MICROWAVE REGENERATED PARTICULATE TRAP

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INTRODUCTION

Since 1988 particulate matter (PM) emitted by diesel engines has decreased in excess of 80% from 0.60 g/BHp-Hr to 0.1 g/BHp-Hr. Diesel engine manufacturers continue to invest in technology to produce diesel engines that are environmentally sociable and compatible with the EPA legislated limits. Engine manufacturers have employed several methods to achieve the legislated EPA requirements listed in Table 1 including; advanced fuel injection systems, combustion and air handling technology and exhaust aftertreatment, e.g., catalysts, soot filters and particulate traps.

Table 1. Legislated Diesel Emission Requirements, g/BHp-Hr by year.

Year	Automotive HD	Urban Bus
Pre 1988	---	---
1988	0.6	0.25
1991	0.25	0.1
1994	0.1	0.05
2004	0.1	0.025

The diesel oxidation catalyst represents the single exhaust aftertreatment device equipped on production volume diesel engines. Although diesel particulate filters benefit from nearly thirty years of extensive research and evaluation many technical barriers remain unresolved including:

1. Extracting at least 90% of the particulate matter without degrading engine performance due to excessive exhaust restriction;
2. reducing thermal stresses produced by thermal gradients;
3. eliminating the catastrophic exothermic reaction that occurs when non-combusted particulate matter accumulates over several cycles suddenly ignites, melting the filter media; and
4. demonstrating system durability and reliability that are comparable to other engine components.

Previous efforts to develop a diesel exhaust particulate filter used an extruded cordierite wall flow filter that is heated by resistive or a fossil fuel burner [1, 2]. This effort focuses on developing a novel technology to reduce the particulate matter (PM) emitted by diesel engines while addressing the previous issues. This technology involves using a ceramic fibrous filter to collect the PM and microwaves to combust the collected PM or "regenerate" the filter. Compared to previous systems, a microwave filter offers the following potential advantages:

1. the porosity of the fibrous filter is inherent to the structure and not created from fugitive materials as with wall flow filters. This produces a structure without closed porosity that weakens the structure without participating in the filtration of the PM;
2. the filters are produced using current industry practices that can be readily automated; and
3. microwave heating produces rapid and uniform heating that reduces ther-mal gradients minimizes the resulting thermal stresses.

It has been demonstrated that microwaves can heat filters and combust particulate matter [3, 4]. However, it has not been adequately demonstrated that a microwave system possesses the robustness necessary for the diesel environment. In addition to evaluating filter performance, this paper also examines the robustness of the magnetron in a simulated diesel truck environment.

FILTER DEVELOPMENT AND TESTING

FILTER DEVELOPMENT - The fibrous particulate filter is a composite structure comprised of aluminum oxide (Al2O3) fibers with a chemical vapor infiltrated (CVI) silicon carbide coating (SiC). The filter preform is produced from a paper manufacturing process that combines inorganic Al2O3 fibers with organic constituents to improve green strength. After the preform is cured a silicon carbide coating is applied. A report completed for the California Energy Commission contains a detailed description of filter design and development [5].

HEATING CHARACTERISTICS - After application of the silicon carbide coating the heating characteristics are evaluated using a laboratory bench test at the facilities of FM Technologies. Testing is conducted by wrapping an insulating sheet around the filter and placing the wrapped filter into a stainless steel cavity that is connected to a microwave source. Thermocouples are inserted into the filter at several radial locations and power is initiated to the magnetron. Temperature data are recorded as well as visual observations while the filter is heating. Extensive investigations and analysis by FMT have determined that microwaves are not adversely impacting the temperature measurements. Several tests were conducted where power was terminated and the temperature data does not show an abrupt change in slope. After reinstating the power the heating rate resumed at the initial rate.

A filter that has sufficient coating will display a dull glowing within 30 to 300 seconds and within 600 seconds the entire filter will demonstrate an orange glowing. The plot in Figure 1 depicts the rapid heating rates and the minimal thermal gradients that can be achieved using microwaves. A filter that is not coated properly will not demonstrate uniform heating or display the orange glow. Results of scanning electron microscopy, spectral analysis and a high temperature heat treatment suggest that filters that exhibit nonuniform heating do not contain sufficient silicon carbide on the interior. The filter in Figure 2 has completed a high temperature heat treatment and displays grayish regions devoid of structural rigidity. Elemental analysis indicates these regions are comprised primarily of aluminum with lesser amounts of silicon. Unlike silicon carbide the alumina fibers do not heat as readily in the presence of microwaves.

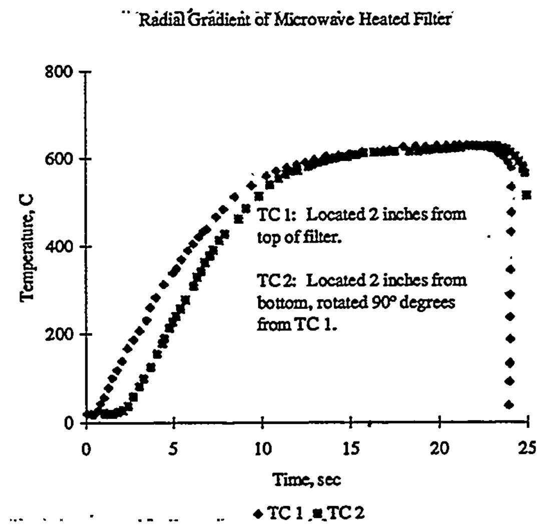

Figure 1. Plot of heating rate and thermal gradients for tibrous filter.

ENGINE TESTING - Engine tests have been completed using the silicon carbide coated fibrous particulate filter to evaluate particulate reduction and back pressure. Particulate emission reduction was evaluated using the transient emissions cycle and back pressure results were obtained using bench test evaluation.

Particulate reduction measurements were completed on two filters (81 D and 85M) by the Emissions Measurement Laboratory at the Cummins Technical Center (CTC). Both filters were evaluated over the transient emission

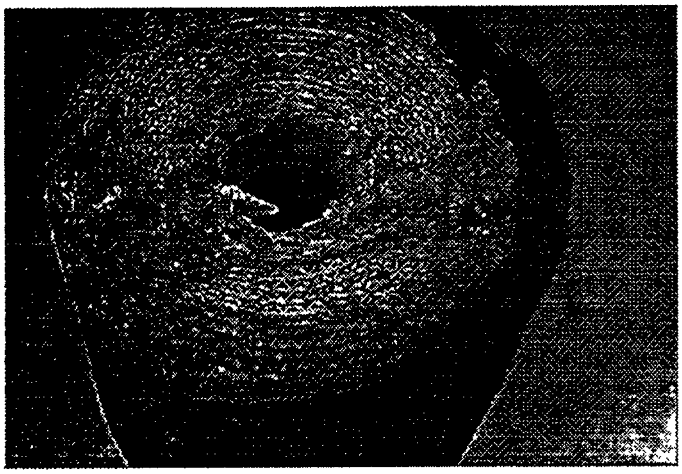

Figure 2. Photograph showing damaged regions on the Interior that were not fully coated and do not possess adequate structural rigidity.

cycle using production engines. Filter 81 D was canned by Nelson and installed in the test cell behind a 175 Hp B 5.9 liter engine. The filter was subjected to four hot cycles and one cold cycle. A review of the data indicated that the particulate levels increased compared to the baseline configuration (engine with catalyst).

After removing the filter from the test cell visual inspection revealed the exhaust pressure displaced and fractured the center core into smaller sections (Figure 3). It is likely that the small sections from the damaged core collected on the filter patch producing the apparent particulate increase. Before submitting filter 85M to the CTC emissions laboratory the core was sealed with a ceramic adhesive to prevent it from being displaced. It was canned by Nelson and then installed into the test cell behind a 215 Hp B5.9 liter engine. The results from this testing provided more encouragement than the first emissions test. Although visual inspection revealed that the core (the entire core remained in the can) was also displaced during testing, the data showed that a fifty percent reduction in particulate matter was achieved. Absence of the core resulted in an eleven percent increase in open frontal area that does not contribute significantly to exhaust filtration. Alternative methods of sealing the center are being evaluated. This filter was repaired and submitted for bench test evaluation.

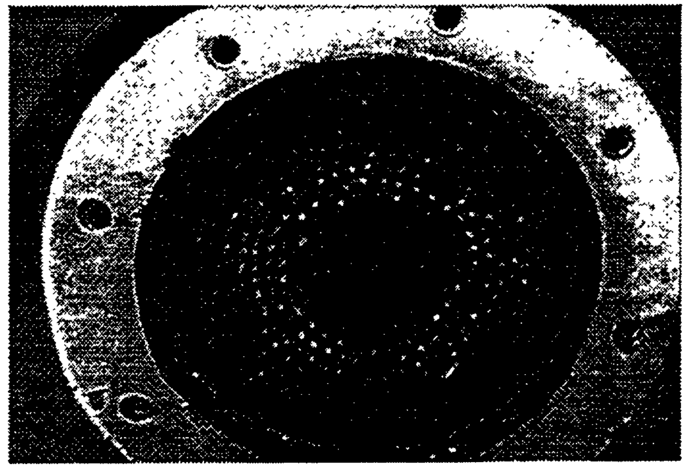

Figure 3. Photo of filter 81D without center core after completing transient emissions testing.

BENCH TEST EVALUATION - The bench test evaluation is used to evaluate the performance of new filter designs under a controlled environment and to compare the results with historical data. Bench testing consists of a typical test cell with dynamometer and engine; however, a by pass loop has been installed that restricts exhaust flow between thirteen and twenty two percent of full exhaust flow. This allows testing smaller units that would otherwise be incapable of withstanding the full exhaust flow and maintaining space velocities. Generally it is easier to fabricate smaller prototype filters in the range of six inches in diameter. The bench test evaluates characteristics such as, loading rates, balance point and engine back pressure. The balance point may be defined as the temperature at which the rate soot loading and combustion are equivalent.

After filter 85M was removed from the emissions test laboratory it was installed for bench test evaluation. The core was replaced with a sheet of kaowool insulation that was rolled to the correct diameter and inserted. The sheet was then trimmed to correspond to the filter length.

Figure 4 shows the results of the bench evaluation and comparison to a dense cordierite filter. Compared to the cordierite filter the fbrous filter demonstrated extremely low engine back pressure. The slope of the fibrous filter curve indicate that particulates may be collec-ting at a faster rate or more effectively than the cordierite filter.

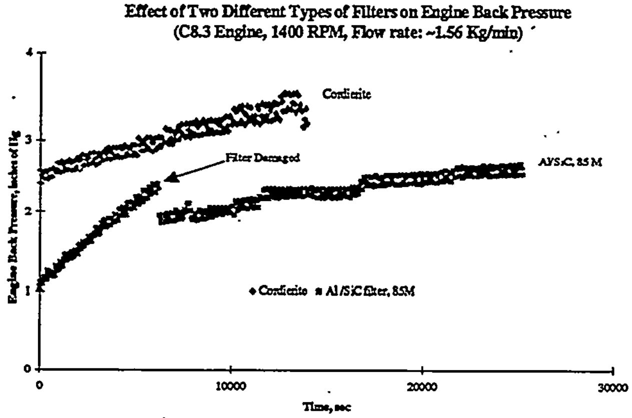

Figure 4. Effect of engine back pressure for fibrous and wall flow filters.

MAGNETRON DURABILITY

During the development of the microwave particulate filter significant process has been made on how to deliver or "port" microwaves to the filter. Previous researchers [3, 4] have demonstrated that it possible to heat particulate filters and combust particulates using microwaves instead of resistive or fossil fuel burners. In fact our work has repeatedly demonstrated that microwave heating of a filter is readily accomplished; however, the robustness of the components associated with producing microwaves (magnetron) has not been evaluated. This is an important consideration since development of the diesel oxidation catalyst [6, 71 required extensive research, design and testing to ensure durability and reliability. Notwithstanding, the Environmental Protection Agency (EPA) legislated durability requirements of 8 years/290,000 miles for exhaust aftertreatment devices, customers expect all engine components to exhibit durability comparable to the engine. In the case of diesel engines today one million miles is not unrealistic.

Cummins has extensive knowledge and experience assessing the durability of electronic components, many of our engines incorporate electronics in the fuel injection systems. A first step to understanding the durability is to expose the component to a simulated diesel operating environment, including road and cab vibration, severe thermal conditions, and salt and humidity.

VIBRATION TESTING - Initial screening of magnetron robustness was assessed by conducting vibration testing for twenty hours on three mutually perpendicular primary axes (x, y, z).

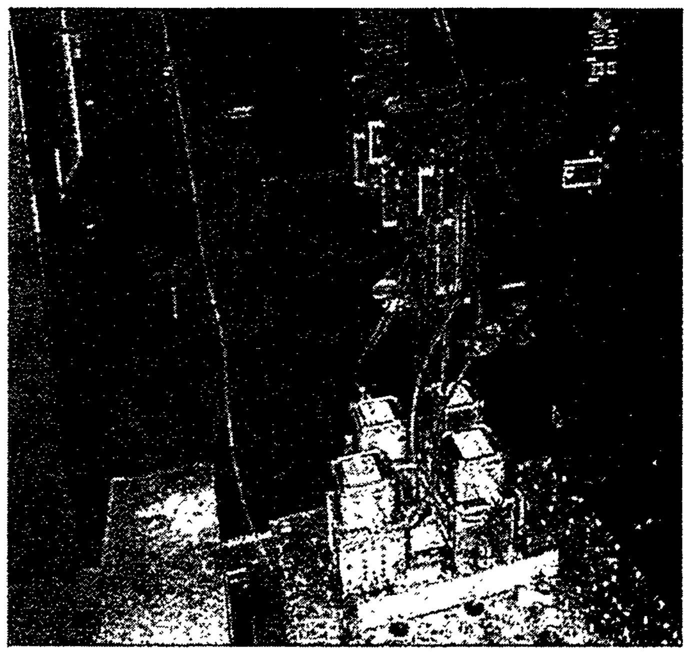

Figure 5. Photograph of magnetrons Installed on vibration stand prepared for "hot" testing.

Figure 5 shows the magnetrons being installed for vibration testing. The spectrum used to complete the testing was acquired from vehicles during operation. Before proceeding to production, new electronic components must demonstrate an ability to complete this testing without incident.

There were four sets of testing completed on three groups of magnetrons. Post test inspection evaluated mechanical damage and electrical characteristics. Initially the magnetrons were tested without current supplied to the filament (referred to as "cold" testing). Once cold testing was successfully completed, electrical current was connected to evaluate the robustness of a "hot" filament.

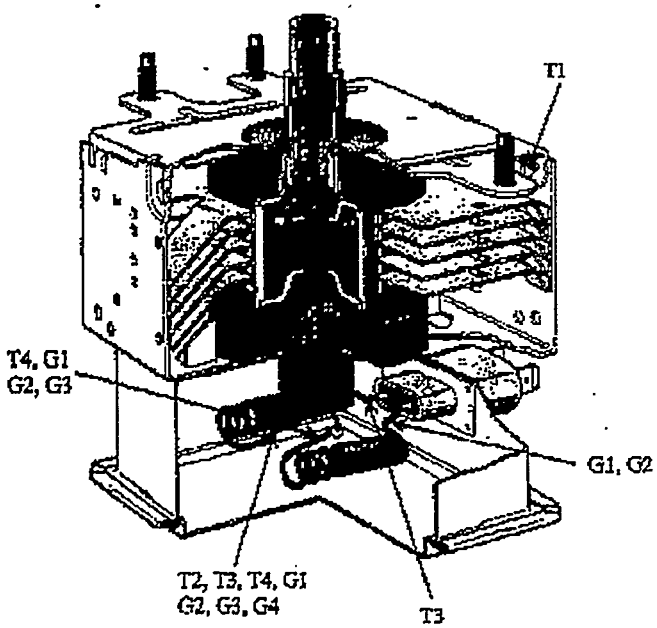

Figure 6. Schematic of magnetron Indicating location of failures.

During the cold tests nine out of the ten magnetrons incurred damage at the inductor and the remainder at the housing tab (Figure 6). After analyzing the failures it was determined that by reinforcing the "weak" spots the components would survive the test. The inductors were reinforced by applying a silicone based adhesive and allowing it to cure at ambient temperature. The reinforced magnetron's were then subjected to a cold test and all completed the test without incident. Next the same set of reinforced magnetrons were connected to power supplies that would allow current to flow without generating microwaves. The current output was monitored during testing to determine when a failure occurred. One of the magnetrons suffered a fatigue failure on a mechanical tab during the first twenty hours; however, the remainder completed the test without incident.

ON BOARD POWER

All testing previously presented was conducted by powering the magnetrons using 110 V from a standard power outlet. However, on-board operation requires using the power available from the vehicle's electrical system. To investigate the feasibility of operating the magnetron using on board power a bench test was developed consisting of a 5 horsepower engine, a 150 amp alternator, a battery, and an inverter (Figure 7). The engine operated the alternator at 8325 RPM which produced 150 A with a 0.1 ohm load. The system was then connected to the inverter which generated 110 V used to power the magnetron's, 143 amps went to the load and 7 amps went to the battery. The magnetron was successfully powered by the setup and the filter heated up.

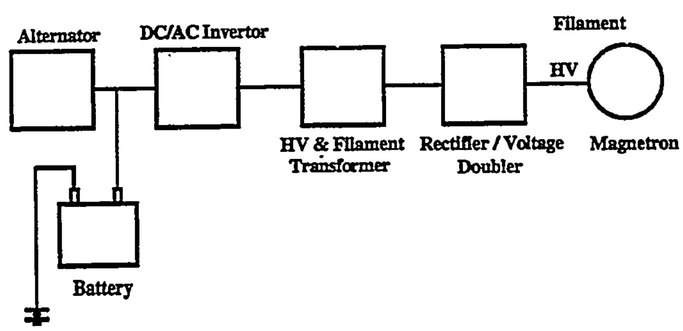

Figure 7. Schematic of circuit designed to operate a microwave power on-board a diesel truck.

SUMMARY

It has been demonstrated that a fibrous particulate filter can extract particulate matter from the diesel exhaust. However, additional engineering efforts remains to achieve the design target of 90%. It has also be shown that with minor modifications magnetrons produced for home ovens can endure a simulated diesel operating environment.

Much work remains to develop a robust product ready to complete extensive engine testing and evaluation. These efforts include,

1. additional environmental testing of magnetrons;

2. vibration testing of the filter in the housing;
3. evaluating alternative methods/ designs to seal the center bore: and
4. determining the optimum coating thickness that provides sufficient structural integrity while maintaining rapid heating rates.

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