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DIESEL PARTICULATE FILTER DEVELOPMENT PROJECT

MICROWAVE REGENERATED HEATING PERFORMANCE and ROUND PLEATED FILTER CARTRIDGE DEVELOPMENT

FINAL REPORT

FY1999 – 2005 Program

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1 Abstract

The U.S. Department of Energy's (DOE) Partnership for the New Generation Vehicle and Freedom Car Programs both supported new technology to control particulate emissions from diesel engine exhaust. Industrial Ceramic Solutions, LLC (ICS) invented a low thermal-mass ceramic fiber filter capable of greater than 95% particulate matter (PM) reduction at low backpressure. An optional microwave device capable of cleaning the filter cartridge during diesel vehicle operation was also developed. This report recounts the development activities, their results, conclusions, and future work that occurred between FY1999 and FY2005. The work is divided into two sections, based upon the two distinct foci of the funded objectives. The first section addresses the development of a microwave sensitive ceramic fiber filter media and a microwave system capable of cleaning the diesel soot from the filter. Data is presented to show the performance of the filter and the adjoining microwave-cleaning system. This data includes filtration efficiency in the diesel exhaust and microwave-cleaning efficiency of a soot-laden filter. After the FY2003 funding, DOE and its diesel engine industrial partners elected to move away from the microwave system project in order to concentrate specifically on developing a round pleated filter cartridge that would be suitable for any type of regeneration system. The development process for the round pleated filter is discussed in second section. The ceramic fiber filter media for the pleated filter was improved to provide better customer performance on a diesel engine by increasing the filter strength and the diesel soot loading capacity. This advancement also reduced the size of the round pleated filter package. The design and fabrication of a round pleated filter suitable for a 7.3-liter Ford diesel pickup is discussed.

2 Introduction

DOE's Partnership for the New Generation Vehicle Program (PNGV) and its member automobile manufacturers established an initiative to develop a small diesel engine to improve fuel efficiency for large gasoline powered vehicles. This diesel engine technology implementation would also reduce "greenhouse" gas emissions to the atmosphere. Public concern over particulate emissions from diesel engine exhausts currently impedes efforts to replace gasoline engines with small diesels. A positive control technology for the diesel particulate pollution would free the diesel engine industry and the auto and truck manufacturers to expand the use of fuel-efficient diesel engines in small trucks and passenger vehicles. To this end, ICS invented a low mass ceramic fiber filter capable of greater than 95% particulate matter reduction at low backpressure. An optional microwave device capable of cleaning the filter cartridge during diesel vehicle operation was also developed. The patented silicon carbide fiber component makes efficient microwave heating of the filter cartridge possible.

This filter concept was presented to the PNGV committee consisting of representatives from DOE, EPA, Chrysler, Ford and General Motors, in early 1999. The initial concern of the automobile manufacturer members was the microwave filter system's ability to achieve carbon combustion temperatures at any level of engine exhaust flow through the filter. A firm requirement for exhaust control is a simple system that does not require moving parts in the exhaust piping, such as valves, dampers, or multiple filter rotation. Past experience in the auto industry has shown that life-cycle failure is almost certain when mechanically moving parts are in an exhaust stream. The PNGV members requested a testing program to investigate the ability of the Microwave Regenerated Ceramic Filter to reach carbon ignition temperatures (> 550^{o}C without a catalyst) under dynamic exhaust flow conditions.

After an early bench-top experiment conducted in FY1999 proved that the microwave-regeneration system was capable of reaching carbon combustion temperatures, Ford volunteered a test cell at their Dearborn laboratory for an engine test. The Microwave-Regenerated Ceramic Filter was tested on the experimental Ford DIATA 1.2 liter Diesel Engine at the Ford Scientific Research Laboratory. Mechanical durability, filtration efficiency, and microwave regeneration efficiency were investigated. The experimental results from this test showed that the filter could remove diesel particulate with 80-90% efficiency in operating conditions ranging from idle to cruising speed. The ceramic cartridge, regenerated by microwave energy at engine idle speed, was cleaned, in place, to its original filter condition. The test cell results showed that the pressure drop across the ceramic paper filter cartridge is significantly less than that experienced by existing extruded cordierite wall-flow filters.

Engine and Vehicle Testing

In FY2001, a second stationary engine test was conducted on a Volkswagen 1.9-liter TDI engine at Oak Ridge National Laboratory (ORNL), using microwave energy to clean a ceramic fiber corrugated wall-flow filter. A filter efficiency of greater than 95% was demonstrated. Prior to this Volkswagen engine test, the strength of the filter media was increased from 1 pounds/inch^2 to 6 pounds/inch^2 burst strength using improved ceramic processing. Also, finite element modeling of the microwave field was applied to improve the uniformity of the microwave cartridge heating.

In the first vehicle test., the filter cartridge (without a microwave unit) was mounted on a Ford F250 7.3-liter diesel pickup truck for approximately 6,000 miles and nine months of road testing. Filter cleaning was accomplished off-line in a laboratory furnace. This Ford truck was used as the test vehicle for diesel particulate filter (DPF) prototypes through the end of the program.

The next vehicle test was to be conducted using a 1998 Volkswagen Jetta with a 1.9-liter TDI engine. A filter and a microwave regeneration system were installed on the Volkswagen and tested for 200 miles and six microwave regenerations; however, the test was cancelled due to irreparable damage to the EGR system that occurred before ICS received the vehicle. Also in FY2002, the first pleated ceramic fiber filter was fabricated and tested on the Ford truck. This pleated filter design exhibited a tenth of the backpressure experienced with a standard wall-flow honeycomb DPF filter. The pleated filter was then tested for particulate removal efficiency at ORNL on a 1.7-liter Mercedes engine in FY2003. The efficiency was measured at greater than 96%. A microwave-regeneration system was designed and fabricated to test a pleated, rectangular filter cartridge on the 7.3-liter Ford truck. This system was road-tested through a full range of engine operating conditions with limited success in achieving full regeneration due to non-uniformity of microwave heating.

Round Pleated Filter Cartridge

The pleated ceramic fiber diesel particulate cartridge used prior to FY2004 was rectangular in shape, but most automotive applications required a round shape. All FY2004 and FY2005 work was directed toward designing, developing, and fabricating the round pleated filter. The microwave regeneration work was put on hold, and a filter was designed to accommodate the exhaust of the Ford 7.3-liter diesel truck. A ceramic injection molding process was investigated to apply a frame to the fiber filter media. Furthermore, mechanical stress loading and size constraints required some improvements in the ICS ceramic fiber media. The burst strength of the media was increased from approximately 150 to 415 inches of water, and the soot-holding capacity was increased from 0.86 grams/foot^2 to 1.4 grams/foot^2. With these improvements in place, a joint development agreement was entered between ICS and a major Tier I automotive parts supplier with the objective of taking the pleated ceramic fiber filter cartridge into the commercial marketplace.

The backpressure and soot-holding capacity of a fiber filter has advantages over the ceramic wall-flow filter, as seen in Figure 1. Particles are trapped by “depth filtration” rather than the mechanical membrane filtration of the wall-flow filter. Depth filtration allows the pore size of the fiber filter to be many times greater than the particle diameter that is being removed. Particles are trapped by adhering to the individual fibers, rather than being stopped by very fine holes in the ceramic wall. The net result is filtration efficiency equivalent to the ceramic wall-flow filter with approximately one fifth of the backpressure increase. Another advantage is the ability of the fiber filter to trap any size particle down to less than 10 nanometers in diameter.

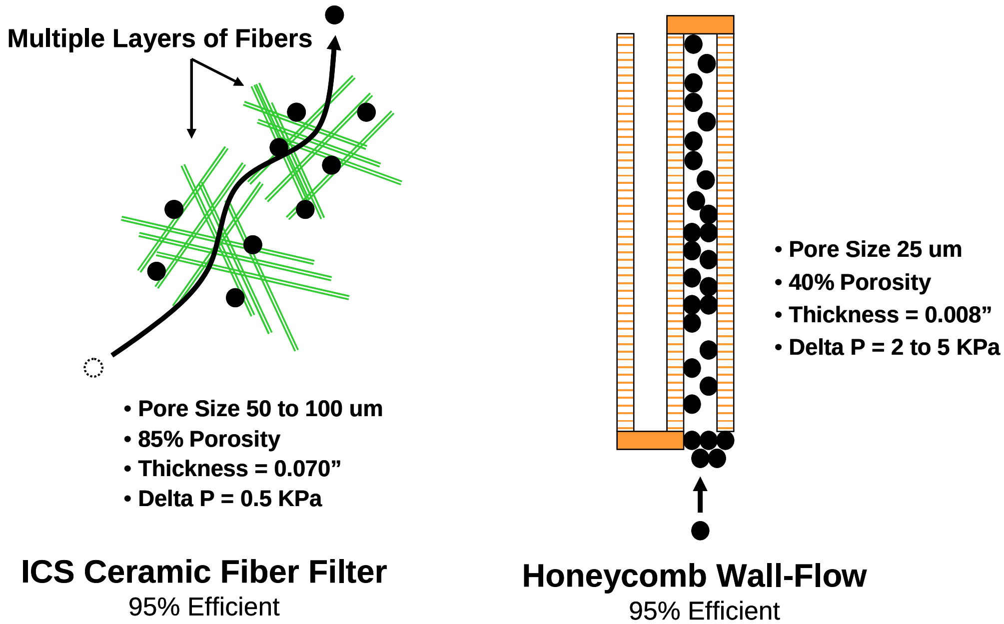


Figure 1. Fiber filter vs. wall-flow filter advantages

3 FY 1999 Experimental Procedure and Results

Microwave regeneration of the ICS fiber filter is potentially the most efficient method to remove the soot from a loaded DPF. The patented ICS silicon carbide fiber demonstrates unique properties in a microwave field. The fiber is neither reflective nor transparent to microwaves. Rather, the microwaves are absorbed by the fibers and converted to thermal energy that quickly raises the temperature of the filter cartridge. Typically, only three minutes are required to microwave heat the cartridge above 600^{o}C. This is particularly advantageous when using a catalyst coated filter. During normal heating methods, efficiency is lost as heat is transferred from a source, to the exhaust gas, to the filter cartridge, and finally to the catalyst. The microwave heating of the silicon carbide fibers provides a shortcut. The microwaves directly heat the fibers on which the catalyst particles are located, significantly improving heating efficiency.

For the initial bench-top proof-of-concept conducted in 1999, a 2-inch diameter silicon carbide filter cartridge was wrapped with a 0.5-inch thick, high temperature, fiber-wool insulation material. The 3-inch diameter cartridge/insulation package was inserted in the 2-inch thick rigid oxide fiber insulation cylinder in a microwave cavity. This created a 3-inch insulation wall between the silicon carbide fiber cartridge and the steel microwave cavity wall.

Each cartridge test was run with airflows through the cartridge of 5, 8.5, 10, and 15 cfm. The microwave power inputs tested at each airflow setting were 500, 800 and 1,000 watts. During each experimental run, room temperature-compressed air flow was brought to equilibrium through the filter cartridge at the designated flow rate. Microwave power at the designated setting was initiated. Temperature readings on the filter cartridge were recorded at 5, 10, 15, 20, 30, 40, 50, 60, 75, 90, and 120 seconds. The temperature of the filter cartridge was measured by a Mikron M90 Series Portable

Infrared Thermometer. The hot filter, as viewed through the pyrometer, is shown in Figure 2; the microwave oven is shown in Figure 3.

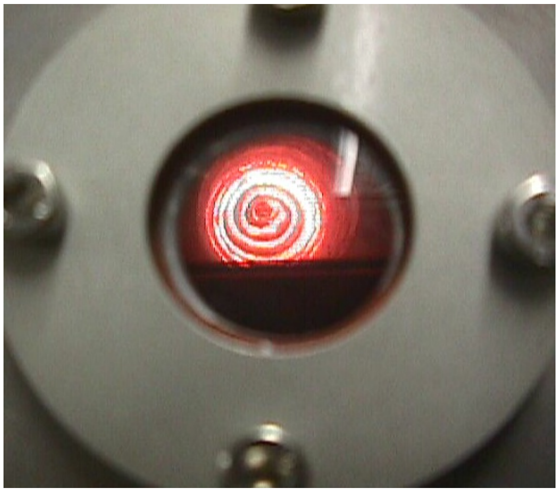


Figure 2. Microwave-heated cartridge at 15 cfm air flow

Figure 3. Microwave oven

Heat from the microwave field coupling to the silicon carbide fibers increases the temperature of the filter until the heat produced in the fibers equals the heat removed from the filter media by the exhaust stream plus the stored heat. The equilibrium zone is reached when the heat exchanger values stop increasing or begin to level. It is assumed that the filter temperature will stop increasing near the end of this equilibrium zone. This is verified by observing the actual filter cartridge temperature performance readings shown in the graph in Figure 4.

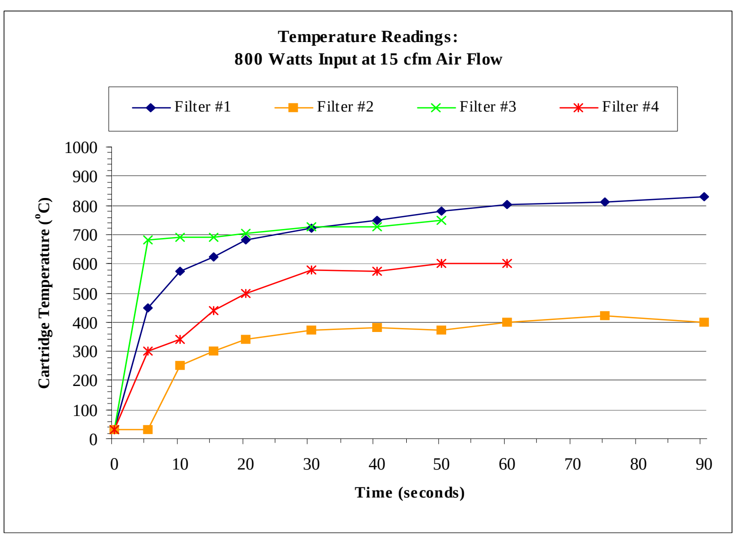


Figure 4. Microwave heating rate of filter cartridge

Three different SiC fiber contents in filters reached the goal of greater than 550°C in less than 30 seconds at 800 watts of microwave input and 15 cubic feet per minute exhaust flow. It is therefore possible for the ICS filter to trap soot at a high efficiency and to be regenerated by microwave energy at some exhaust flow condition (idle).

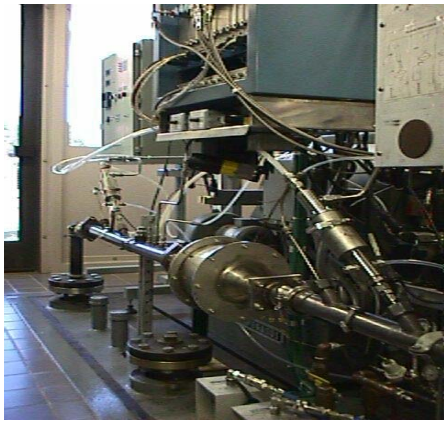
4 FY 2000 Experimental Procedure and Results

The first engine testing of the ceramic fiber filter was conducted on a 1.2-liter DIATA diesel engine at the Ford Scientific Research Laboratory in Dearborn, MI. The filters and test set up are shown in Figure 5 after loading the filters with soot from 0.5 KPa to 2.5 KPa. Figure 6 shows the filter can/microwave applicator installed in the DIATA engine exhaust system.

Exhaust Exit

Exhaust Entry

Figure 5. ICS fiber filter cartridges in can



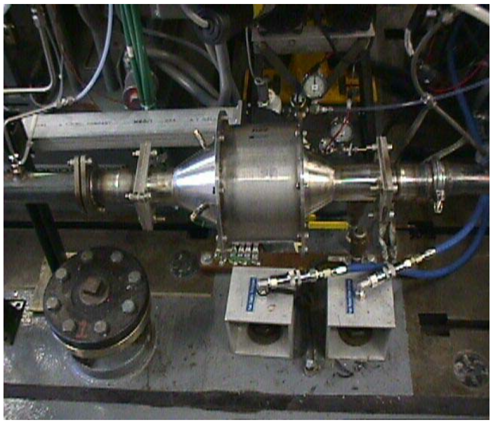


Figure 6. Microwave filter system installed in DIATA test cell

The microwave filter system was installed in the DIATA engine exhaust approximately three (3) meters from the exhaust manifold as shown in Figure 6. The microwave power supply was connected to the filter by three (3) meters of rectangular aluminum waveguide tubing. The engine was operated at several steady-state speeds to load the filter. A typical regeneration event is shown in Figure 7.

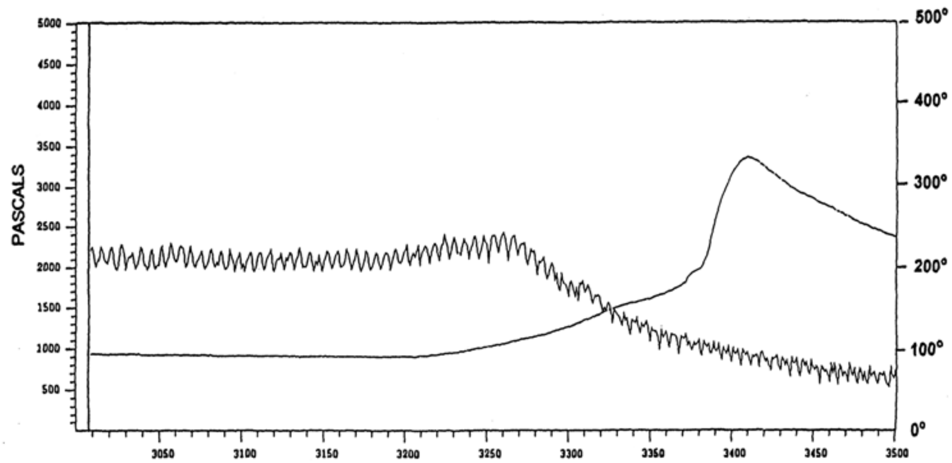


Figure 7. Regeneration at 1,000-RPM high-idle speed after 1 hour operation at 2,600 RPM

The filtration efficiency for diesel particulate removal was 86%, and the microwave cleaning returned the filter cartridge to within 97% of its fresh filter condition.

5 FY 2001 and 2002 Experimental Procedure and Results

The microwave filter technology is unique due to the discovery and use of a special silicon carbide fiber that efficiently converts microwave energy to heat energy. These fibers can achieve the unusually high temperature of 1,200°C in 9 seconds in a standard household microwave oven. The resolution of several diesel vehicle exhaust problems was anticipated through the application of this phenomenon.

Two vehicles were selected for on-road testing of the microwave filter system. Instrumentation was designed, fabricated, and tested to continuously monitor the backpressure resulting from carbon particulate accumulation on the filter, the exhaust flow, and the temperature of the exhaust during vehicle operation. The instrumented exhaust filter systems were installed on a Ford F-250 7.3-liter diesel pickup (Figure 8) and a Volkswagen Jetta 1.9-liter diesel car provided by DOE (Figure 9). The Ford truck was tested under routine highway driving conditions for approximately 6,000 miles. The filter was removed and microwave-regenerated in the laboratory to understand the effects of microwave heating on the particulate loaded cartridge. The Volkswagen Jetta was equipped with an on-board microwave regeneration system. This vehicle was to be driven for 7,000 miles under controlled test track conditions by the Transportation Research Center near Columbus, OH; however, the testing was cancelled after only 200 miles due to an irreparably damaged EGR system that could not be controlled. This damage was found during testing and was determined to have been present prior to delivery to ICS.

The Volkswagen DPF system was moved to a stationary test cell at the ORNL where it recorded better than 97% particulate removal efficiency over a spectrum of steady-state operating conditions. The ICS filter on the 7.3-liter truck was subjected to the full engine load of exhaust rate of 1,000 cubic feet/minute without any apparent damage.

Figure 8. Ford 7.3-liter test truck

Figure 9. Volkswagen 1.9-liter Microwave-cleaned DPF vehicle

6 FY 2003 Experimental Procedure and Results

The development of a pleated ceramic fiber filter cartridge occurred early in FY2003. Many experiments were conducted to determine the optimum geometry of the filter and the best means to fabricate this geometry in the laboratory. A pleating process, using an ICS proprietary ceramic binder, was developed. A number of structural designs to enclose and support the pleated fiber media in the exhaust were investigated; the finished product is shown in Figure 10. Since the pleated cartridge was a significant change from the wall-flow design that has been used over the previous several years, verification of the PM removal efficiency was needed. Pleated filter cartridges were canned and tested by ORNL on a 1.7-liter Mercedes stationary test cell. The particulate removal efficiency from those tests measured 98% for carbon mass and 96% for nanoparticulate soot in a particle size distribution measurement.

Figure 10. ICS rectangular pleated ceramic fiber filter

A microwave-regenerated DPF system was designed and fabricated for the Ford F-250 7.3-liter diesel truck. The system was installed on the truck bed as shown in Figure 11. This arrangement accommodated placement of the temperature and pressure sensors, and facilitated disassembly of the can during periodic filter cartridge examinations. All microwave equipment, system controls, monitoring sensors, and computer data acquisition were installed on the truck for the road and track testing. As testing began, a noticeable deficiency in microwave heating of the cartridges was observed. Further investigation revealed the need to reduce the thermal mass of the filter cartridges, to include more insulation around the filter can, and to improve the microwave field concentration on the filters. The microwave DPF system was then put on hold to concentrate on the development of the pleated filter cartridge.

Figure 11. Microwave regenerated DPF System installed in the Ford 7.3-liter diesel truck

7 FY 2004 and 2005 Experimental Procedures and Results

In experiments conducted by ICS and others under the FY2003 program, much less exhaust backpressure was experienced by the diesel engine with the pleated ceramic fiber DPF. This feature will improve engine performance and reduce the fuel penalty imposed by the PM control device. The pleated ceramic fiber DPF, which weighs significantly less than the extruded wall-flow filter, exhibits a lower thermal mass to achieve faster soot combustion temperatures and adds less weight to the vehicle.

The transition from the flat pleated filter to the round pleated filter cartridge was necessary due to the demands of the automotive exhaust system manufacturers for a round DPF shape to fit their established canning processes. ICS designed a round pleated filter cartridge based upon the diesel engine testing data from the rectangular pleated filter cartridge**.** Extensive road testing on the Ford F250 diesel truck had shown that the eight (8) square feet of media in the rectangular, pleated filters is approximately 20% less than that required for optimum filter operation. ICS approached the project with an initial round pleated filter that was approximately seven (7) inches in diameter and twelve (12) inches long. This configuration yielded the ten (10) square feet of effective filter media surface area to accommodate a full spectrum of diesel exhaust flow rates on the 7.3-liter test truck. ICS employed a mechanical engineer to design a computer modeling program that could determine the optimum pleat geometry and cartridge size needed to accommodate the Ford truck's exhaust flow. ICS worked with an experienced ceramic injection molding company to develop structural support for the pleated filter media. The efforts of the filter cartridge design engineer and the injection-molding company were coordinated to produce a robust round filter cartridge structure suitable for the first round diesel exhaust prototype test cartridge as shown in Figure 12.

ICS fabricated a can assembly for testing the pleated filters on the Ford F250 truck. The exhaust is directed through the bed of the truck to facilitate installation and removal of filter cartridges for evaluation (Figure 13). ICS can test both round and flat pleated filters in this test device. It has been valuable in investigating the durability of support structures and soot loading capacity of the pleated filter cartridges.

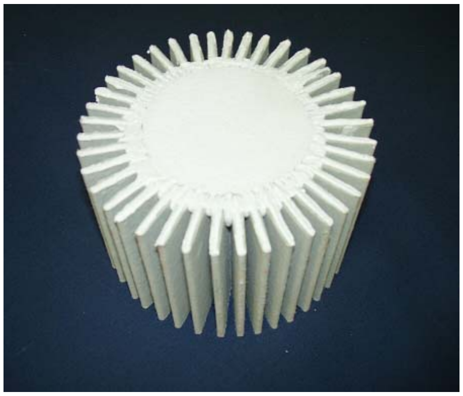


Figure 12. First fabricated round pleated prototype

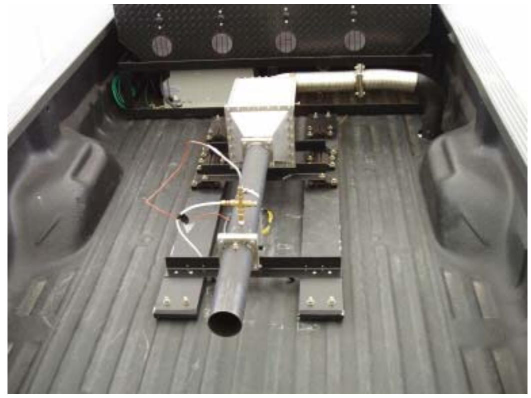


Figure 13. Round pleated filter test set up for 7.3-liter truck

FY2005 funding was used to design and fabricate a full-scale prototype test filter for the Ford truck, as shown in Figure 14. Significant work was done on materials improvements to allow the fabrication and testing of this larger round pleated filter. Experiments were conducted in the ICS laboratory with a number of commercial binders and commercially available ceramic fibers, and the binder-fiber mix was subsequently optimized to improve filter durability. The improved mix was then used in commercial papermaking equipment to produce continuous rolls of filter media that would be pleated and incorporated into test cartridges.

Figure 14. Full-Scale 6” diameter x 12” long round pleated filter ready for canning and truck testing (first prototype shown at bottom of figure)

The filter media burst strength was improved from the 185 inches of water, at the end of 2004, to 415 inches of water in 2005. Burst strength improvements over the life of the program are shown in Figure 14. The soot-loading capacity was increased from the 0.86 grams/square foot recorded in 2004 to 1.4 grams/square foot in 2005. The improved filter media, converted to continuous paper and then to filter cartridges, was road-tested on the Ford 7.3-liter truck. Twenty (20) road tests on a pair of rectangular, pleated filters were completed loading the filter to over 80 inches of water backpressure during each test. The filter was regenerated at 700°C after each road test, and there was no damage to the filter cartridge during testing or the regeneration procedures.

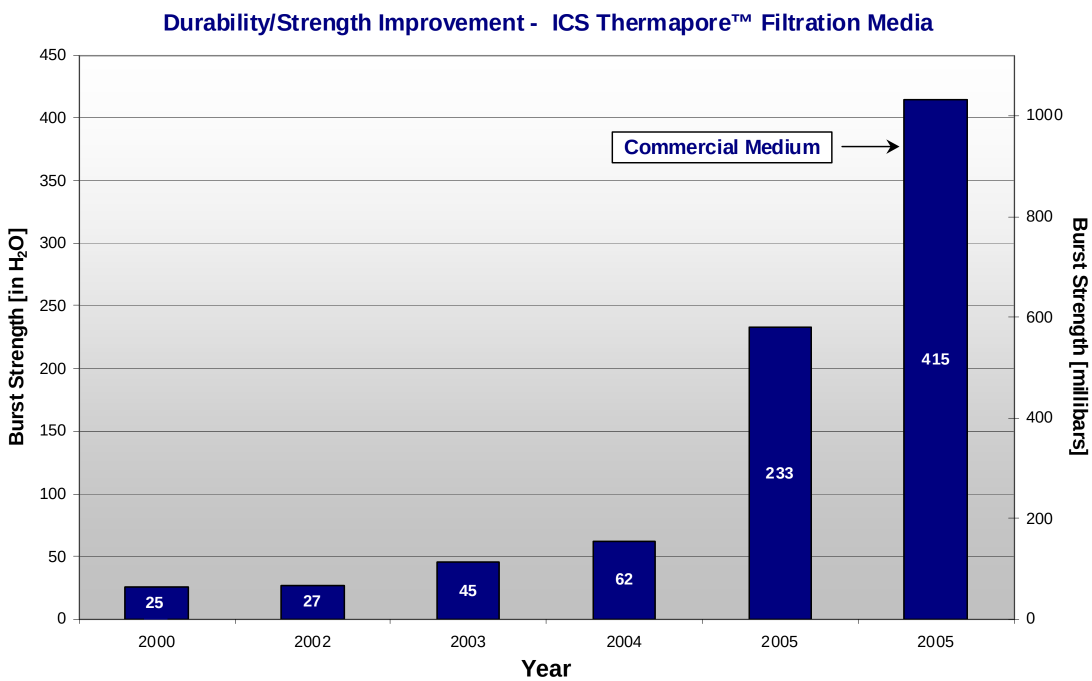


Figure 15. Program progress for improving filter media strength and durability

8 Final Program Conclusions

In 1999, this program began with the concept of using a special silicon carbide fiber that was very efficient at converting microwave energy to thermal energy as a new type of diesel exhaust particulate filter. The ceramic fiber filter cartridge, regenerated by microwave energy, was a unique invention in a field dominated by extruded ceramic honeycomb wall-flow DPF's. This new concept was foreign to the automotive industry and was only able to proceed through the support of the U.S. Department of Energy, as a new and unique technology.

Commercialized products are often quite different than the original concepts or discoveries that inspired their development. In this case, the microwave-regeneration of a DPF led to the invention of a novel pleated ceramic fiber DPF cartridge that can be regenerated by all commercial methods. Continued DOE support of the cartridge development, even after the microwave-regeneration system became marginal, allowed ICS to make significant improvements in the filter cartridge design, materials, and manufacturing process.

The pleated ceramic fiber filter cartridge demonstrates lower backpressure and thermal mass than those of conventional wall-flow DPFs. These two advantages make it a viable option for all types of diesel PM control systems. ICS is currently working with a major international filter manufacturer to license the use of the technology and to supply the large volume of filter cartridges required to supply the worldwide diesel industry. ICS is also collaborating with several vehicle manufacturers to develop improved commercial exhaust control systems for the 2010 market. The gasoline engine catalytic converter was introduced in 1975; however, did not reach a stage of optimum efficiency until 2005. The current diesel engine DPF control systems will be installed on diesel vehicles in 2007. Since these systems do not yet have a proven operating record or customer acceptance in volume vehicle applications, there are still opportunities for new technologies, such as the ICS pleated filter cartridge, to be introduced into the commercial marketplace. Advantages offered by the ICS DPF technology will contribute to the optimization of existing and future diesel emission control systems.

9 Future Work

A pilot production line is being assembled for semi-continuous, volume production of ICS round pleated filter cartridges. Many diesel industry companies are interested in product testing for 2010 exhaust system applications, and ICS has a number of programs in progress to further improve the performance characteristics of the filter cartridge.. Customer prototypes will be available in 2006.

The microwave-regeneration concept, which DOE ceased to fund in FY2003, is still of interest to a number of automotive and off-road diesel engine customers. ICS has joined with a major microwave systems company to advance this technology. Microwave-regeneration is ideal for use in diesel hybrids, and DOE should once again consider funding related projects if interest in the production of diesel hybrids in the U.S. grows.

Program Publications

J. Green, R. Nixdorf, J. Story, and R. Wagner, "*Microwave-Regenerated Diesel Exhaust Particulate Filter,*" SAE Paper 2001-01-0903, Society of Automotive Engineers, Warrendale, PA.

R. Nixdorf, "Microwave-Regenerated Diesel Particulate Filter" presented at the Society of Automotive Engineers World Congress, March 5-8, Detroit, MI, 2001.

R. Nixdorf, "Microwave-Cleaned Ceramic Filter Using Silicon Carbide Fibers" presented at the American Filtration Society National Technical Conference, May 1-4, Tampa, FL, 2001.

J. Wainwright, R. Nixdorf, "Microwave-Regenerated Diesel Particulate Filter" presented at The University of Wisconsin Exhaust Aftertreatment Symposium, June 12-13, Madison, WI, 2001.

R. Nixdorf, "In-Situ Microwave Cleaning of Silicon Carbide Fiber Filtration Media," TechTextile Symposium North America, Atlanta, GA, April 2002.

R. Nixdorf, "Microwave-Regenerated Particulate Filter," DOE National Laboratory Advanced Combustion Engine R&D Merit Review and Peer Evaluation, Argonne National Laboratory, May 13-15, 2003.

R. Nixdorf, "Microwave-Regenerated Particulate Filter," American Filtration Society Diesel and Gasoline Engine Emission Solutions Conference, Ann Arbor, MI, October 2003.

R. Nixdorf, "Advances in Filter Media Development for Diesel Exhaust Systems, Ceramic Bonded Ceramic Fiber Pleated DPF Cartridge," American Filtration and Separation Society Diesel and Gas Engine Emissions Solutions Conference, Ann Arbor, MI, September, 2005.

Program Patents Filed

"Ceramic and Fiber-Based Filter Web and Method," US Patent issued July 2005

"Filter System Employing Microwave Regeneration," US Patent issued February 2005