the catalyst during resistive heating (oxidation catalyst simulation), and 2) variations in heating times during Bags 1 and 3 of the FTP. In Tables 1 and 2 the heating times mentioned refer to preheating before and heating after start. Addition of air is denoted by the secondary regulator pressure given in units of psi. Air was added only from the time of engine start to the end of resistive heating.

The Camet catalyst was tested without resistive heating but with the addition of air during Bags 1 and 3. Air was added for 20 seconds following engine start during Bag 1 and for 15 seconds following engine start in Bag 3. The catalyst was also tested with resistive heating but without the addition of air.

Emission levels from each of these two configurations were generally only slightly lower than those from the unheated/no air added configuration over Bag 1. In addition, emission levels from each pollutant category were similar for both configurations over the FTP. HC, CO and NOx emissions were also very similar between the unheated/no air added configuration and the two configurations mentioned above. It appears that resistive heating or the addition of air did not provide a substantial emission reduction benefit when employed as separate strategies.

The simultaneous addition of air and resistive heating was then evaluated as an operating strategy. This mode involved 10/20-Bag 1 and 5/15-Bag 3 heat times as well as the addition of air at 6 psi. The result was a substantial decrease in Bag 1 HC and CO levels, to 0.66 and 12.07 grams, respectively. This corresponds to a 40 percent increase in HC and CO efficiency from stock catalyst Bag 1 levels. Weighted FTP efficiency increases of 42 and 50 percent respectively over stock catalyst HC and CO levels were obtained with this heat/air added strategy. NOx levels changed little from those measured from Camet catalyst testing without heating or the addition of air; adding heat and air did not provide a NOx benefit.

The next strategy evaluated was increasing the air flow over the catalyst while keeping the same heating scheme (to 12 psi air). This did not result in substantial emissions reduction. HC and CO levels over the FTP were very similar to those obtained with the previous heating/air addition configuration. NOx over the FTP dropped to 0.67 grams per mile; this was essentially the same level as the Camet converter no heat/no air configuration level of 0.72 grams per mile.

Increasing the catalyst preheat times to 20 seconds in Bag 1 and 10 seconds in Bag 3 (air added at 12 psi) reduced FTP HC and CO emissions to 0.048 grams per mile and 0.65 grams per mile, respectively. This represented 52 percent and 60 percent decreases in HC and CO respectively from stock catalyst levels, a considerable improvement. NOx was measured at 0.66 grams per mile, essentially unchanged from the 0.67 grams per mile obtained with the 10/20, 5/15, 12 psi resistive heating/air addition scheme testing.

A further decrease in HC and CO emissions was obtained by using a 20/20 Bag 1, 10/15 Bag 3 heating scheme, and increasing the air flowrate over the catalyst to 20 psi. HC emissions were reduced to an average 0.043 grams per mile over the FTP, the lowest levels measured during this evaluation. CO was reduced to 0.57 grams per mile over the FTP. NOx was unchanged from the 0.67 grams per mile measured during the previous resistive heating/air scheme testing.

The secondary regulator was then opened to maximum pressure, 30 psi, during the heat-on/engine-operating portions of Bags 1 and 3. HC level increased slightly from tHe immediate previous configuration to 0.049 grams per mile over the FTP. CO levels remained approximately at the same level from the previous mode, 0.56 grams per mile over the FTP. This was the first time during the variation of either heating scheme or air flow over the catalyst that HC or CO levels had increased after heating or air flow had been increased. Previous evaluation of this technology on a methanol-fueled vehicle [2] suggested that increased heating time in Bag 1 may not increase catalyst midbed temperature substantially from temperatures caused by a 20/20 heating scheme. The first part of the evaluation was ended with the heating/air-flow scheme of 20/20 Bag 1 heating, 10/15 Bag 3 heating, 20 psi air, selected as the overall most effective scheme of those tested.

Formaldehyde levels were also measured during this testing. The stock catalyst lowered FTP formaldehyde levels to 5 milligrams per mile; the Camet catalyst reduced this further to approximately 1-2 milligrams per mile. Levels lower than this are difficult to precisely ascertain, given the accuracy of our current formaldehyde measuring system. Resistive heating and the addition of air did not appear to lower formaldehyde below this 1-2 milligrams per mile level.

Figures 1 and 2 graphically depict the ability of the catalyst configurations tested to oxidize the pollutants of greatest interest here, HC and CO. Figure 1 presents HC and CO in grams over Bag 1 of the FTP for four catalyst configurations. The stock catalyst reduces HC and CO levels substantially while the Camet catalyst in the no-heat/no-air mode provides a slight improvement over stock catalyst levels. The most efficient heating/air-addition scheme for Bag 1 HC and CO with the Camet catalyst is also depicted. This particular scheme had HC and CO efficiencies of 61 and 60 percent respectively over Bag 1 levels obtained with the stock catalyst, a substantial improvement.

Figure 2 shows the decrease in HC and CO Bag 1 emission levels with increasing heating/air-addition schemes. A 50 percent increase in HC and CO efficiency over no-heat/no-air Camet operation was provided by the 20/20 Bag 1 heating, 20 psi air addition scheme.

Figure 3 depicts HC and CO levels in grams per mile over the FTP for several configurations tested. Stock catalyst as well as heat/no air and no-heat/air Camet configuration HC and CO levels are included. Results from two other Camet configurations representing increased resistive heating and air addition are also included. The trend toward increasing HC and CO efficiencies over the FTP with increased resistive heating/air addition in Bag 1 is evident here.

B. <u>20°F Ambient Temperature Testing</u>

The second phase of this evaluation of the resistively heated metal monolith technology involved testing at lower ambient temperature conditions. 20°F was chosen for this temperature as it was the lowest temperature to which our cold test cell could be reliably lowered to and maintained.

This testing was conducted over the FTP cycle. The vehicle was driven over the LA-4 prep cycle prior to testing and soaked overnight outside of the laboratory. Overnight soak temperatures ranged between 30°-40°F. Prior to testing the vehicle was placed in the cold test cell and force-cooled to 20°F. Coolant and oil sump temperatures were monitored to determine 20°F vehicle engine temperature.

The catalyst was evaluated in four different operating modes. First, the converter was tested in an ordinary three-way catalyst configuration; no resistive heating was applied nor was extra air added in front of the catalyst during this testing. The catalyst was then resistively heated during Bags 1 and 3 without additional air. The catalyst was preheated for 10 seconds prior to cold start in Bag 1; resistive heating continued for 30 seconds following cold start. No resistive heating was applied during Bag 2. Resistive heating was applied for 5 seconds prior to hot start in Bag 3; heating continued for 20 seconds following hot start.

Two different resistive heating/oxidation catalyst simulation strategies were evaluated. The first strategy involved the same heating scheme as given above; air at 30 psi was added in front of the catalyst during the simultaneous resistive heating/engine running portions of Bags 1 and 3. The second strategy involved increasing the post-start resistive heating period in Bag 1 to 50 seconds. Air at 30 psi was added during the resistive heating/engine running portions of Bags 1 and 3.

Emission results from the Bag 1 and 3 portions of this testing are given in grams in Tables 3 and 4, while Table 5 presents weighted emission level averages over the FTP.

The effect of the difference in catalyst light-off times between Bags 1 and 3 for a typical three-way catalyst at 20°F is underscored by the no heat/no air configuration test results in Tables 3 and 4. HC emissions during Bag 1 were roughly 30 times higher than levels under hot start Bag 3 conditions. CO level differences were even more profound; Bag 1 CO levels were approximately 100 times greater than those from Bag 3. A comparison of Bag 3 HC and CO levels from Table C-1 in Appendix C (72-74°F testing) and Table 4 (20°F) indicate that the catalyst was operating with similar efficiencies over this portion of the FTP under those widely different ambient temperature conditions. Clearly, a strategy to substantially lower FTP emissions of HC and CO at 20°F ambient conditions would have to lower these emissions during cold start and catalyst warm up.

Heating the catalyst without the addition of bottled air did not lower emissions of HC and CO over the FTP at 20°F. The catalyst was preheated for 10 seconds prior to engine start and for 30 seconds following start during Bag 1. Table 3 shows that average HC and CO emissions over Bag 1 were not reduced by resistive heating. NOx levels over Bag 1 were relatively unaffected by the resistive heating. Bag 3 HC and CO emission levels were unaffected by resistive heating. Weighted FTP average emissions for HC and CO were also unchanged or slightly higher than those from no heat/no air mode testing. Though only a very minimum number of tests were conducted, resistive heating during an early part of Bag 1 without the addition of excess air appeared to provide very little emissions benefit over the no heat/no air configuration.

The use of resistive heating and the simultaneous addition of excess air appeared to cause a slight reduction in emissions of HC and CO. When air at 30 psi (2.4 SCFM) was added during catalyst heating/engine operation HC and CO levels fell to 7.81 and 175.6 grams, respectively, over Bag 1; this compares to 8.58 and 190.5 grams, respectively, for the no heat/no air configuration. This represents an almost 9 percent increase in both HC and CO efficiency over Bag 1. Weighted FTP efficiencies increased by over 7 percent for both HC and CO through the use of this heating/air addition strategy.

Increasing the amount of time the catalyst was resistively heated during Bag 1 while adding air at 30 psi during the simultaneous heating/engine running period was then evaluated. The Bag 1 preheat time was kept at 10 seconds; the time that the catalyst was resistively heated after cold start was increased to 50 seconds, an increase from the 30 second heating time of the previous configuration.

Table 3

Average Mass of Emissions 20°F Testing, Bag 1 of FTP Cycle

Camet Configuration	HC (g)	CO (g)	CO2 (g)	NOx (g)
No heat, no air	8.58	190.5	1370.	1.15
Heat 10/30, no air	8.89	191.7	1340.	1.18
Heat 10/30, 30 psi air	7.81	175.6	1375.	1.80
Heat 10/50, 30 psi air	8.73	192.2	1350.	1.70

Table 4

Bag 3 of FTP Cycle 20°F Testing

Camet Configuration	HC (g)	CO (g)	CO2 (g)	NOx (g)
No heat, no air	0.26	1.8	1166.	1.73
Heat 10/30, no air	0.29	1.8	1149.	2.37
Heat 10/30, 30 psi air	0.26	1.7	1140.	2.28

Table 5

Emission Levels Over the FTP Cycle

20°F Testing

Camet Configuration	HC (g/mi)	CO (g/mi)	CO2 (g/mi)	NOx (g/mi)
No heat, no air	0.525	11.19	351.	0.47
Heat 10/30 Bag 1, 5/20 Bag 3, no air	0.574	11.31	351.	0.73
Heat 10/30 Bag 1, 5/20 Bag 3, 30 psi air	0.487	10.36	355.	0.69
Heat 10/50 Bag 1, 5/20 Bag 3, 30 psi air	0.540	11.37	344.	0.75

The increased heating did not lower HC and CO emissions below levels from the previously tested configuration. HC and CO weighted FTP average emissions were essentially unchanged from levels with the Camet catalyst in the no heat/no air mode. HC and CO emissions over Bags 1 and 3 were also unchanged from levels measured with the no heat/no air configuration.

CO by percent in undiluted exhaust (ahead of the CVS) was continuously monitored during the Bag 1 portion of the tests, which utilized the 10/50 heating scheme and addition of air over the catalyst at 30 psi. CO was measured at 9 percent of undiluted exhaust during the 3 minutes of Bag 1 at 20°F ambient conditions. CO concentration dropped to approximately 6 percent during the period of 180 to 240 seconds into a test; after approximately 4 minutes of engine operation, CO levels dropped sharply to stable value much less than 1 percent. The level did not change after that time.

We also attempted to measure midbed catalyst gas temperature during this testing. The thermocouples used invariably made contact with the resistively heated walls shortly after commencing the test; the data collected was very unreliable as a result.

The amount of power necessary to bring a stream of raw exhaust from an engine soaked and operated at 20°F conditions to catalyst-active temperature shortly after cold start has been calculated to be possibly greater than 10,000 watts.[7] The Camet catalyst is capable of delivering approximately 2200 watts in its present configuration. A rather large shortfall between power required and power supplied, at these ambient conditions, is obvious.

A refinement of the catalyst heating scheme/excess air addition scheme may be required in order to obtain substantial HC and CO emissions reduction at 20°F ambient conditions. HC and CO levels were substantially reduced by catalyst resistive heating/air addition from no heat/no air catalyst configuration levels at 72-74°F conditions. At 20°F, however, the resistive heating may not transfer sufficient heat quickly enough to bring boundary layer gases to catalyst active temperatures. This resistive heating may be wasted by heating exhaust gas to catalyst inactive temperatures during the relatively short residence time in the converter. The warmed, but yet chemically unconverted exhaust gas may have been passed to the atmosphere in its unconverted state during the approximately 50 seconds of resistive heating following cold start.

The CO data collected during this testing suggests that CO levels remain very high for the first 4 minutes of Bag 1 at 20°F ambient conditions. Any reduction of CO levels during this 4 minute period could substantially reduce weighted FTP CO emissions. More carefully controlled testing may determine the catalyst temperature at which resistive heating and the addition of excess air would provide optimum HC and CO emissions benefit, given the present resistive heating hardware and a similar sized catalyst. Resistive heating would be catalyst gas temperature controlled; heating may not commence prior to vehicle start, as was the case in the evaluation reported on here.

Another variable not addressed here was the location of the catalyst in the exhaust stream. The present evaluation used an underfloor catalyst location; catalyst performance at 20°F ambient conditions might have been better if it was located closer to the engine.

VIII. Highlights From Testing

The Camet catalyst-equipped vehicle in the no-heat/no-air mode had lower HC and CO emission levels over the FTP than the stock catalyst that the vehicle was originally equipped with. NOx levels over the FTP were higher than stock catalyst levels; this may be due to the difference in the composition of the actual noble metals used between these two catalytic converters, however.

Resistively heating the Camet catalyst without the addition of excess air did not substantially lower HC and CO below no-heat/no-air catalyst levels. Addition of air in the absence of resistive heating also did not lower HC and CO emissions below no-heat/no-air configuration levels.

The simultaneous use of resistive heating and the addition of excess air in front of the catalyst caused a decrease in HC and CO from the no-heat/no-air strategy test. HC and CO were reduced to 0.043 and 0.57 grams per mile respectively, with the most efficient strategy tested. This strategy consisted of preheating the catalyst for 20 seconds prior to Bag 1 cold start and heating for 20 seconds following cold start; preheating for 10 seconds prior to hot start and heating for 15 seconds following hot start in Bag 3. Air at 20 psi (2.0 SCFM) was added in front of the catalyst during resistive-heating/engine-running conditions. Emissions benefits from resistively heating the catalyst and two resistive heating/excess air addition strategies were not observed at 20°F ambient conditions, however.

IX. Acknowledgements

The catalyst used in this test program was supplied by Camet, located in Hiram. OH. Camet is a manufacturer and sales agent for W. R. Grace and Company. The test vehicle used in this program was supplied by Volkswagen of America.

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X. 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	1987 Volkswagen Golf
Fuel	Indolene clear
Engine:	
Displacement	1.78 liter
Bore	8.10 cm
Stroke	8.64 cm
Compression ratio	9.0 to 1
Maximum output SAE net	85 hp at 5250 rpm
Fuel System	Continuous injection system (fuel injection) with Lambda feedback control, electric fuel pump
Transmission:	
Type	Hydrodynamic torque converter and planetary gearing with three forward and one reverse gear
Torque converter stall torque ratio	2.50
Torque converter stall speed	2400-2600 rpm
Gear ratios:	
1	2.71
2	1.50
3	1.00
Axle	3.41
Curb weight	2340 lbs
Equivalent test weight	2500 lbs

APPENDIX C

AVERAGE MASS OF EMISSIONS - BAG 3 OF FTP CYCLE 72-74°F AMBIENT CONDITION TESTING

Table C-1

Average Mass of Emissions Bag 3 of FTP Cycle 72-74°F Testing

Catalyst Configuration	HC (g)	NMHC (g)	CO (g)	CO2 (g)	NOx (g)	Aldy. (mg)
Baseline (no catalyst)	3.34	3.20	34.09	1131.	14.96	134.
Stock catalyst	0.35	0.25	4.67	1280.	0.82	12.
Camet no heat, no air	0.21	0.16	1.64	1171.	2.00	3.
Camet heat 5/15, no air	0.19	0.14	1.87	1181.	1.18	6.
Camet no heat, 30 psi air	0.18	0.12	1.42	1184.	2.04	6.
Camet heat 5/15, 6 psi air	0.17	0.12	1.71	1160.	2.39	8.
Camet heat 5/15, 12 psi air	0.17	0.12	1.69	1162.	2.00	9.
Camet heat 10/15, 12 psi air	0.16	0.11	1.49	1144.	1.99	5.
Camet heat 10/15, 20 psi air	0.16	0.11	1.50	1146.	2.01	N/A
Camet heat 10/15, 30 psi air	0.15	N/A	1.50	1149.	1.98	3.

N/A Not available.

APPENDIX D

INDIVIDUAL FTP RESULTS - 72-74°F AMBIENT CONDITION TESTING

Table D-1

Individual FTP Test Results

VW Golf Vehicle

Test Number/Type	HC (g/mi)	NMHC (g/mi)	CO (g/mi)	CO2 (g/mi)	NOx (g/mi)	Aldy. (mg/mi)
885190/baseline (no catalyst)	1.02	0.98	10.65	346.	3.73	42.0
890124/baseline (no catalyst)	1.05	1.00	14.02	349.	3.23	39.7
884951/stock catalyst	0.10	0.08	1.63	377.	0.20	4.3
884952/stock catalyst	0.10	0.08	1.62	374.	0.19	5.5
885191/Camet, no heat, no air	0.087	0.073	1.12	357.	0.68	1.4
885546/Camet, no heat, no air	0.067	0.052	1.00	350.	0.76	1.2
885192/Camet, heat 10/20 Bag 1, 5/15 Bag 3, no air	0.070	0.057	0.99	349.	0.81	1.6
885193/Camet, heat 10/20 Bag 1, 5/15 Bag 3, no air	0.082	0.068	1.17	358.	0.61	1.3
885245/Camet, heat 10/20 Bag 1, 5/15 Bag 3, no air	0.063	0.051	1.02	355.	0.53	1.4
890787/Camet, heat 10/20 Bag 1, 5/15 Bag 3, no air	0.070	0.056	1.11	354.	0.61	2.3
890969/Camet, heat 10/20 Bag 1, 5/15 Bag 3, no air	0.071	0.056	1.13	365.	0.57	2.6
885349/Camet, heat 10/20 Bag 1, 5/15 Bag 3, 6 psi air	0.060	0.045	0.82	348.	0.86	2.1
885350/Camet, heat 10/20 Bag 1, 5/15 Bag 3, 6 psi air	0.056	0.042	0.84	349.	0.69	1.4
885351/Camet, heat 10/20 Bag 1, 5/15 Bag 3, 12 psi air	0.057	0.043	0.76	351.	0.67	3.8

Table D-1 (cont'd)

Individual FTP Test Results

VW Golf Vehicle

Test Number/Type	HC (g/mi)	NMHC (g/mi)	CO (g/mi)	CO2 (g/mi)	NOx (g/mi)	Aldy. (mg/mi)
885389/Camet, heat 20/20 Bag 1, 10/15 Bag 3, 12 psi air	0.049	0.034	0.63	346.	0.66	1.3
885400/Camet, heat 20/20 Bag 1, 10/15 Bag 3, 12 psi air	0.047	0.032	0.66	347.	0.66	N/A
885401/Camet, heat 20/20 Bag 1, 10/15 Bag 3, 20 psi air	0.043	0.029	0.57	343.	0.67	1.6
885402/Camet, heat 20/20 Bag 1, 10/15 Bag 3, 30 psi air	0.049	NA	0.56	346.	0.66	1.1
885403/Camet, no heat, 30 psi air	0.071	0.056	1.07	354.	0.71	2.2
885545/Camet, no heat, 30 psi air	0.071	0.055	1.00	356.	0.68	1.3

APPENDIX E

INDIVIDUAL FTP RESULTS - LOWER AMBIENT TEMPERATURE EVALUATION

Table E-1

Individual FTP Test Results

Camet Catalyst - 20°F Ambient Conditions

Test Number/Type	HC (g/mi)	CO (g/mi)	CO2 (g/mi)	NOx (g/mi)
890125, no heat, no air	0.525	11.19	351.	0.47
890126, Heat 10/30 Bag 1, 5/20 Bag 3, no air	0.576	11.56	352.	0.63
890127, Heat 10/30 Bag 1, 5/20 Bag 3, no air	0.572	11.05	349.	0.83
890128, Heat 10/30 Bag 1, 5/20 Bag 3, 30 psi air	0.478	10.62	355.	0.74
890636, Heat 10/30 Bag 1, 5/20 Bag 3, 30 psi air	0.495	10.09	355.	0.64
890781, Heat 10/50 Bag 1, 5/20 Bag 3, 30 psi air	0.527	10.80	337.	0.73
890782, Heat 10/50 Bag 1, 5/20 Bag 3, 30 psi heat	0.552	11.86	350.	0.76