EPA/AA/TDG/93-06

Technical Report

Evaluation of Three Catalysts Formulated for Methane Oxidation on a CNG-Fueled Pickup Truck

by

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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.

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UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

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DEC 22 1993

OFFICE OF
AIR AND RADIATION

MEMORANDUM

SUBJECT: Exemption From Peer and Administrative Review

FROM: Karl H. Hellman, Chief
Technology Development Group

TO: Charles L. Gray, Jr., Director
Regulatory Programs and Technology Division

The attached report entitled "Evaluation of Three Catalysts Formulated for Methane Oxidation on a CNG-Fueled Pickup Truck," (EPA/AA/TDG/93-06) describes the emission results obtained from the evaluation of three specialized methane catalysts supplied by three different catalyst manufacturers. The catalysts were evaluated using a CNG-fueled Dodge Dakota pickup truck.

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., Director, RPT

Date: 1-4-94

Attachment

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I. **Summary**

Three fresh catalysts formulated for methane oxidation were evaluated by U.S. EPA on a compressed natural gas (CNG) vehicle. The first catalyst was an electrically heated, compact, quick lightoff converter, provided by W. R. Grace Company. The other two catalysts were larger in volume and were similar in size to the stock main catalyst on the test vehicle. These two larger volume catalysts were provided by Kemira Oy and AlliedSignal. No durability miles were accumulated on any of the catalysts.

The CNG-fueled test vehicle was a 1991 Dodge Dakota pickup equipped with a 318-CID engine provided by Stewart & Stevenson Power, Inc. Although the truck was equipped for dual fuel (either gasoline or CNG) operation, all the testing described here was performed with CNG fuel operation over the Federal Test Procedure (FTP) driving cycle.

The Grace quick lightoff catalyst was tested without the use of a larger main catalyst downstream. The effect of electrical heating and secondary air injection upstream of this catalyst were also investigated. The two larger volume catalysts were also tested in an underfloor location. The effect of secondary air assist was also evaluated on these two catalysts.

The low-volume Grace catalyst caused substantial emission level reductions in non-methane hydrocarbons (NMHC), carbon monoxide (CO), and oxides of nitrogen (NOx). With 20/40-second heat assist (resistive heating applied for 20 seconds prior to key-on and 40 seconds after key-on in Bag 1 only), NMHC and CO emission levels were measured at 0.10 grams/mile and 11.6 grams/mile respectively over the FTP cycle, over 60 percent reductions from engine-out levels. The lowest NOx levels were obtained without any catalyst assist and were measured at 0.8 grams/mile over the FTP cycle, over a 50 percent reduction from engine-out levels.

The two larger volume main catalysts both resulted in emissions over the FTP cycle that were below the levels of the California ultra-low emission vehicle (ULEV) standards, with and without secondary air assist. The test data taken for this report did not permit the calculation of non-methane organic gases (NMOG) as required by the California regulations, nor was a Reactivity Adjustment Factor (RAF) applied to the data. Nevertheless, it is the opinion of the authors that the test results are low enough that a 0.04 grams/mile NMOG level would be met at zero miles with a fresh catalyst. The Kemira Oy catalyst without air assist resulted in NMHC/CO/NOx emission levels of 0.02/0.4/0.2 grams/mile over the FTP. These emission levels were attained at zero accumulated system miles. The AlliedSignal catalyst (smaller in volume than the Kemira Oy unit) resulted in similar low levels of 0.01/0.8/0.2 grams/mile without air assist. Secondary air assist provided little additional emission reductions from the unassisted catalyst levels for both units.

II. Introduction

The current U.S. highway vehicle fleet is almost totally dependent on petroleum-based (i.e., gasoline and Diesel) fuels. Alternatives to petroleum-based fuels may become increasingly important in future years because of their potential contribution to a solution for air quality problems as well as a means to lessen the demand for imported oil in the U.S. [1,2]

One candidate for serious consideration as an alternative motor vehicle fuel is compressed natural gas (CNG). CNG is composed primarily of methane (CH_4), but it may contain up to 10 percent higher weight hydrocarbons (mostly ethane, propane and butane). [3] Ozone-forming photochemically reactive fuel-related emissions from CNG vehicles consist primarily of non-methane hydrocarbons (NMHC). CNG-fueled vehicle exhaust is 90-95 percent methane, a relatively non-reactive hydrocarbon (HC) species. Gasoline vehicle exhaust HC consists of 65-95 percent more reactive non-methane hydrocarbon species, however. [1] It is estimated that CNG-fueled vehicles may have 36-93 percent lower volatile organic compound (VOC) emissions, determined on a reactivity-equivalent basis, than gasoline-fueled vehicles (depending on the configuration of the CNG vehicles as either dual-fuel or optimized for CNG). [1]

The large methane fraction of the HC exhaust emissions from CNG-fueled vehicles is a problem for engine designers, because methane is the most difficult HC to oxidize catalytically. Some vehicle emission tests conducted at General Motors Research Laboratories showed that poor methane conversion on lean calibrated CNG-fueled vehicles occurred over the FTP cycle when commercial three-way catalysts were used. [4] Recently further General Motors research indicated good methane conversion occurred when a palladium/alumina catalyst was used together with slightly rich feedstream conditions. [5] Other catalyst development work to date suggests that with proper engine controls, selected catalyst formulations can effectively control methane emissions from CNG-fueled vehicles. [6]

EPA's Technology Development Group routinely conducts and publishes the results from emission control technology evaluations to spur further interest in new technologies. Recently, three catalyst companies furnished EPA with samples of fresh, unaged catalysts specifically formulated for use on CNG-fueled vehicles. These catalysts were evaluated on a CNG-fueled pickup truck at the EPA National Vehicle and Fuel Emissions Laboratory. The results from this evaluation are presented in this report.

III. Description of Catalytic Converters

The first converter evaluated here was a quick lightoff electrically heated catalyst supplied by Grace Company. This single-segment, metallic foil substrate had a total volume of 0.22 liters (Figure 1). The energy required for electrically heating this catalyst was supplied from a dedicated 12-volt, 115 amp-hour, deep-cycle battery. The current delivered to the catalyst averaged about 500 amps during the time of resistive heating. A switch and engine starter motor relay were used to supply energy from the dedicated battery when desired. Table 1 contains more detailed specifications of the Grace electrically heated catalyst. The catalyst pictured here is much smaller in volume than a conventional main converter and was not designed as a substitute for a main underfloor catalyst.

Figure 1
<u>Grace Electrically Heated Catalyst</u>

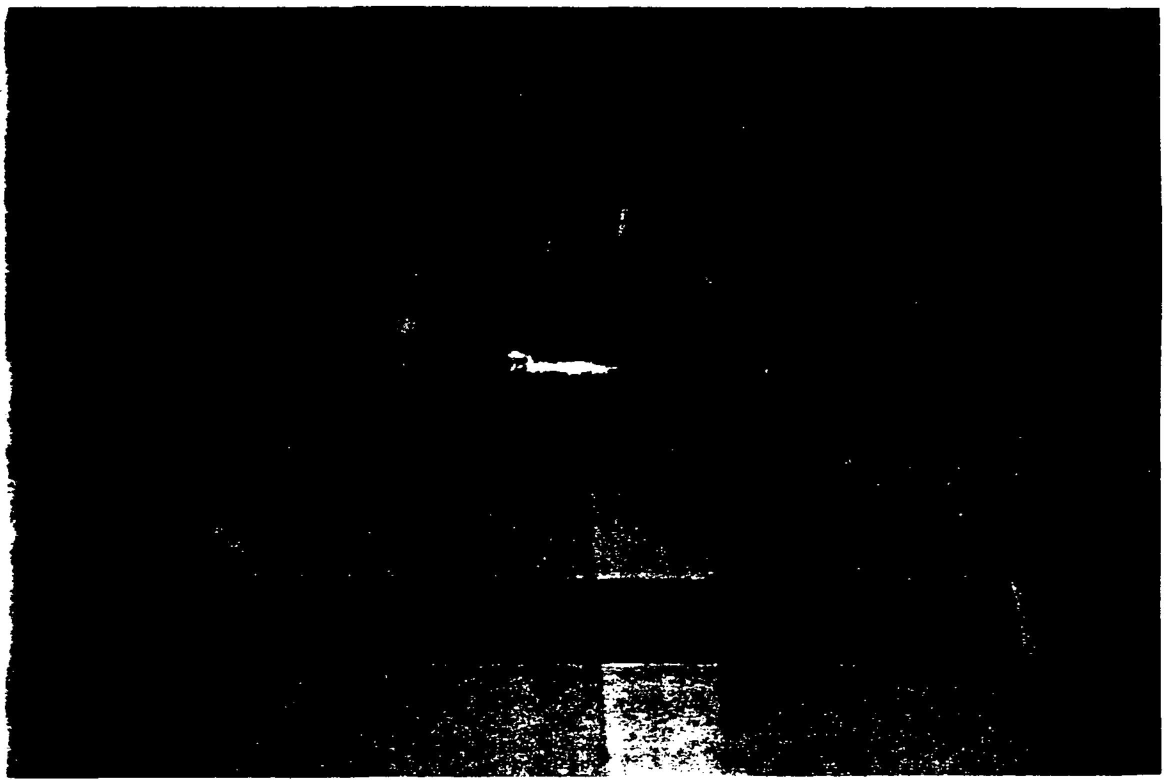


Table 1
Grace Electrically Heated Methane Catalyst
List of Detailed Specifications

	Specifications
Catalyst diameter	2.61 inches
Catalyst length	2.75 inches
Catalyst volume	13.34 in^3
Total substrate weight	335 grams
Cells per square inch	160
Noble metal loading	30 g/ft^3
Ratio of noble metals	Pt:Pd:Rh 0:1:0

The second converter evaluated was provided by Kemira Oy of Finland. This unit was cylindrical in shape and had the largest volume (4.71 dm^3) of the three converters evaluated. This converter was designed for heavy-duty truck applications utilizing CNG fuel. This converter utilized a single metallic foil substrate and was mounted in the underfloor location for our testing. A picture of this unit is provided as Figure 2; a more detailed list of specifications for the Kemira Oy catalyst is provided in Table 2.

Figure 2
Kemira Oy Methane Catalyst

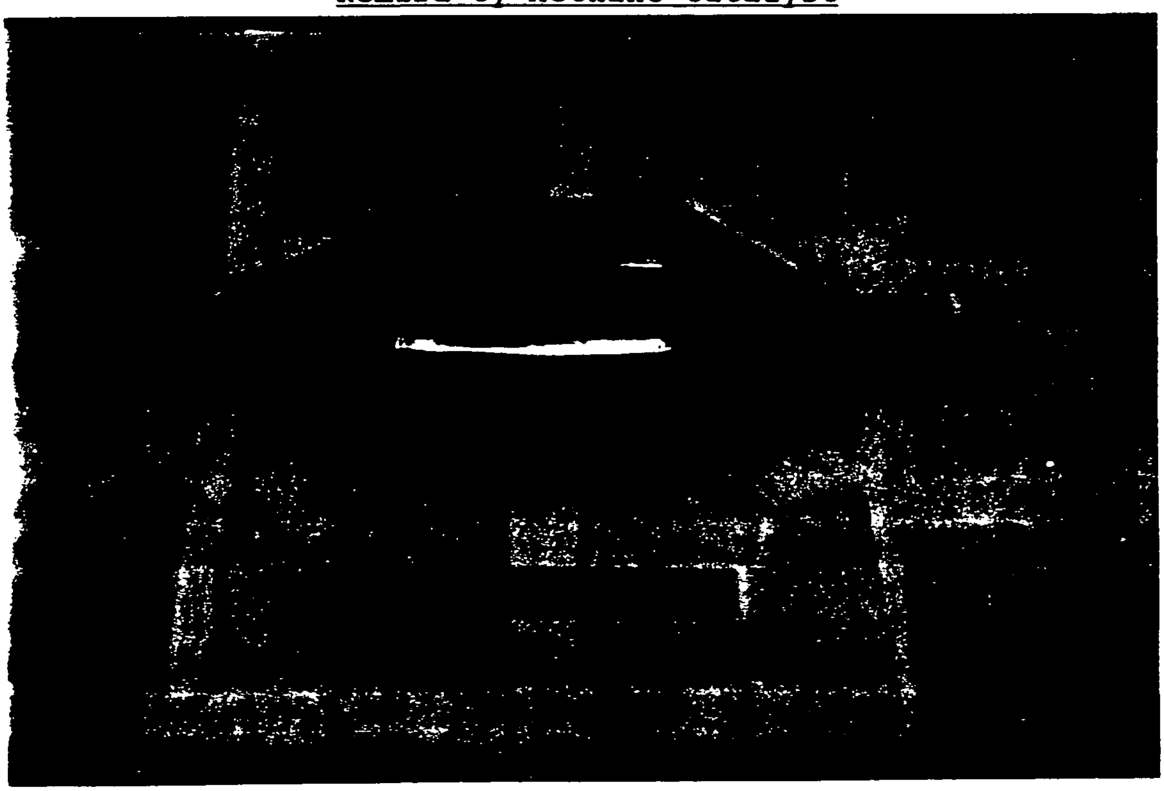


Table 2

Kemira Oy Methane Catalyst

List of Detailed Specifications

	Specification
Prototype identification number	5382
Total weight of converter	7300g
Substrate:	
Diameter	200mm
Length	150mm
Volume	4.71 dm^3
Cells per square inch	600
Total surface area	18.8m^2
Cross section	314.2cm^2
Precious metal loading	1.77g/dm^3
Total precious metal	8.34g
Precious metal ratio	1:1:0 Pt:Pd:Rh
Foil material	W 1.4767
Foil thickness	0.05mm
Weight of substrate	4118g
Shell material	W 1.4512
Shell thickness	1.5mm

The last converter evaluated in this program was supplied by AlliedSignal Inc. This catalyst had a total substrate volume between the two other units (2.78dm^3) and was similar in size to the stock catalyst on the truck. This catalyst utilized two ceramic substrates with similar sizes and loadings and was also evaluated in the underfloor location. A picture of this converter is provided in Figure 3 below, and a detailed list of catalyst specifications is provided in Table 3.

Figure 3
AlliedSignal Methane Catalyst

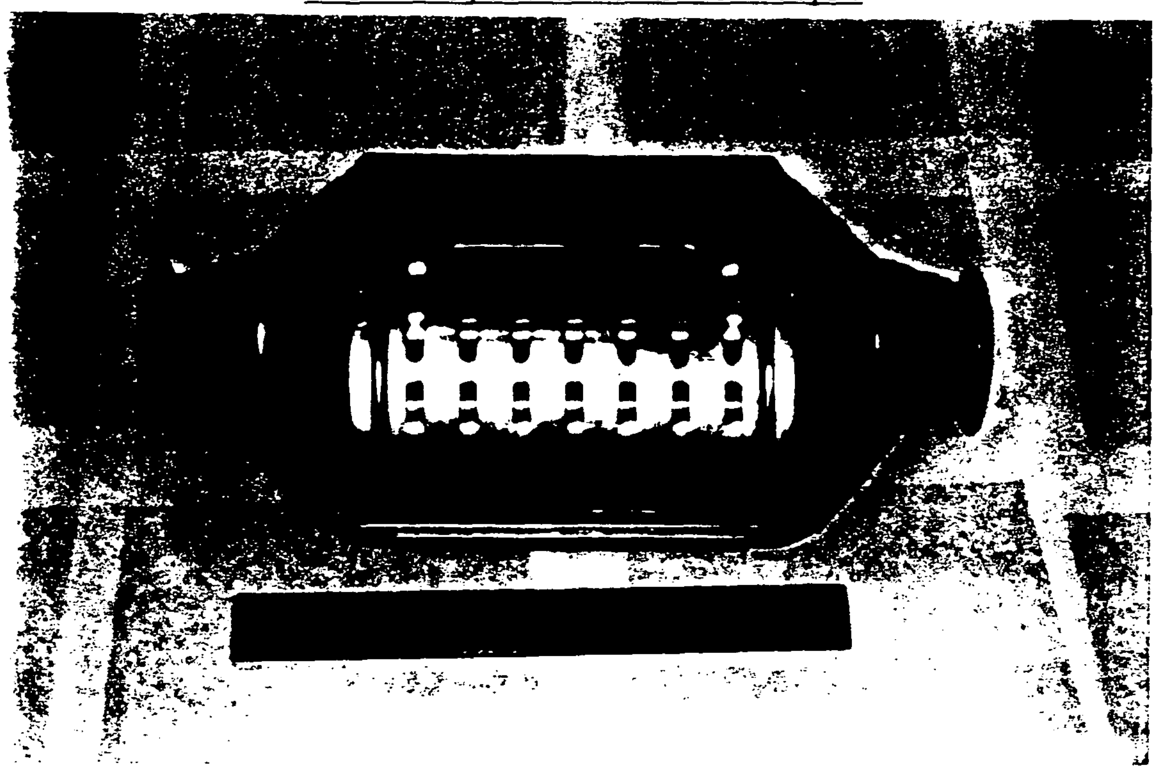


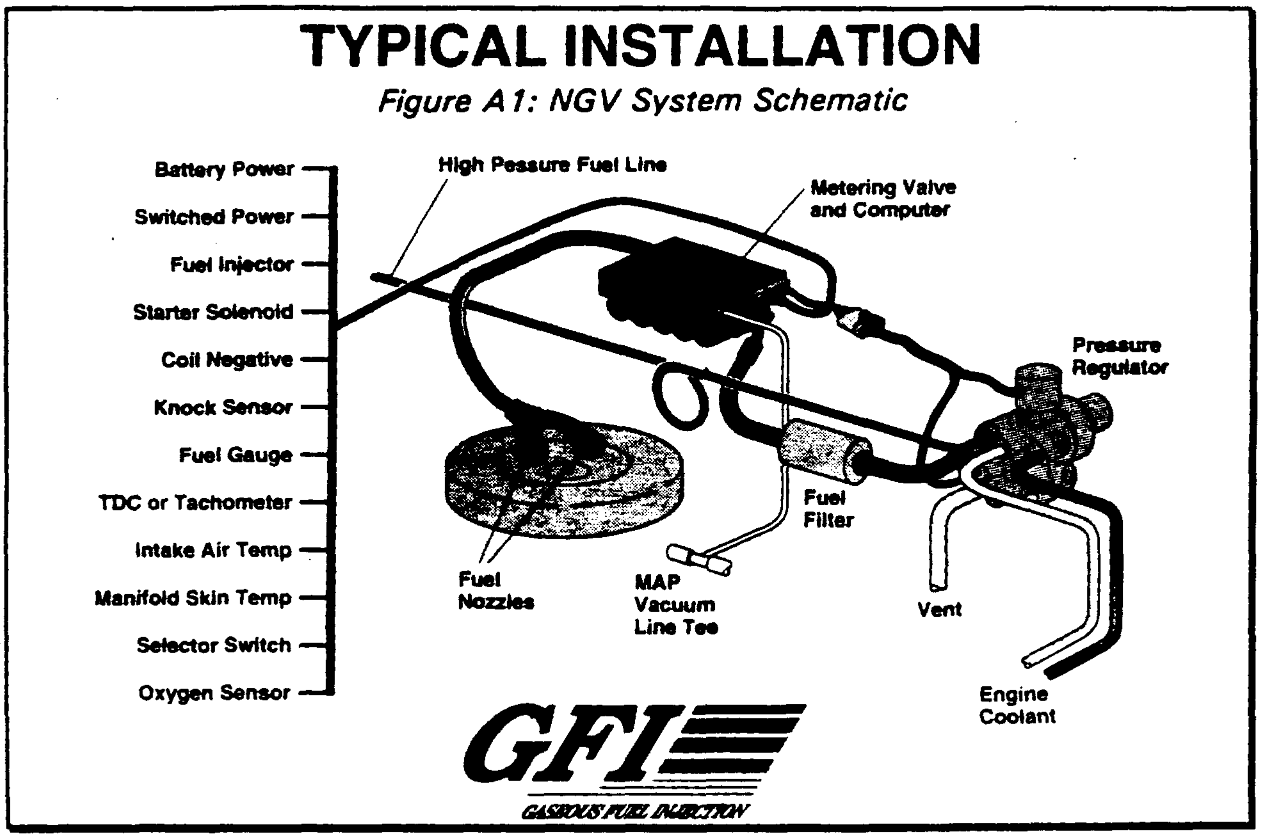
Table 3
AlliedSignal Methane Catalyst
List of Detailed Specifications

Material	Ceramic
Total catalyst volume	169.66 in^3
Cross section (oval)	4.5 x 7.0 in
Length	3.4 in
Cells per square inch	400
Noble metal loading	100 g/ft^3
Ratio of noble metals	0:10:1 Pt:Pd:Rh

IV. **Description of Test Vehicle**

The test vehicle used for this evaluation was a 1991 Dodge Dakota pickup truck. The truck was converted to CNG operation by Stewart & Stevēnson Power, Inc. of Commerce City, Colorado, using their patented Gaseous Fuel Injection (GFI) system. The truck had dual-fuel (gasoline or CNG) capability; fuel selection was governed by a switch inside the passenger compartment. Figure 4 depicts the GFI system.

Figure 4
Gaseous Fuel Injection System



High pressure CNG was supplied from storage cylinders to a single-stage regulator where the pressure was reduced to 100 psig. Two CNG storage tanks were located inside the passenger compartment and were capable of filling to approximately 3,500 psig pressure. EPA, however, filled these tanks only to a maximum 2,500 psig pressure when refueling. With this fill level, it was possible to conduct approximately four tests over the FTP cycle before the truck was refueled. EPA also installed two excess flow valves at the outlet of each storage tank for safety purposes.

One hundred psig fuel passes from the pressure regulator to a primary fuel filter and then to a regulator referred to as a compu-valve. The compu-valve commands the appropriate combination of solenoids and injectors to operate for the required period of time necessary to meter the desired amount of fuel. The metered fuel then passes from the metering valve to spray nozzles in the intake system of the engine, in this case the air cleaner. These nozzles introduce fuel into the intake air stream and promote mixing of the inlet air and fuel.

The GFI system used speed density calculations for both fuel flow and air flow and solved for the correct air/fuel mixture based on a fixed (software) stoichiometric value of the fuel consumption in the area of operation. Speed density calculations are based on engine speed and the temperature and pressure of the inlet air and fuel. The GFI system senses manifold absolute pressure, barometric absolute pressure, and fuel absolute pressure. Temperatures monitored include intake air temperature, manifold skin temperature (air temperature at engine intake valve), and fuel regulated temperature. The first two sensors are remotely located, and the last is embedded in the metering valve.

Figure 5 is a picture of the test vehicle. The truck was tested at 4,750 lbs equivalent test weight and 13.0 actual dynamometer horsepower. The vehicle was loaned to U.S. EPA by Stewart & Stevenson Power, Inc.

Figure 5
CNG-Fueled Dodge Dakota Test Vehicle

V. Test Facilities and Analytical Methods

Emissions-testing at EPA 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 constant volume sampler has a nominal capacity of 600 standard cubic feet per minute. NOx emissions were determined by a Beckman Model 951A chemiluminescent NOx analyzer. Methane (CH_4) emissions were measured with a Model 8205 Bendix methane analyzer. Hydrocarbon emissions were determined using a Beckman Model 400 flame ionization detector. CO and CO_2 were measured using a Bendix Model 8501-5CA infrared analyzer.

Procedures were developed for the determination of both total and non-methane hydrocarbons and fuel economy for natural gas vehicles based on the properties of the natural gas fuel. The natural gas used to refuel the test vehicle was obtained from a commercial pipeline located near the EPA motor vehicle laboratory. This fuel was not specifically analyzed, but it was assumed to be typical of natural gas used in the Detroit area for home heating applications. The properties used in these calculations (Appendix A) were provided to EPA by a local gas company. Appendix A also presents natural gas fuel economy and a gasoline equivalent fuel economy value.

The properties of the natural gas fuel included mole percent compositions of nitrogen, carbon dioxide, helium, hydrogen, and hydrocarbons. These values were used to calculate specific gravity and net (lower) heating value. This data was then used to determine the properties seen in Appendix A such as:

1. Composite H/C ratio for the total hydrocarbon components in the fuel, H/C_{THC};

2. Composite H/C ratio for all non-methane hydrocarbon components in the fuel, H/C_{NMHC};

3. Non-methane carbon weight fraction (CWF_{NMHC}) of the fuel, grams of carbon per gram of non-methane hydrocarbon, excluding CO_2 and inert gases not consumed in the combustion process;

4. Mass fraction, grams of fuel per gram of carbon, where carbon is based on carbon in hydrocarbon components (and CO_2) in the fuel, g NGV fuel/g C in NGV fuel; and

5. Energy density of the fuel in BTU's per gram of fuel, expressed as net (lower) heating value, BTU/g NGV fuel.

From these properties, corrected total and non-methane hydrocarbon values were obtained based on the fuel's components in their proper mole fractions. Calculations for CO, CO_2, and NOx exhaust emissions were unchanged from procedures described in Section 86.144-78, Title 40, of the Code of Federal Regulations.

Specific calculations for determining adjusted total and non-methane hydrocarbon emissions were detailed in a previous EPA technical report describing testing of several natural gas vehicles. [7]

VI. **Test Procedures**

The goal of this program was the evaluation of three catalytic converters on a natural gas fueled truck. Three separate catalyst manufacturers supplied EPA with prototype converters for evaluation.

The first catalyst evaluated was an electrically-heated quick lightoff converter supplied by the W. R. Grace Company. EPA conducted this evaluation with and without catalyst heat and air assist. Resistive heating was applied to the catalyst for 20 seconds prior to key-on in the Bag 1 portion of the FTP and for 40 seconds after key-on in Bag 1. No resistive heat was applied to the catalyst for the remainder of the FTP. The effect of secondary air assist when combined with the resistive heating strategy described previously was also investigated. This air assist period was 60 seconds after key-on in the Bag 1 portion of the FTP only. The air assist time was limited to 60 seconds so that the conversion of NOx emissions would not be inhibited. Air flow to the catalyst was kept constant at 5 standard cubic feet per minute and was provided by a shop air hose.

The two additional catalysts did not arrive at EPA until approximately six months after the testing with the Grace catalyst was complete. No emission tests were performed with the Dakota truck during this six-month period; the truck was started and driven periodically to keep the battery charged.

The second catalyst evaluated was provided to EPA by Kemira Oy of Finland. Three different configurations of this catalyst were evaluated. A straight pipe was inserted in place of the stock underfloor catalyst to enable the determination of engine-out levels. The engine-out levels measured during this testing were significantly different than those measured prior to testing the Grace catalyst, so they are reported separately. The Kemira Oy catalyst was then installed on the truck and tested without any assist. The last configuration utilized the Kemira Oy catalyst with 60 seconds of air assist after start in Bag 1. Again, the air assist rate was kept constant at 5 standard cubic feet per minute.

The third catalyst evaluated was supplied by AlliedSignal Inc., located in Tulsa, Oklahoma. This catalyst was tested using procedures similar to those used for the Kemira Oy catalyst evaluation. The engine-out emissions measured prior to installation of the AlliedSignal catalyst were similar to those obtained before the Kemira Oy testing.

VII. **Discussion of Test Results**

A. **Electrically Heated Methane Catalyst**

The results from the EHC evaluation are reported separately because of its much smaller catalyst volume than the others tested. The engine-out emissions measured here differed significantly to those reported in the next section. There was a substantial delay between this testing and the testing described in the next section. The direct effect of this time delay on vehicle hardware and emissions is not known. It is also possible that the difference in elevation at the Stewart & Stevenson facility in Colorado (where the vehicle was converted) and the EPA laboratory in Michigan may have contributed to the change in engine-out emission levels experienced here over time.

Resistive heating and air assist were used only during the cold-start portion of Bag 1 of the FTP. The first 505 seconds of the FTP are referred to as Bag 1; the cold-start portion consists of the initial minutes of Bag 1 during which the engine and exhaust system heat to a relatively steady-state temperature. The following discussion comments on differences in exhaust emission levels which may be related to catalyst reactions, heat assist, or air assist. All testing was conducted at an ambient temperature of 72°-73°F. Bag 1 emission levels are given in grams over the test segment (Bag 1). Composite FTP emissions are reported in grams per mile.

Figure 6 presents Bag 1 total hydrocarbon emission levels obtained during testing with the Grace catalyst. "Engine-out" levels were obtained with no catalyst present in the exhaust system. "Stock Catalyst" represents testing with the stock catalyst in the exhaust system. "No assist" represents testing with only the low-volume Grace electrically heated catalyst in the underfloor location without any catalyst assist. "Heat assist" utilized a 20/40-second resistive heat assist. "Heat & air assist" utilized both a 20/40-second resistive heat scheme and a 60-second air assist after start in Bag 1 only.

The stock catalyst caused a 42 percent reduction in Bag 1 total hydrocarbons from engine-out levels, from 7.44 grams to 4.34 grams. The small-volume Grace catalyst without any assist lowered total hydrocarbons to 5.36 grams over Bag 1. When heat assist was applied to the Grace converter, Bag 1 total hydrocarbon (THC) levels were similar to those measured with the larger volume stock catalyst at 4.53 grams, a 40 percent reduction from engine-out levels.

Combined catalyst resistive heating/air assist caused a slight increase in Bag 1 THC to 4.66 grams. This was unexpected; the addition of air over the catalyst may have caused the catalyst to cool slightly, delaying lightoff. It is not known how significant any cooling effect may have been, as catalyst skin temperature and inlet/outlet air temperatures were not monitored.

Figure 6
Grace Methane Catalyst Evaluation
Bag 1 Total Hydrocarbon Emission Levels

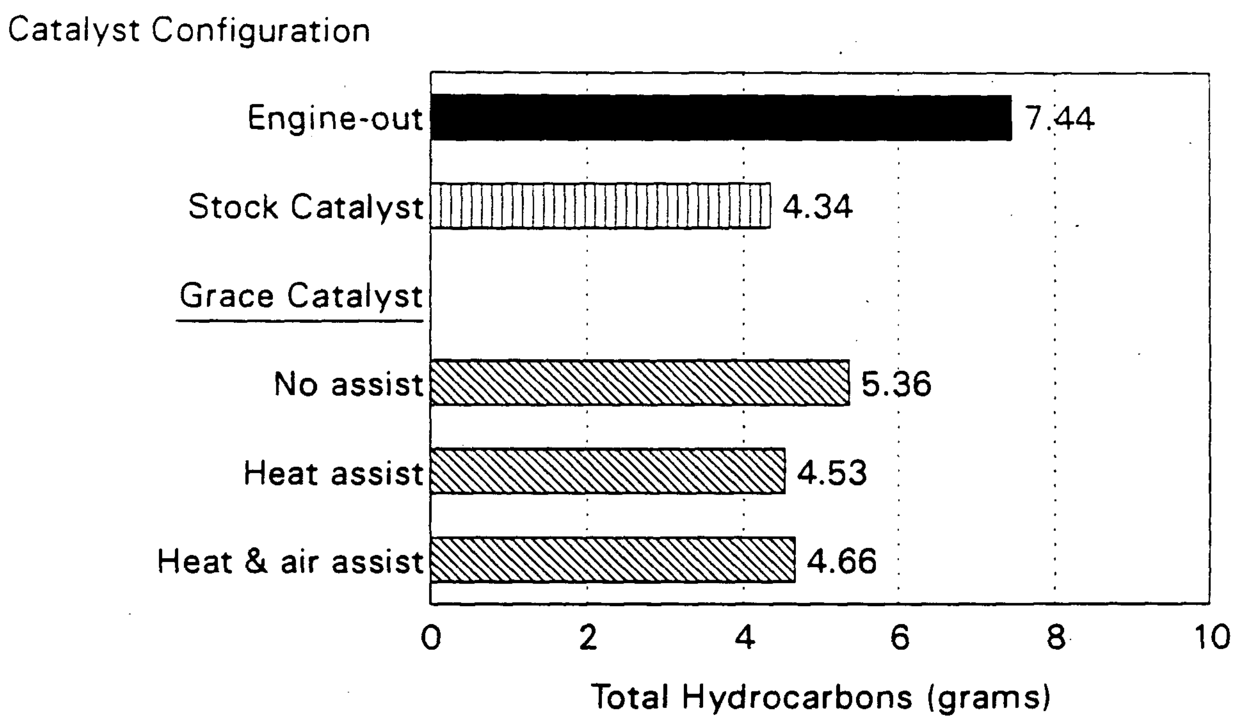


Figure 7 presents Bag 1 carbon monoxide (CO) emission levels using the Grace catalyst for the same catalyst configurations described above. The stock catalyst was again very effective at reducing Bag 1 CO levels from engine-out levels, from 145.0 grams to 32.9 grams. Bag 1 CO levels were measured at 80.3 grams, almost a 45 percent reduction from engine-out levels with the unassisted Grace EHC. Resistive heating further lowered Bag 1 CO levels to 51.0 grams, a 65 percent reduction from engine-out levels. Again, adding air assist to resistive heating had a detrimental effect on Bag 1 CO emissions. In this configuration, Bag 1 CO levels were measured at 57.6 grams, 13 percent higher than resistive heating alone. Each configuration evaluated, however, had higher CO emissions than the larger volume stock converter.

Figure 7

Grace Methane Catalyst Evaluation
Bag 1 Carbon Monoxide Emission Levels

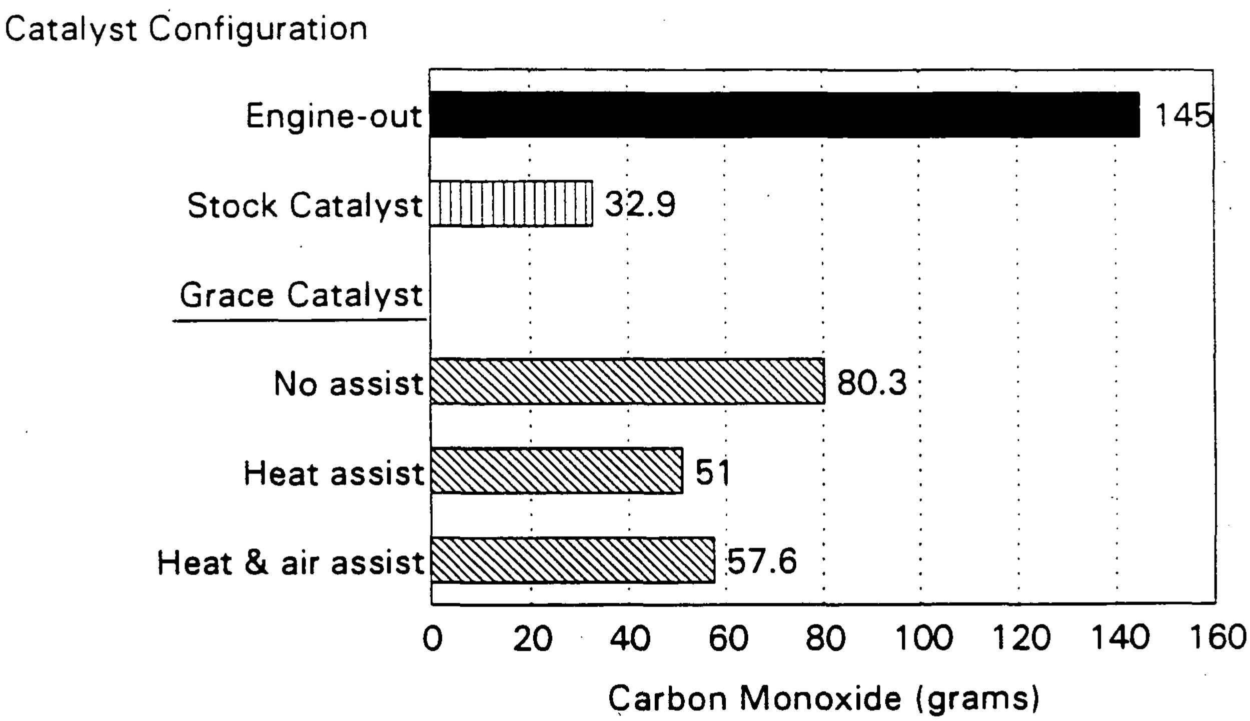


Table 4 presents individual bag emission levels with the small-volume Grace EHC. Methane (CH_4) and non-methane hydrocarbons (NMHC) followed a trend similar to those discussed in Figure 6 for total hydrocarbons. Oxides of nitrogen (NOx) emissions were also reduced significantly over Bag 1 with the unassisted Grace catalyst, from 6.4 grams engine-out to 2.6 grams. Resistive heating slightly increased Bag 1 NOx levels to 3.1 grams. There was no noticeable change when heat and air assist were combined, compared to heat-assist-only levels when considering NOx.

Table 4

Grace Methane Catalyst Evaluation						
Individual Bag Emission Levels (grams)						
Catalyst Configuration	**THC**	**CH_4**	**NMHC**	**CO**	**CO_2**	**NOx**
Bag 1:						
Engine-out	7.44	6.18	1.26	145.0	1632	6.4
Stock catalyst	4.34	4.34	**	32.9	1774	1.7
No assist	5.36	4.73	0.62	80.3	1686	2.6
Heat assist	4.53	4.11	0.43	51.0	1718	3.1
Heat & air assist	4.66	4.22	0.44	57.6	1744	3.0
Bag 2:						
Engine-out	6.43	5.18	1.25	119.2	1758	5.8
Stock catalyst	2.57	2.50	0.08	11.3	1944	2.0
No assist	5.04	4.56	0.48	71.2	1848	1.8
Heat assist	4.52	4.16	0.37	42.0	1855	2.5
Heat & air assist	4.62	4.20	0.42	43.8	1876	2.4
Bag 3:						
Engine-out	5.62	4.55	1.08	90.2	1388	8.4
Stock catalyst	3.38	3.38	**	14.9	1518	2.7
No assist	4.45	3.94	0.50	64.8	1430	3.1
Heat assist	4.03	3.64	0.40	39.8	1448	4.0
Heat & air assist	4.08	3.62	0.46	41.2	1469	3.9
** Less than 0.005 grams measured.						

Table 5 presents composite FTP emission levels as well as a computed natural gas fuel economy (CNG MPG) value based on the properties of the fuel used with the Grace EHC.

Table 5

Grace Methane Catalyst Evaluation							
FTP Emission Levels (grams/mile)							
Catalyst Configuration	**THC**	**CH_4**	**NMHC**	**CO**	**CO_2**	**NOx**	**CNG MPG**
Engine-out	1.72	1.40	0.32	31.2	436	1.8	13.7
Stock catalyst	0.86	0.85	0.01	4.6	480	0.5	13.7
No assist	1.32	1.18	0.14	19.0	453	0.6	13.8
Heat assist	1.18	1.07	0.10	11.6	459	0.8	14.0
Heat & air assist	1.20	1.08	0.12	12.3	464	0.8	13.8

The lowest composite emission levels of THC and CO using the Grace catalyst occurred with the resistive heat assist only. THC were measured at 1.18 grams/mile in this configuration, which also resulted in the lowest non-methane hydrocarbon level at 0.10 grams/mile. This configuration resulted in a 11.6 grams/mile composite level for CO. Not unexpectedly, the lowest composite NOx level measured with the low-volume Grace catalyst occurred without any heat or air assist at 0.6 grams/mile. Natural gas fuel economy was not appreciably influenced by the use of the Grace catalyst.

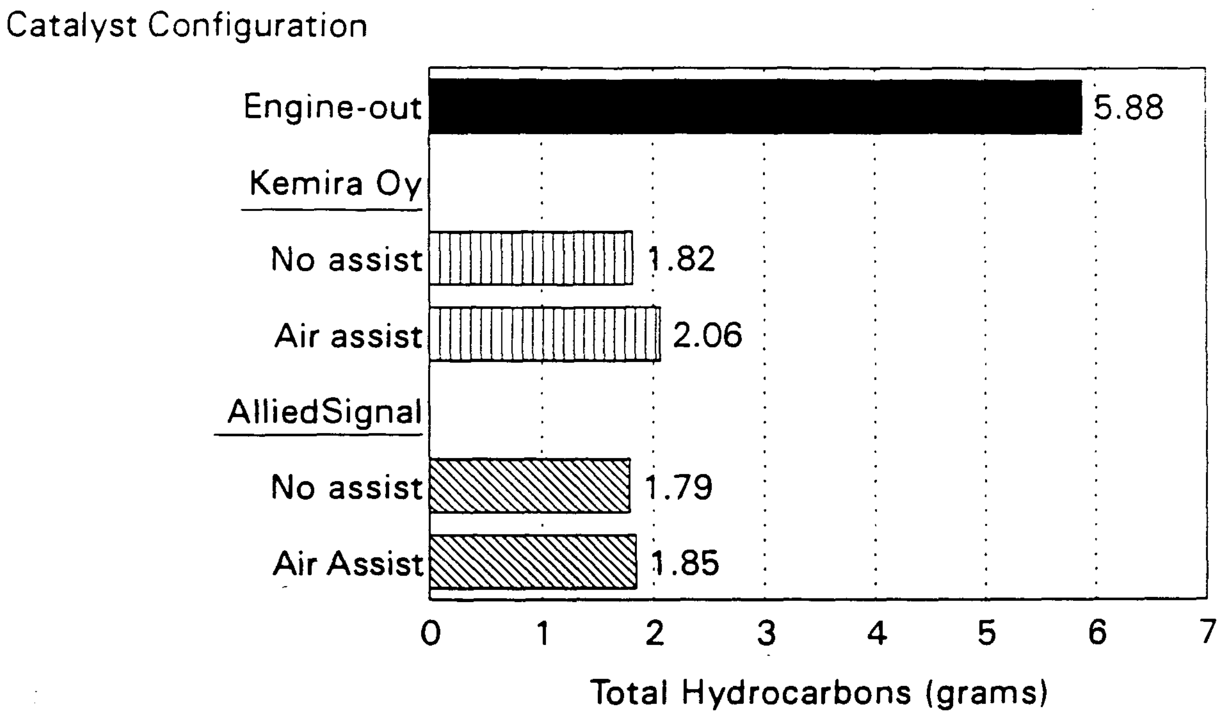
B. **Main Underfloor Catalysts**

Two larger volume main catalysts were also evaluated; these were supplied by Kemira Oy and by AlliedSignal Inc. These catalysts were evaluated using three different configurations: "engine-out" (no catalyst present in the exhaust system), "no assist" (catalyst without supplemental air assist), and "air assist" (60 seconds of air assist to the catalyst after key-on in Bag 1 only). Engine-out emission levels here, measured before testing each of these catalysts, were very similar and are averaged in the figures below. They differed substantially, however, from engine-out levels measured prior to the Grace catalyst testing described in the previous section.

Figure 8 presents Bag 1 emission levels of total hydrocarbons when utilizing these two larger volume catalysts.

Figure 8

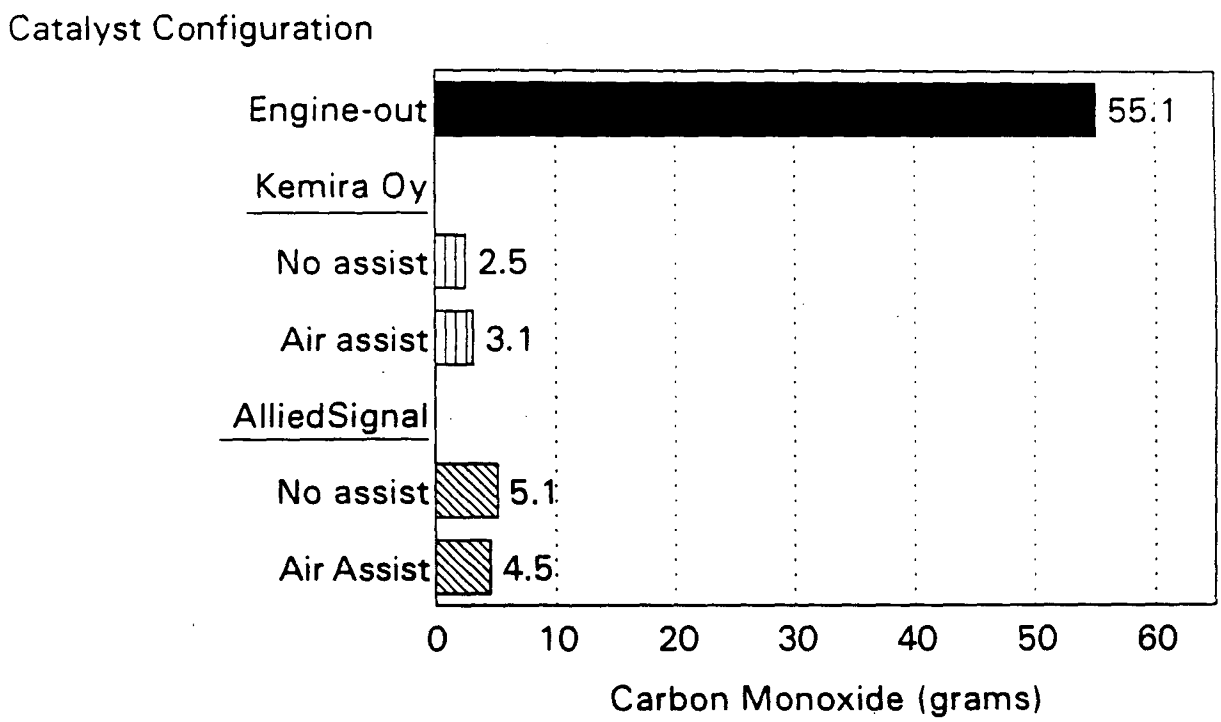
Larger Volume Main Catalyst Evaluation Bag 1 Total Hydrocarbon Emission Levels



Both catalysts were very effective at reducing Bag 1 total hydrocarbons. With the Kemira Oy catalyst, Bag 1 hydrocarbons levels were reduced from the averaged engine-out level of 5.88 grams to 1.82 grams without any catalyst assist, a 69 percent reduction. Similarly, the AlliedSignal catalyst reduced Bag 1 hydrocarbon levels to 1.79 grams, almost a 70 percent reduction from engine-out levels. Adding secondary air assist upstream of each catalyst did not additionally decrease Bag 1 hydrocarbon emissions; in fact, these levels slightly increased above unassisted catalyst levels.

Similar trends were noted in Bag 1 CO emission levels as with Bag 1 hydrocarbons, as seen in Figure 9 below. The larger volume Kemira Oy catalyst reduced Bag 1 CO by almost 96 percent from engine-out levels, even without air assist. (Engine-out CO levels were measured at 55.1 grams, the unassisted Kemira Oy catalyst at 2.5 grams.) As with Bag 1 HC, when 60 seconds of air assist was added to the Kemira Oy catalyst, Bag 1 CO levels increased slightly.

Figure 9
Larger Volume Main Catalyst Evaluation
Bag 1 Carbon Monoxide Emission Levels



The fresh AlliedSignal catalyst also effectively reduced Bag 1 CO levels from the 55.1-gram engine-out level. Without catalyst assist, Bag 1 CO levels were measured at 5.1 grams when using the AlliedSignal catalyst, almost a 91 percent reduction from engine-out levels. When air assist was applied to this catalyst during the first minute of Bag 1, CO levels were further reduced to 4.5 grams.

Tables 6 and 7 present individual Bag emission levels using both the Kemira Oy and AlliedSignal catalysts. Different engine-out levels are presented in each table here and were obtained prior to initiating testing with either catalyst. These values were averaged in the previous two figures for simplicity.

Table 6

Kemira Oy Methane Catalyst Evaluation						
Individual Bag Results (grams)						
Catalyst Configuration	**HC**	**NOx**	**CO_2**	**CO**	**CH_4**	**NMHC**
Bag 1:						
Engine-out	5.79	7.8	1678	54.0	5.40	0.39
No assist	1.82	0.6	1773	2.5	1.67	0.16
Air assist	2.06	0.6	1758	3.1	1.98	0.08
Bag 2:						
Engine-out	5.25	7.1	1814	44.0	5.03	0.44
No assist	0.51	0.5	1905	1.3	0.49	0.02
Air assist	0.56	0.3	1900	1.6	0.55	0.01
Bag 3:						
Engine-out	4.95	9.3	1423	39.9	4.53	0.42
No assist	1.39	1.7	1504	0.7	1.36	0.04
Air assist	1.46	1.6	1498	0.8	1.44	0.02

Table 7

AlliedSignal Methane Catalyst Evaluation						
Individual Bag Results (grams)						
Catalyst Configuration	**HC**	**NOx**	**CO_2**	**CO**	**CH_4**	**NMHC**
Bag 1:						
Engine-out	5.96	8.4	1673	56.2	5.54	0.39
No assist	1.79	0.5	1852	5.1	1.66	0.13
Air assist	1.85	0.7	1765	4.5	1.65	0.19
Bag 2:						
Engine-out	5.59	7.7	1797	49.8	5.26	0.32
No assist	0.57	0.2	1907	2.6	0.56	0.01
Air assist	0.56	0.2	1914	2.5	0.56	**
Bag 3:						
Engine-out	5.03	10.3	1419	41.2	4.70	0.33
No assist	1.29	1.4	1524	1.7	1.28	0.01
Air assist	1.39	1.6	1495	1.5	1.39	**
** Less than 0.005 grams measured.						

Tables 8 and 9 present composite FTP emission levels when using both the Kemira Oy and AlliedSignal catalysts.

Table 8

Kemira Oy Methane Catalyst Evaluation							
FTP Composite Emission Levels(grams/mile)							
Catalyst Configuration	HC	NOx	CO_2	CO	CH_4	NMHC	CNG MPG
Engine-out	1.45	2.1	451	12.2	1.33	0.12	14.0
No assist	0.28	0.2	472	0.4	0.26	0.02	13.9
Air assist	0.30	0.2	470	0.5	0.29	0.01	14.0

Table 9

AlliedSignal Methane Catalyst Evaluation							
FTP Composite Emission Levels(grams/mile)							
Catalyst Configuration	HC	NOx	CO_2	CO	CH_4	NMHC	CNG MPG
Engine-out	1.48	2.3	446	13.0	1.39	0.09	14.0
No assist	0.28	0.2	479	0.8	0.27	0.01	13.7
Air assist	0.29	0.2	473	0.7	0.28	0.01	13.9

In the absence of any catalyst assist, use of either the Kemira Oy or AlliedSignal catalyst resulted in low emission levels over the FTP; these levels were below the levels of the California ULEV Standards of 0.04/1.7/0.2 grams/mile for NMHC/CO/NOx respectively. The test data taken for this report did not permit the calculation of non-methane organic gases (NMOG) as required by the California regulations, nor was a Reactivity Adjustment Factor (RAF) applied to the data. Nevertheless, it is the opinion of the authors that the test results are low enough that a 0.04 grams/mile NMOG level would be met at zero miles with a fresh catalyst. The bulk of the total hydrocarbons are methane emissions, therefore, non-methane hydrocarbon values are very low (0.02 grams/mile with the Kemira Oy catalyst and 0.01 grams/mile with the AlliedSignal unit). CO levels were very low with each catalyst and well below the ULEV CO level of 1.7 grams/mile. NOx emissions with either catalyst was measured at 0.2 grams/mile. Again, these emission levels were attained at zero accumulated system miles.

Adding air assist provided little benefit in reducing composite FTP emission levels. The only noticeable benefit from air assist resulted with the Kemira Oy catalyst and non-methane hydrocarbon emissions. When air assist was used with this catalyst, non-methane emissions were reduced from the already low 0.02 grams/mile to 0.01 grams/mile.

VIII. Conclusions

1. It is difficult to compare the results from the evaluation of the Grace EHC with those from the other catalysts tested because of the operation and smaller volume of the Grace converter. Despite its small size, the unassisted EHC was effective at reducing Bag 1 THC, CO and NOx emission levels.

Resistive heating in Bag 1 further lowered Bag 1 emissions of THC and CO. Emissions over the Bag 2 and 3 segments of this heat-assist testing were also lowered. The addition of catalyst air assist did not appear to further lower emission levels. Testing using air assist without resistive heating was not conducted.

2. The Kemira Oy catalyst was very effective in reducing emission levels of NMHC, CO and even NOx. Engine out NMHC emissions were reduced to extremely low levels, as low as 0.02 grams/mile over the FTP. CO emissions were also very low. The use of catalyst air assist did not further lower CO emissions, to our surprise. NOx emissions were also reduced to approximately 0.2 grams/mile. NOx reduction activity was not greatly affected by the use of catalyst air assist during the Bag 1 segment of this testing.

3. The emissions levels with the AlliedSignal catalyst were very similar to those from the evaluation of the Kemira Oy catalyst.

IX. Acknowledgements

The first catalyst evaluated in this test program was supplied to EPA by the W.R. Grace and Company. The second catalyst was supplied by Kemira Oy, located in Vihtavuori, Finland. The last catalyst used in this program was provided by AlliedSignal Inc., located in Tulsa, Oklahoma. The natural gas fueled Dodge Dakota truck was loaned to EPA by Stewart & Stevenson Power, Inc., located in Commerce City, Colorado. The authors would like to thank these companies for their cooperation and support.

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NATURAL GAS VEHICLE TEST ANALYSIS

Dyno: D209 Test No: 93-1548 Processed: 06/25/93 11:18

Input Data for 1B7GL23Y8NS529176

Test No.	MFR	Vehicle ID	Veh Version	Test Type	Procedure	Test No.
93-1548	20	1B7GL23Y8NS529176	0	05	02	93-1548

Identification

REQ ID	MFR Initials	Driver ID	Oper ID	LA4 Prep ID		Test Date	Key Start
22024	0	54768	54721	54768		6/10/93	9:53

Flags

EVAP Flag	PARTIC	RETEST	RFCC	RUN CHG	Tire	Prep Date	Prep Key Off
0	0	0	0	0	0	6/9/93	16:21

Disposition and Accounting

Veh Disp	Test Disp	Void Code	TPS		# Preps	Acc Code	Acc Code
0	0	0	0		0	0	0

Dynamometer and Analyzer Site

Dyno	IW Set	TWHP	Coast Down	Odometer	CVS	Analyzer	HFID
D209	4750	13	0:00	1766	27C	A203	A203

Dyno/CVS	Distance	VMIX	Seconds	Fuel Meter	Reading	Ambient Conditions	
Bag 1	8378	4983	505.00		0	Barometer	29.05
Bag 2	8999	8512	864.00		0	Ambient	76.5
Bag 3	8375	4964	505.00		0	Dew Point	47.8
Units	R			Units	0	Temp Units	D

	Exhaust		Background		
HC FID	**Range**	**Meter**	**Range**	**Meter**	**HC FID**
Bag 1	14	86.3	14	3.4	Bag 1
Bag 2	14	49.7	14	3.2	Bag 2
Bag 3	14	74.2	14	3.4	Bag 3
CO					**CO**
Bag 1	18	71	18	0.2	Bag 1
Bag 2	18	38.1	18	0.3	Bag 2
Bag 3	18	56.5	18	0.3	Bag 3
CO2					**CO2**
Bag 1	22	69.9	22	4	Bag 1
Bag 2	22	47	22	4.1	Bag 2
Bag 3	22	61	22	4.1	Bag 3
NOx					**NOx**
Bag 1	15	64.2	15	0.2	Bag 1
Bag 2	15	35.3	15	0.2	Bag 2
Bag 3	[illegible]	77.2	15	0.2	Bag 3
Methane					**Methane**
Bag 1	[illegible]	12.2	18	0.7	Bag 1
Bag 2	[illegible]	7	18	0.7	Bag 2
Bag 3	[illegible]	10.4	18	0.7	Bag 3

NG Fuel Properties	THC H/C Ratio	NMHC H/C Ratio	NG NG/C Ratio	CNG THC CWF	CO2 WF	GHV BTU/ft^3	Specific Gravity
	3.886	2.891	1.441	0.667	0.096	1000	0.593

COMMENTS:	0 0 0

THIS TEST WAS CONDUCTED AT THE U.S. EPA NATIONAL VEHICLE AND FUEL EMISSIONS LABORATORY - EOD, ANN ARBOR, MICHIGA

NATURAL GAS VEHICLE TEST ANALYSIS page 2/3

Dyno: D209 Test No: 93-1548 Processed: 06/25/93 11:18

Raw Emission Determination for 1B7GL23Y8NS529176

Ambient Conditions	Baro "Hg	Dry Bulb °F	Dew Point °F	Spec. Humid.	Rel. Humid.	NOx Corr.
	29.05	76.5	47.8	50.76	36.28	0.8977

	Exhaust			Background			
HC	Range	Meter	ppm	Range	Meter	ppm	HC
Bag 1	14	86.3	64.71	14	3.4	2.52	Bag 1
Bag 2	14	49.7	37.13	14	3.2	2.37	Bag 2
Bag 3	14	74.2	55.59	14	3.4	2.52	Bag 3
CO	Range	Meter	ppm	Range	Meter	ppm	CO
Bag 1	18	71	326.58	18	0.2	0.79	Bag 1
Bag 2	18	38.1	160.24	18	0.3	1.19	Bag 2
Bag 3	18	56.5	248.94	18	0.3	1.19	Bag 3
CO2			percent			percent	CO2
Bag 1	22	69.9	0.683	22	4	0.036	Bag 1
Bag 2	22	47	0.449	22	4.1	0.037	Bag 2
Bag 3	22	61	0.591	22	4.1	0.037	Bag 3
NOx			ppm			ppm	NOx
Bag 1	15	64.2	31.88	15	0.2	0.10	Bag 1
Bag 2	15	35.3	17.45	15	0.2	0.10	Bag 2
Bag 3	15	77.2	38.42	15	0.2	0.10	Bag 3
Methane			ppm			ppm	Methane
Bag 1	18	12.2	60.51	18	0.7	3.47	Bag 1
Bag 2	18	7	34.70	18	0.7	3.47	Bag 2
Bag 3	18	10.4	51.57	18	0.7	3.47	Bag 3
NMHCe	CH4 Response		ppm	CH4 Response		ppm	NMHCe
Bag 1	1.105		0.00	1.105		0.00	Bag 1
Bag 2	1.105		0.00	1.105		0.00	Bag 2
Bag 3	[illegible]		0.00	1.105		0.00	Bag 3
THC Resp Adjust	[illegible]		ppm			ppm	THC
Bag 1	[illegible]		60.51			3.47	Bag 1
Bag 2	[illegible]		34.70			3.47	Bag 2
Bag 3	[illegible]		51.57			3.47	Bag 3

COMMENTS:	
	0
	0
	0

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NATURAL GAS VEHICLE TEST ANALYSIS

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Dyno: D209 Test No: 93-1548

Processed: 06/25/93 11:18

Emission, Mass, and Fuel Economy for 1B7GL23Y8NS529176

Natural Gas	THC H/C Ratio	THC Density	THC CWF	NMHC H/C Ratio	NMHC Density	NMHC CWF	CO2 WF
Properties	3.8860	18.749	0.754	2.8910	17.568	0.805	0.096

Natural Gas	NG NG/C Ratio	NG CWF	CNG THC CWF	Specific Gravity	GHV BTU/ft^3	NHV BTU/g	NG Density
Properties	1.4410	0.694	0.667	0.593	1000	43.967	20.470

Dyno/CVS	VMIX	Roll Revs	Miles	Dilut Factor Numerator	Dilut Factor	Correct
Bag 1	4983	8378	3.593	9.656	13.374	0.9252272
Bag 2	8512	8999	3.860		20.608	0.9514749
Bag 3	4964	8375	3.592		15.543	0.9356608

CVS Corrected Concentrations	CH4c ppm	NMHCc ppm	TOTAL HC ppm	COc ppm	CO2c %	NOxc ppm
Bag 1	57.30	0.00	57.30	325.85	0.650	31.79
Bag 2	31.40	0.00	31.40	159.11	0.414	17.35
Bag 3	48.33	0.00	48.33	247.83	0.556	38.33

CVS Mass Emissions	CH4 grams	NMHC grams	TOTAL HC grams	CO grams	CO2 grams	NOx grams
Bag 1	5.39	0.00	5.39	53.53	1677.33	7.70
Bag 2	5.05	0.00	5.05	44.65	1824.15	7.18
Bag 3	4.53	0.00	4.53	40.56	1430.91	9.25

Total Mass Emissions	CH4 grams	NMHC grams	TOTAL HC grams	CO grams	CO2 grams	NOx grams
Bag 1	5.39	0.00	5.39	53.53	1677.33	7.70
Bag 2	5.05	0.00	5.05	44.65	1824.15	7.18
Bag 3	4.53	0.00	4.53	40.56	1430.91	9.25

Mass Emissions	CH4 g/mi	NMHC g/mi	TOTAL HC g/mi	CO g/mi	CO2 g/mi	NOx g/mi
Bag 1	1.501	0.000	1.501	14.898	466.795	2.144
Bag 2	[redacted]	0.000	1.308	11.569	472.625	1.861
Bag 3	[redacted]	0.000	1.261	11.292	398.361	2.576

Composite Emissions	[redacted]	NMHC g/mi	TOTAL HC g/mi	CO g/mi	CO2 g/mi	NOx g/mi
Unrounded	1.33498	0.00000	1.33498	12.183	451.01	2.1159
Rounded	1.335	0.000	1.335	12.2	451	2.12

Natural Gas Fuel Economy	grams C per mile	grams NG per grams C		UTG BTU's per gallon	NG BTU's per mile	NG MPG
	129.349	1.441		114132	8195.182	13.93

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Natural Gas Fuel Economy	FCng Numerator	FCng Denominator	FCng	CO2ng	Numerator	gr C / mile Denominator	Proposed CFR MPG
	129.349	14.205	9.106	17.894	1658.878	124.464	13.33

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