Safety Evaluation of Disposable Diesel Exhaust Filters for Permissible Mining Equipment

Jeffrey L. Ambs and Robert S. Setren

U. S. Bureau of Mines
Twin Cities Research Center
5629 Minnehaha Ave.
Minneapolis, MN 55417

Mine Safety and Health Administration
Approval and Certification Center
RR 1, Box 251
Industrial Park Road
Triadelphia, WV 26059

Abstract

The disposable diesel exhaust filter (DDEF) system developed by the U.S. Bureau of Mines and Industry cooperators for heavy-duty permissible, diesel-powered haulage vehicles, effectively reduces in-mine diesel particulate matter concentrations up to 95%. However, there are concerns about the hazards that exist when the filter is used in situations for which it was not designed. This work investigates the exhaust gas temperature limits to which the filter elements can be exposed without posing a safety or health hazard, such as fire or off-gassing toxic compounds. A filter approved by the Mine Safety and Health Administration (MSHA) and after-market filters were evaluated under varying engine exhaust conditions to determine if after-market filters pose an unacceptable hazard when used in a DDEF system. Filters were laboratory tested at engine exhaust temperatures ranging from 77°C to 290°C. Of the seven filter types tested, six appeared suitable for use on water scrubber-based cooling systems and two appeared suitable for use on dry heat exchanger type exhaust cooling systems with exhaust temperatures up to 150°C. Any filter elements used as exhaust filters on permissible diesel machines must be approved by MSHA for that application. Mine operators who wish to use an after-market filter element should request an MSHA field modification. MSHA will work with the mine and filter manufacturer to ensure its use in this exhaust system application does not pose a health or safety hazard.

Introduction

Disposable pleated element filters, originally designed for cleaning the intake combustion air of diesel engines, have been installed at the outlet of the exhaust gas cooling system on permissible diesel machines which have been approved under Part 36, Title 30, Code of Federal Regulations. The temperature at the outlet of the cooling system can be as high as 77EC for the water scrubber type systems or 150EC for the dry heat exchanger type systems. The use of filters on the outlet of the cooling systems for the removal of diesel particulate from the exhaust gases was tested, evaluated and approved by the Mine Safety and Health Administration (MSHA) Approval and Certification Center (A&CC), first for the water scrubber type systems and more recently for the dry heat exchanger type systems. The use of these disposable diesel exhaust filters (DDEFs) effectively reduces in-mine diesel particulate matter emitted by these machines, resulting in improved mine air quality (Ambs, et. al., 1991) (Ambs, et. al., 1994) (Ambs and Hillman, 1992).

The MSHA approval of the DDEF systems was contingent upon the use of specific filter elements; currently only one type of filter element has specifically been approved for use on each type of exhaust cooling system. Prior to approval of the filtering systems, MSHA developed technical evaluation and test criteria to ensure that the addition of the system onto the permissible machines would not introduce any safety or health hazards. Test procedures for evaluating filter elements in this type of application did not exist, thus, laboratory tests were developed by MSHA and a filter manufacturer to evaluate and approve the use of these first filters. The results of the technical evaluation, laboratory tests, and field observations showed that the filtering system did not adversely affect the safety features of the machine, and the specific filter elements used in the approved systems could be continuously exposed to the maximum operating temperature at the outlet of an exhaust gas cooling system without igniting or giving off any toxic compounds.

After-market replacement filter elements are made by dozens of manufacturers. The maximum temperature that a filter element can be exposed to is dependent upon its material makeup and manufacturing process. Reports from filter and machine manufacturers and the field indicated that despite the lack of appropriate MSHA approval, mine operators installed after-market filter elements. These "will-fit" filter elements physically fit within a filter housing on a permissible diesel machine, however, they have not been evaluated by MSHA. MSHA was concerned that these unapproved filters could represent a hazard.

To address MSHA's safety and health concerns with these will-fit filters, the U.S. Bureau of Mines (USBM), Twin Cities Research Center, conducted a research project to quantify a filter's safe temperature rating, relative to combustion and toxic off-gassing. Some of the questions to be addressed during this research were: (1) within the normal temperature range, could any will-fit air filter be used without specific testing or evaluation without adversely affecting health and safety; (2) could an analytical evaluation method, based on the materials used in the filter elements, be developed to approve the use of a filter element; or (3) should each filter type be tested. If testing of each filter type is required, could a bench test be sufficient to evaluate the filters, or must an expensive and lengthy lab and/or dynamometer test using complex instrumentation be required.

This report describes the initial phase of this research program and is intended to address the general test methods to be used in evaluating diesel exhaust filters for underground mine vehicles. This paper discusses laboratory tests conducted on eight dimensionally equivalent filters and discusses the findings of those tests.

METHODS/APPARATUS

Test Engine

DDEFs were installed in the exhaust stream of a 7-liter, pre-chamber, naturally aspirated, Caterpillar 3304 mining diesel engine. For standard MSHA test conditions, the maximum power rating of this engine is 75 kW (100 hp) at 37 Hz (2200 rpm). A detailed description of the apparatus and overall laboratory description and sampling procedures are given elsewhere (McClure, et. al. 1992) (Anderson, et. al., 1992) (Culshaw and McClure, 1992).

DDEF Filters

Eight different filter types, designated "A" through "H," were obtained from seven different filter suppliers, with one manufacturer supplying two different types of filters. All filters were nominally the same size and had the same amount of filter material as the filters originally approved by MSHA for use on water scrubber type cooling systems. These approved filters are designated filter type "A" in this report.

Gaseous Emissions Sampling System

A Nicolet Rega 7000 RT Fourier Transform Infrared Spectrometer (FTIR) (Heller, et. al., 1990) (Shore and de Vries, 1992) exhaust gas analyzer was used to obtain the emissions measurements during these tests. Unlike the conventional analyzers, the FTIR analyzer is able to measure the exhaust concentrations of multiple discrete compounds directly, concurrently in the same sample, and effectively in real time. Currently the system is set up to measure 25 different compounds such as CO_2, NO and NO_2, with CO, formaldehyde, and hydrocarbons being emphasized for this work. Formaldehyde was chosen because it is an expected component of any gases released from the filters. While the hydrocarbon results obtained by the FTIR method are quantitatively lower than those obtained using the more traditional Flame Ionization Detector (FID) type analyzer, qualitatively the results are equivalent. The FTIR analyzer measures the concentration of HC molecules while the FID analyzer measures the number of carbon atoms in the sample.

Engine Operating Conditions

MSHA approved the use of exhaust filters on permissible diesel powered mining equipment under very specific exhaust temperature constraints. While it seemed apparent that the approved filters were not releasing harmful compounds under normal operating conditions, it was important to verify this fact during testing. In addition, it was clear that there would be cases where the filters would be exposed to temperatures, while not high enough to create a fire hazard, could possibly have caused unwanted compounds to be released from the filters into the mine environment. For this reason, it was important to evaluate potential exhaust filter elements under various conditions. Two general types of evaluations are reported in this work, namely a number of steady-state conditions which are characterized by discrete engine speed-and-torque settings and a screening or "ramp" test (Ambs and McClure, 1993).

The filters were first tested under steady-state conditions for 30 minutes each at two engine operating conditions to yield filter inlet temperatures of both 77 and 100°C. The engine baseline emissions for these steady-state conditions ranged from 1-4 ppm for hydrocarbons and approximately 4 ppm for formaldehyde. After the steady-state tests were complete, a heat exchanger, which was required to simulate the low exhaust temperatures present in water scrubber equipped vehicles, was removed and the filters were retested using the ramp test, which started with a filter inlet temperature of 115°C. The ramp test was allowed to continue until the filter inlet temperature reached approximately 260°C.

Ramp or screening evaluations are obtained by observing emissions while ramping the engine load from 27 N-m (20 lb-ft) (idle torque) to 325 N-m (240 lb-ft) (full load) at a rate of 2.7 N-m/s (2 lb-ft/min), with a corresponding rate of change of temperature of the exhaust of about 0.032 °C/s (3.5 °F/min). This ramp test has been used in previous testing by the USBM and is described in more detail elsewhere (Ambs and McClure, 1993). The ramp tests were used to test a filter over a wide range of operating conditions while still observing any changes associated with a gradual increase in the filter inlet temperature.

Figure 1 shows baseline engine emissions during a typical ramp test for this engine. Note that both hydrocarbons and formaldehyde remain fairly constant over the range of temperatures in the ramp.

RESULTS

Steady-State Tests

Figure 2 is representative of the results for all filters tested under steady-state conditions at filter inlet temperatures of 77 and 100°C. These results indicate that there are no discernable differences between the different filter types at these temperatures. Shown in the figure are hydrocarbon , CO, and formaldehyde emission levels, and the filter inlet temperature. The exhaust temperature remains constant from the start of the test until the engine operating condition and exhaust temperature was changed to give a filter temperature of 100°C. As can be seen from the graph there is little difference between the steady-state engine baseline emission levels and the levels of HC and formaldehyde as the exhaust passes through the DDEF. All of the filters tested use similar materials in their construction except for filter type "G" which uses a phenolic resin-based filter media. When used in this application at one mine site, this type of filter produced objectionable odors prompting workers to quickly remove the filter after installation. While there was no evidence of any unusual chemical release from the filter during the steady-state tests, there was a definite difference observed between the type "G" filters and the other filters during the ramp tests and is described in the section below.

Ramp Tests

Figure 3 shows the results of a ramp test using filter type "A," and is descriptive of the results for the other types of filters. The differences between filter types are the levels and temperatures of off-gassing from the filters, with some filters giving off compounds at lower temperatures or at higher levels. The graph shows an increase in HC levels at approximately 150°C indicating a breakdown in filter materials and release of compounds at that temperature. These levels slowly decrease before rising later as the temperature increases. The formaldehyde levels remained nearly constant until 130°C where levels slowly began to increase. While this filter appears to be suitable for use up to about 130°C, in this case the manufacturer would not recommend that the filters be used at temperatures above 100°C. Most tested filters behaved similarly during the ramp tests, with variations in the temperatures and levels of the release of compounds the main difference between the filters. With one exception, the emission levels followed the engine baseline line levels for the ramp test until compounds were released from the filter elements, with formaldehyde being released beginning at temperatures ranging from 125 to 180°C and HC being released from the filters beginning at about 150°C.

Also observed in the figure, at a filter inlet temperature of approximately 235°C, is the ignition point of this type of filter. This is identified by the sharp increase in CO, HC, and formaldehyde emission levels, indicating hazardous levels of gases being released from the filter. While this test was stopped prior to the actual ignition of the filter, the results indicate that the filter is rapidly decomposing or oxidizing at this temperature and ignition is imminent. Measurements taken during other tests where filter ignition occurred, yielded CO concentrations as high as 7%, and formaldehyde concentrations as high as 500 ppm.

Filter type "G" was the only filter type that exhibited different behavior under these tests. While no unusual results were detected during the steady-state testing, HC compounds were released at concentrations 3-4 times greater than normal exhaust levels at the beginning of the ramp test where the exhaust temperature was approximately 110°C. The HC levels returned to the normal exhaust levels after approximately 5 minutes. This is attributable to the different type of filter material used in this brand of filter. This type filter was used in the DDEF system by one mine without the knowledge of the filter manufacturer, MSHA, or the USBM, and during discussions with the filter manufacturer, they indicated that they would not have recommended that this type of filter be used in the DDEF system. Instead, they offered a second filter type which performed similarly to the rest of the filters in these tests.

CONCLUSIONS

Tests were conducted on both an MSHA-approved exhaust filter, and on a number of aftermarket filter elements which will fit into the housing on an exhaust filtering system for permissible diesel machines. The tests showed similar off-gassing characteristics for formaldehyde and hydrocarbons among all of the filters tested up to a temperature of 100°C. These tests suggest that, with one exception, all of the tested filters appear to be suitable for use as exhaust filters on water scrubber type cooling systems used on permissible diesel-powered mining equipment with exhaust temperatures up to 77°C. Two of the tested filter types appear to be suitable for use on the dry heat exchanger type cooling systems where permissible exhaust temperatures can reach 150°C. However, not all off-gases were measured (such as phenol compounds) during these tests, and dry exhaust gas was used in lieu of the wet exhaust gas discharged from most permissible diesel machines. These concerns are currently being addressed by investigating techniques to detect additional compounds, such as phenols, and by developing techniques to analyze filter materials under conditions more closely resembling the conditions found in wet type exhaust cooling systems. These results do fairly represent the conditions found in the exhaust of the newer dry-type exhaust cooling systems.

While some filters tested during this research appear to be suitable for use as exhaust filters on permissible diesel-powered equipment, only one has been specifically approved by MSHA for that application. The one filter type tested that is definitely not suitable for this application was made of a phenolic resin based filter material and was used in this application without the approval of the filter manufacturer or MSHA. Mine operators who wish to use an after-market filter element for their filtering system should request a field modification from MSHA. MSHA will work with the mine and filter manufacturer to conduct tests and evaluate the new element to ensure its use in this exhaust system application does not pose a health or safety hazard.

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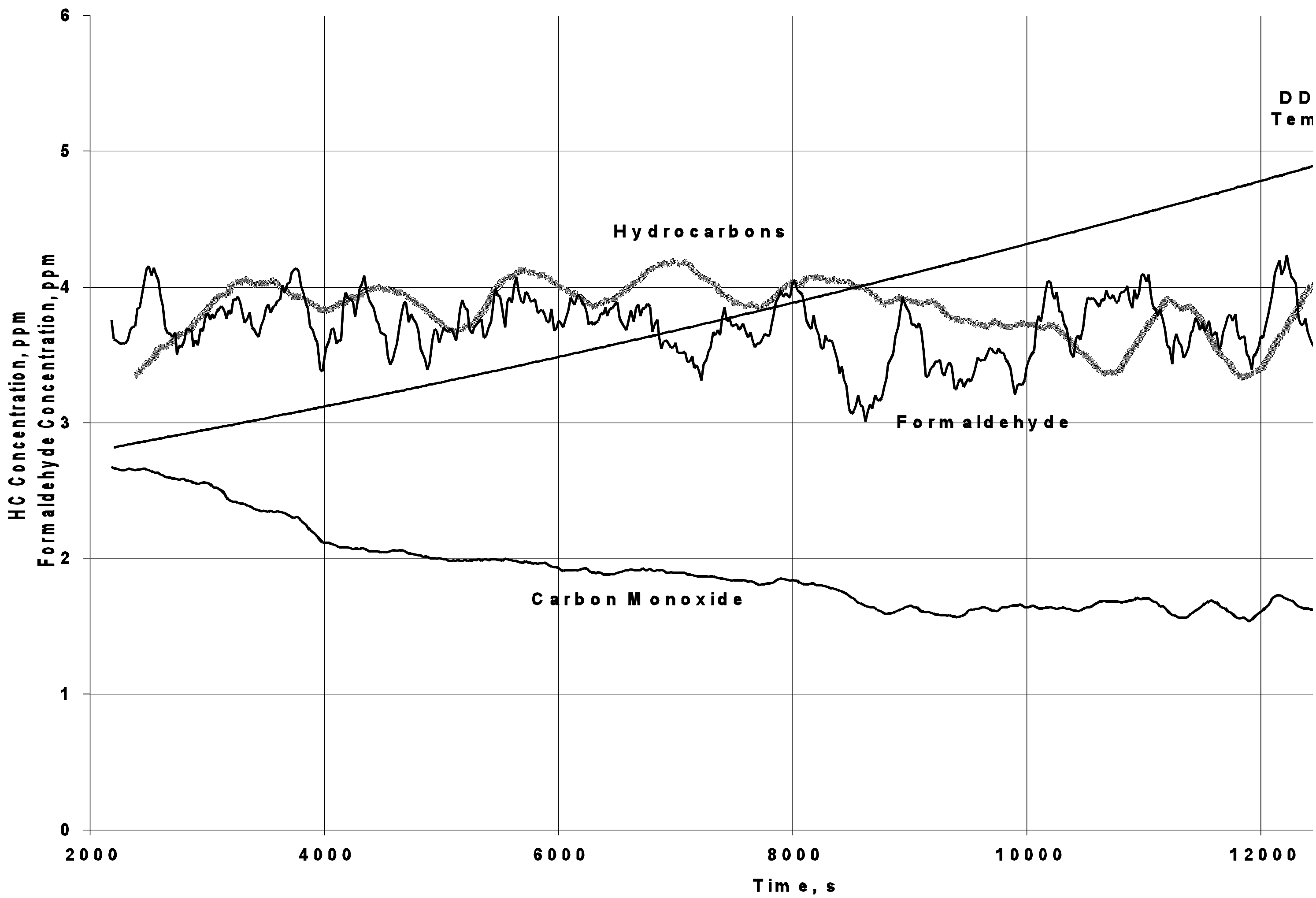

Figure 1 - Engine baseline emissions for a 1500 RPM ramp test, showing CO, hydrocarbon, and formaldehyde concent
temperature.

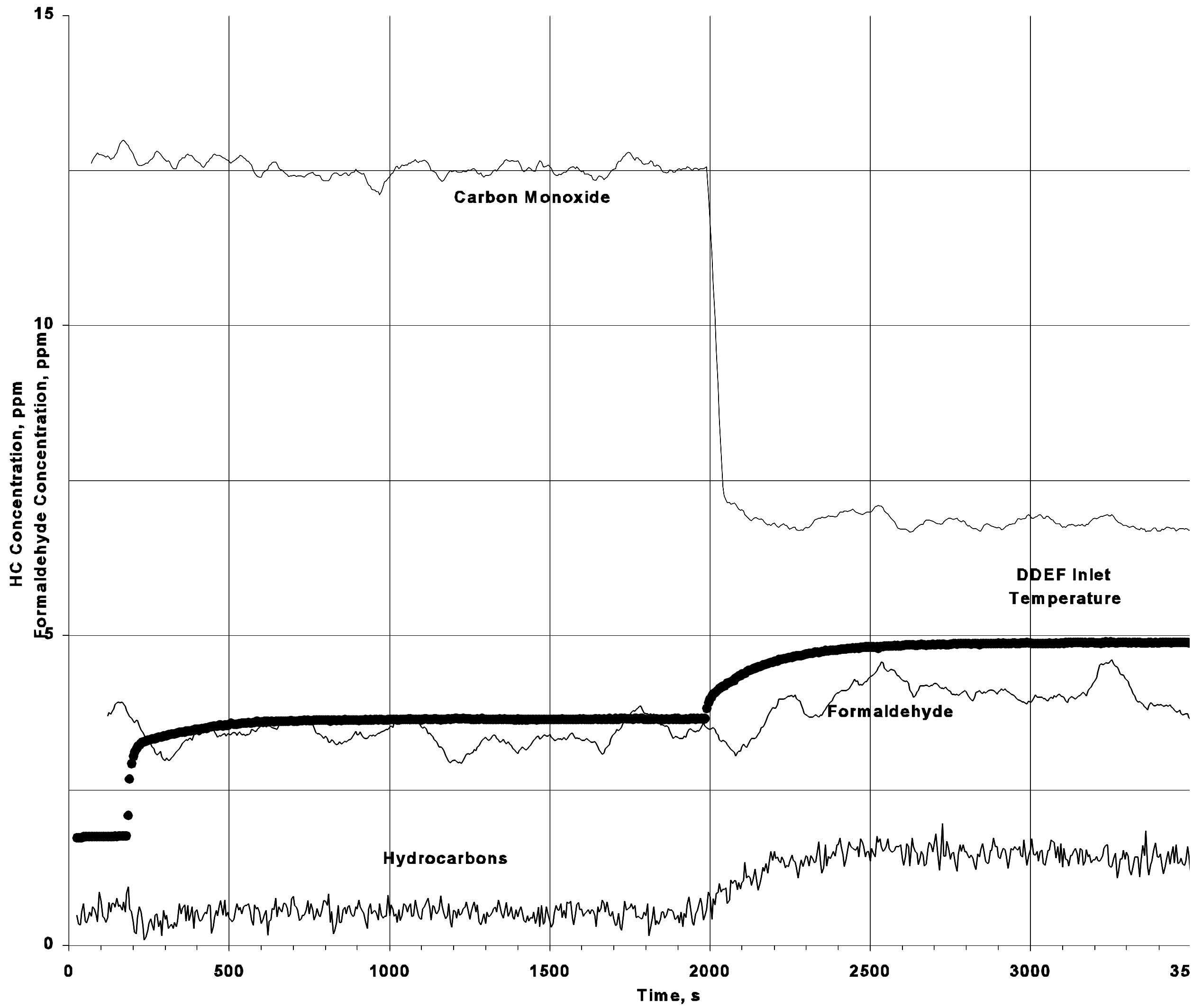

Figure 2 - Steady-state exhaust emissions at DDEF inlet temperatures of 77 and 100ºC.

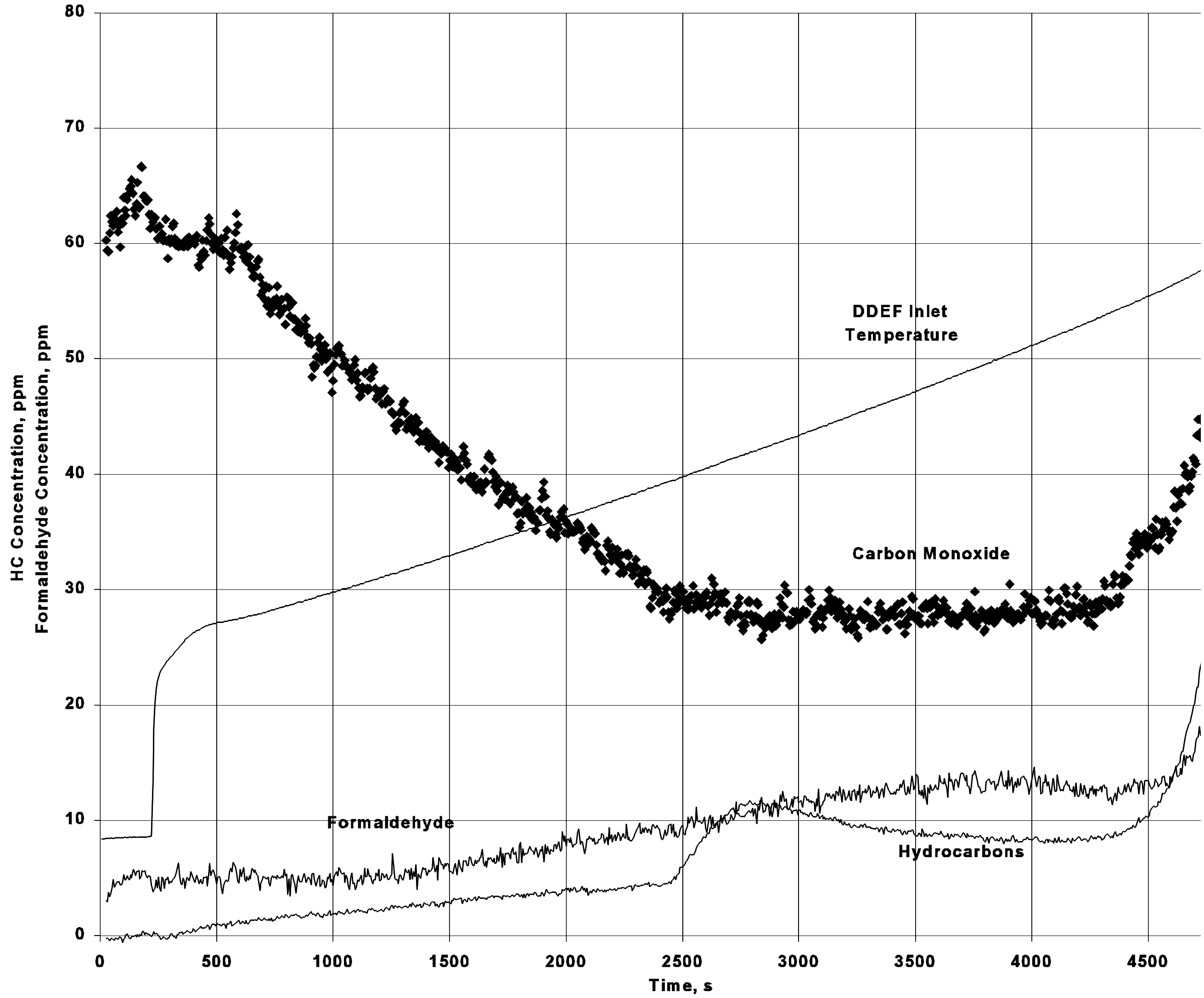

Figure 3 - Ramp test results for MSHA approved DDEF showing CO, hydrocarbom, and formaldehyde emission levels f