Improved Diesel Particulate Filter Cartridge for Diesel Exhaust Systems

Ceramic Bonded Ceramic Fiber
Pleated DPF Cartridge

(Microwave-Regeneration Option)

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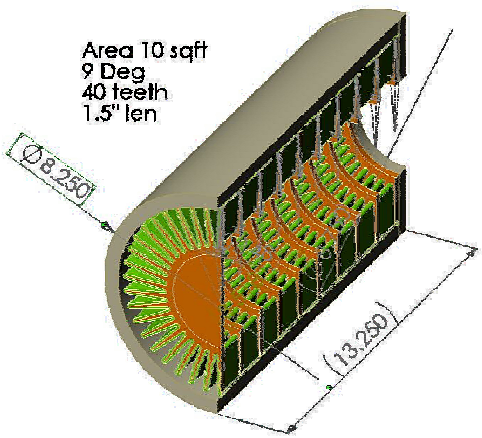
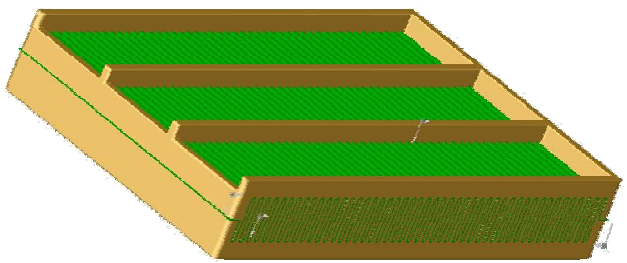
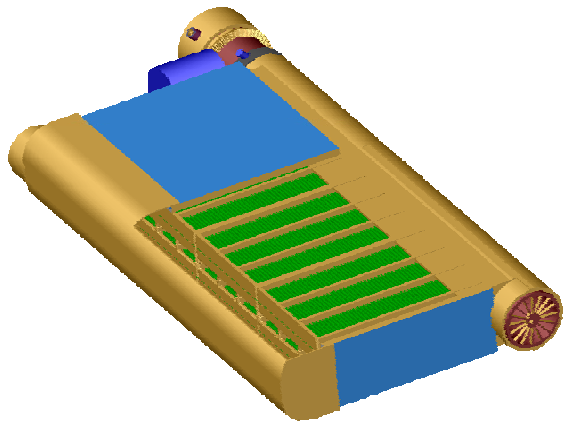




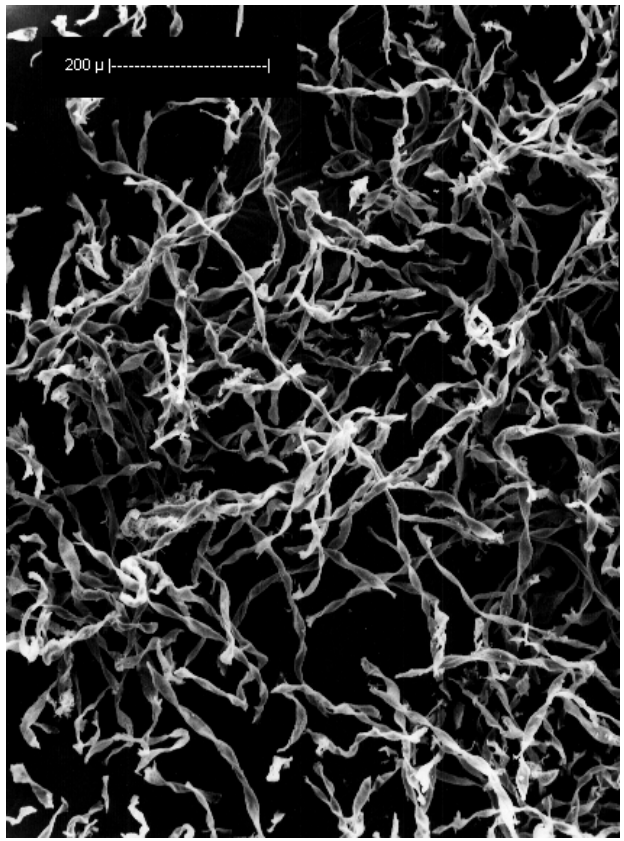


New Diesel Particulate Filter Cartridge for Diesel Exhaust Systems

1. **DPF Cartridge Development Progress**
2. **Advantages of the Round Pleated Filter Cartridge**
3. **Comparison of the Pleated Filter to Wall-Flow Products**
4. **Vehicle and Engine Testing from 2000 to 2006**
5. **Improvements in Durability and Soot Capacity**
6. **Honeywell Participation in Commercialization**
7. **GE Locomotive Joint Development Work**
8. **Schedule for Commercial DPF Prototype Deliveries**
9. **Jaguar Microwave-Regen Joint Development Agreement Work**

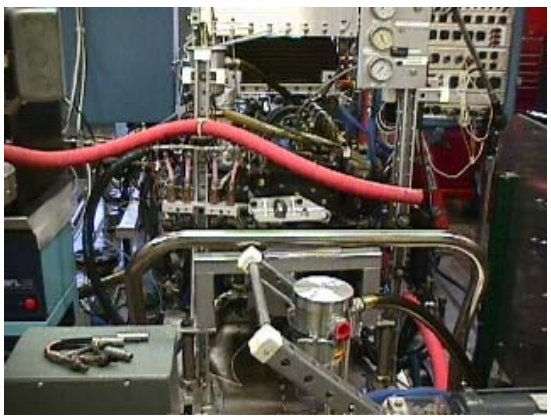
ICS Silicon Carbide Fibers
"The Core of the Technology"

- **Low thermal mass with high thermal conductivity**
- **High temperature durability of silicon carbide (>2,200°F)**
- **Existing volume production capacity**
- **Patented by ICS**



Ford SRL Testing in 2000
1.2-Liter DIATA Engine

Filter achieved 89% PM removal at four steady-state conditions



Microwave-regeneration achieved 95% cleaning

ICS Wall-Flow Ceramic Fiber Filter
1998 - 2003

- **Subsequent testing demonstrated PM filtration efficiency above 95%**
- **Soot holding capacity was about 80% of similar sized wall-flow filter capacity**
- **Manufacturing costs were greater than wall-flow filters**

A different technology was needed to compete…

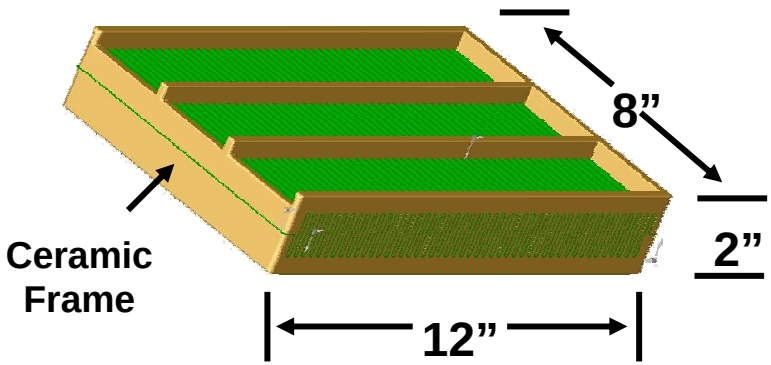
ICS's New Idea for a DPF Cartridge

- **Extruded wall-flow filter** = a ceramic membrane with high surface area, low porosity and high backpressure
- **ICS ceramic fiber DPF** = a "depth" filter with low surface area, high porosity, and low backpressure

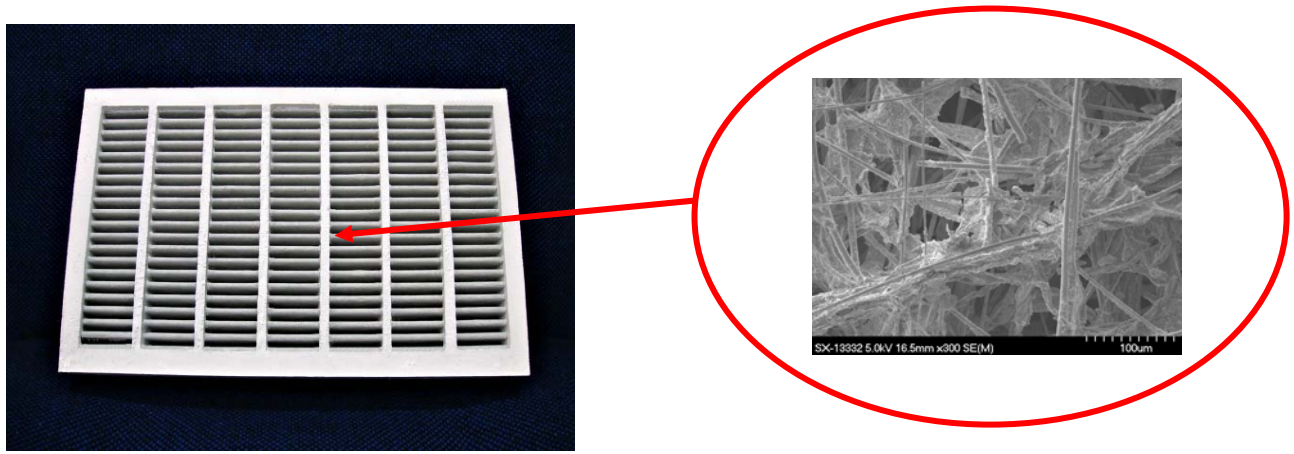
Diesel exhaust is a high velocity gas stream which normally uses a depth filter

ICS elected to develop a low-cost, pleated design to accommodate the high velocity diesel exhaust

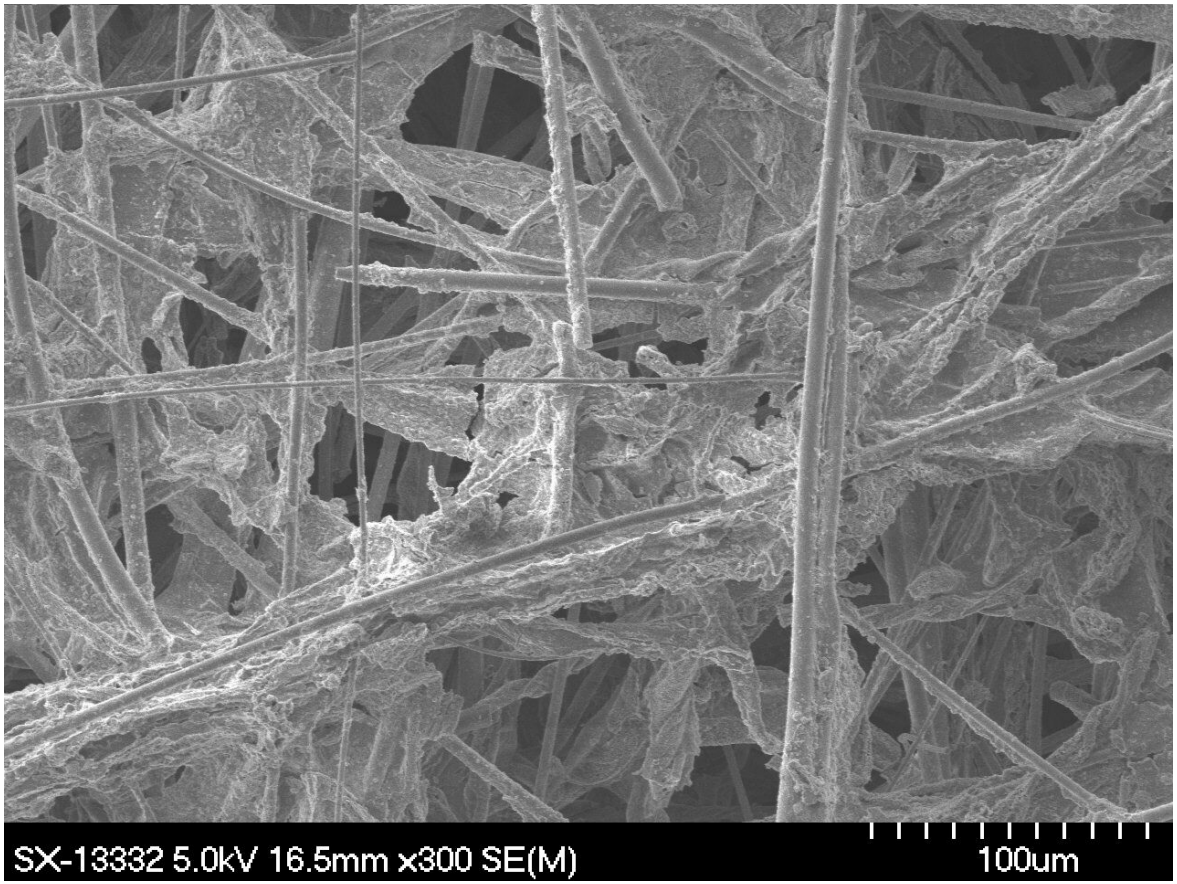
Early Flat Pleated Filter Cassette



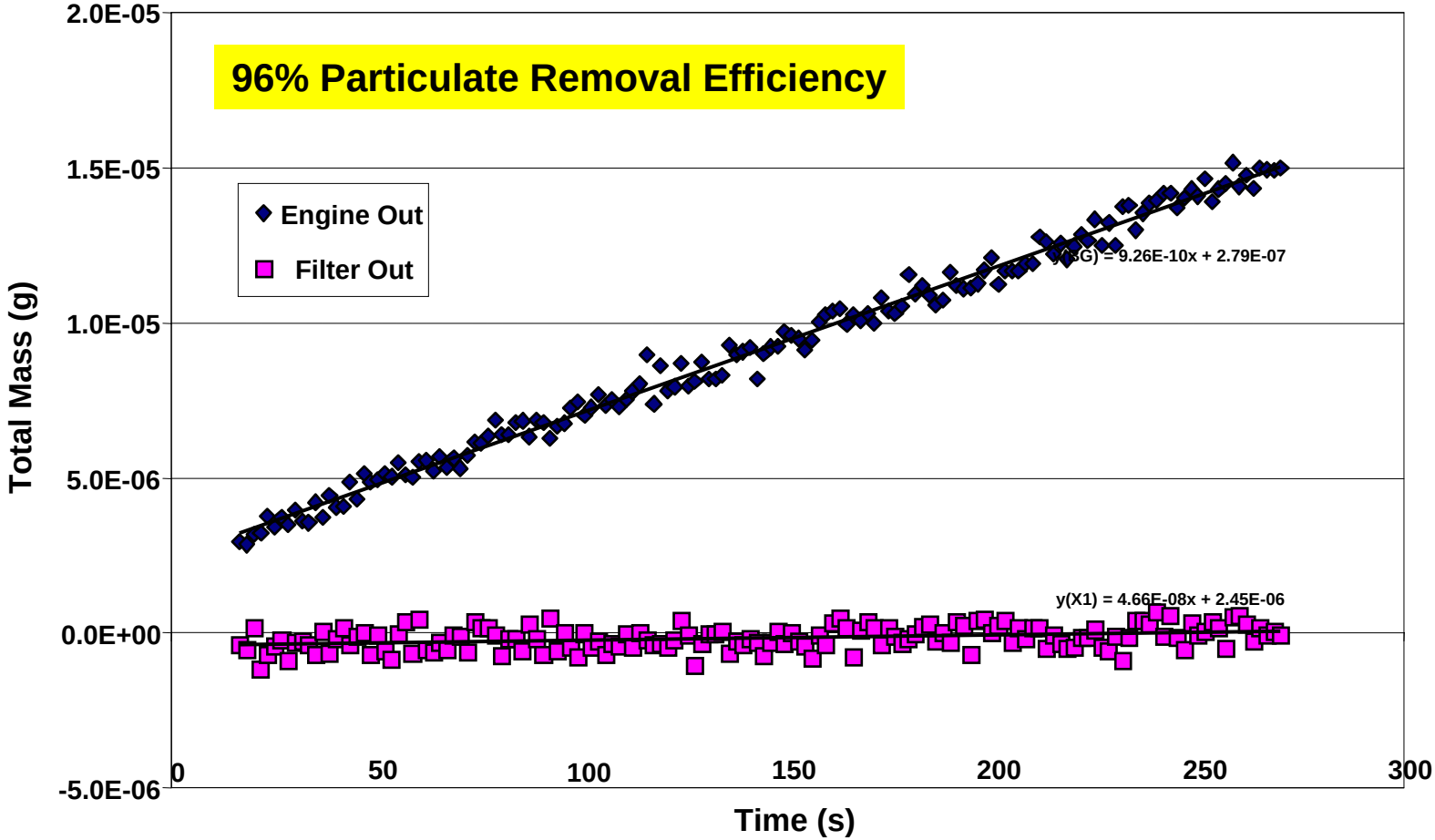
- **50 to 100 micron pore size**
- **Greater than 95% PM efficiency**
- **Backpressure = 1/5th of wall-flow honeycomb ceramic filters**
- **High soot conditions preferred**
- **Low thermal mass**



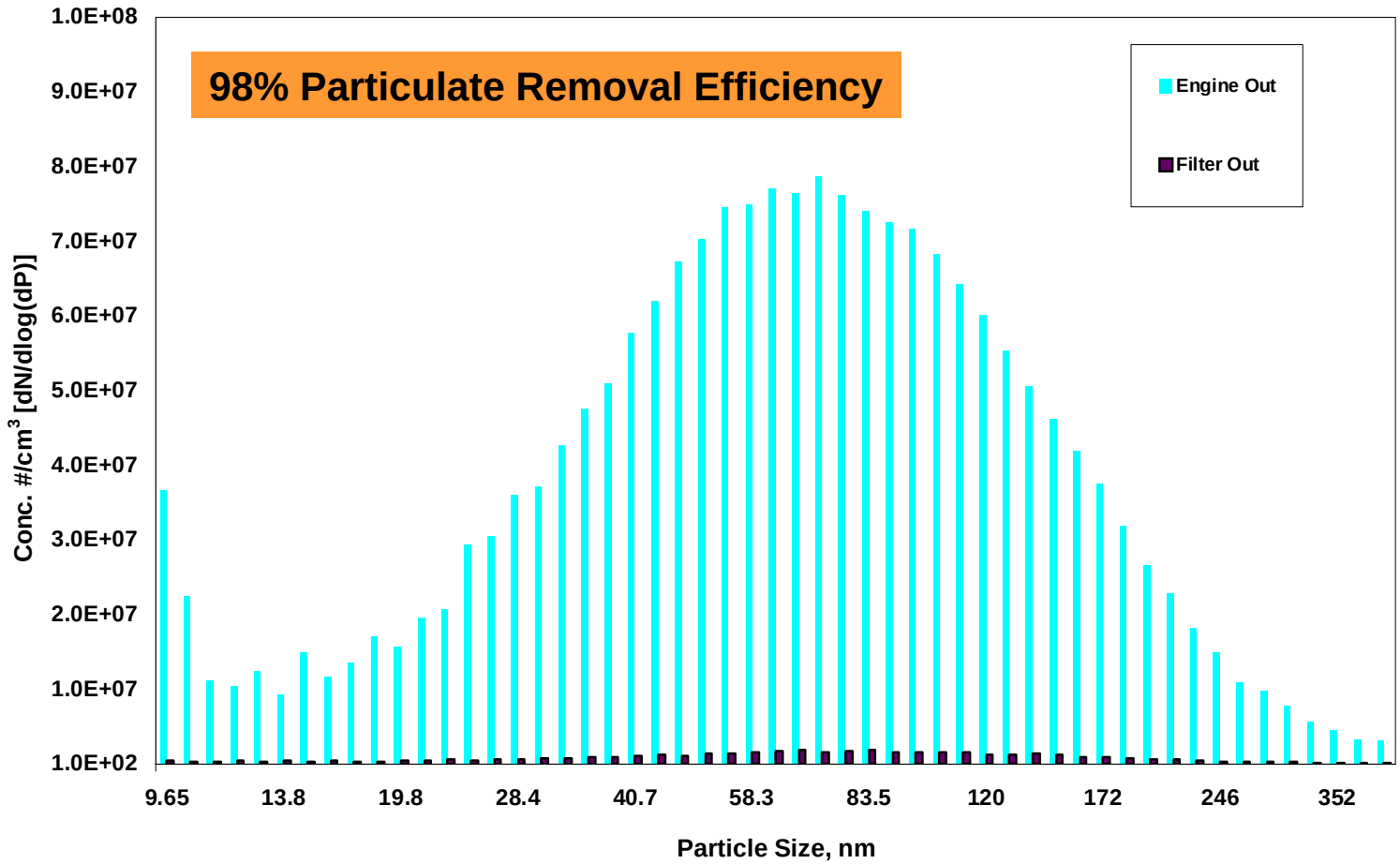
Depth Filtration
Backpressure vs. Filtration Efficiency Advantages



Pleated Filter TEOM Carbon Mass Data
1.7-Liter Mercedes at Oak Ridge National Lab

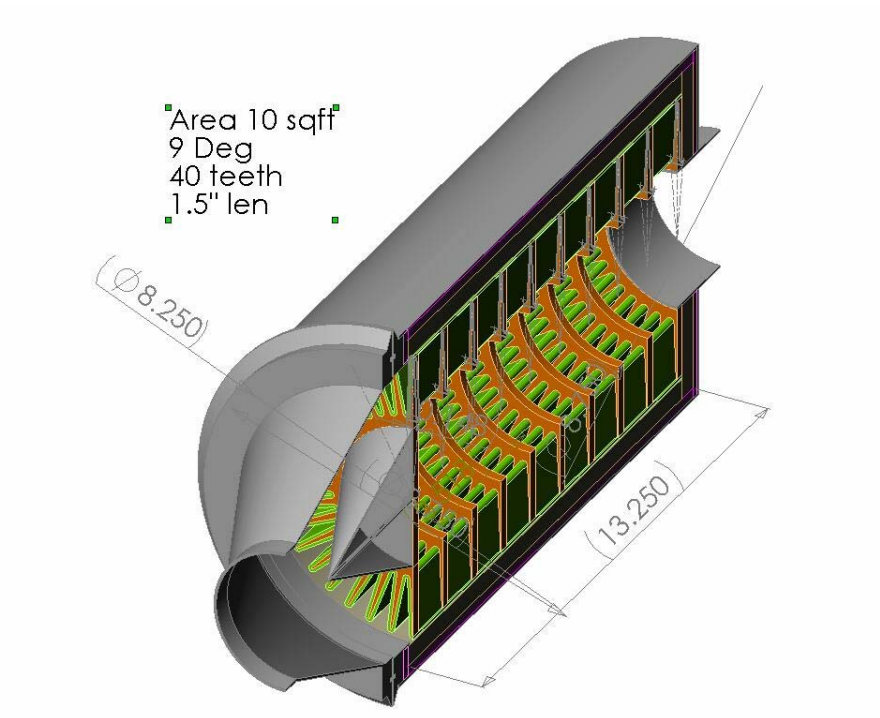


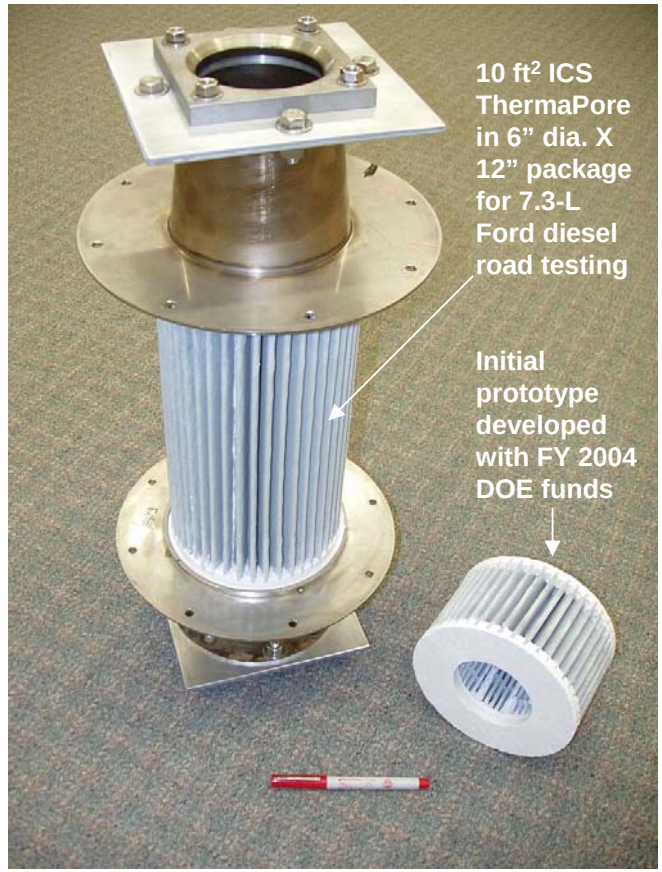
Pleated Filter Particle Size Removal Data
1.7-Liter Mercedes by ORNL



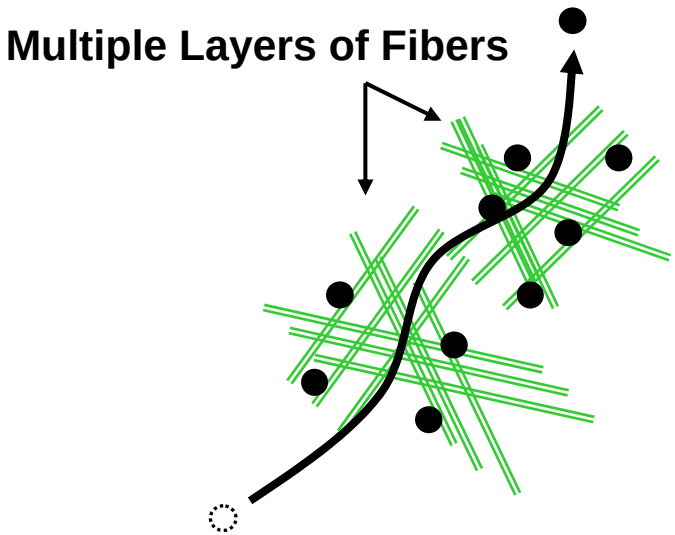
Round Pleated Filter

Concept & Full-Scale Prototype



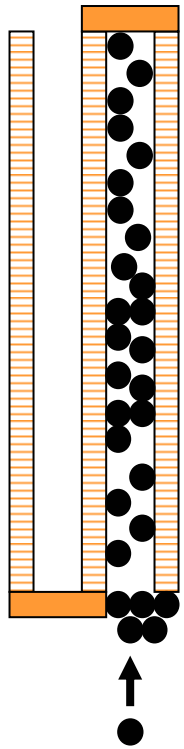


The Honeywell Ceramic Fiber Filter vs. The Extruded Ceramic Wall-Flow Filter



- Pore Size 50 to 100 um
- 85% Porosity
- Thickness = 0.070”
- Delta P = 0.5 KPa

ICS Ceramic Fiber Filter
95% Efficient



- Pore Size 25 um
- 40% Porosity
- Thickness = 0.008”
- Delta P = 2 to 5 KPa

Honeycomb Wall-Flow
95% Efficient

The Pleated Ceramic Fiber Filter vs. The Extruded Ceramic Wall-Flow Filter

For 6 to 7 Liter Diesel Engines

Property	SiC Wall-Flow 9” Dia x 12”	Pleated Fiber 6” Dia x 12”
Volume	12.5 liter	6 liter
% Porosity	40% - 60%	85%
Weight (Thermal Mass)	44 lbs	10 lbs
Pore Size	15 to 25 µm	50 to 100 µm
Soot Capacity	8 g/liter	5 g/liter

ICS Filter System Advantages

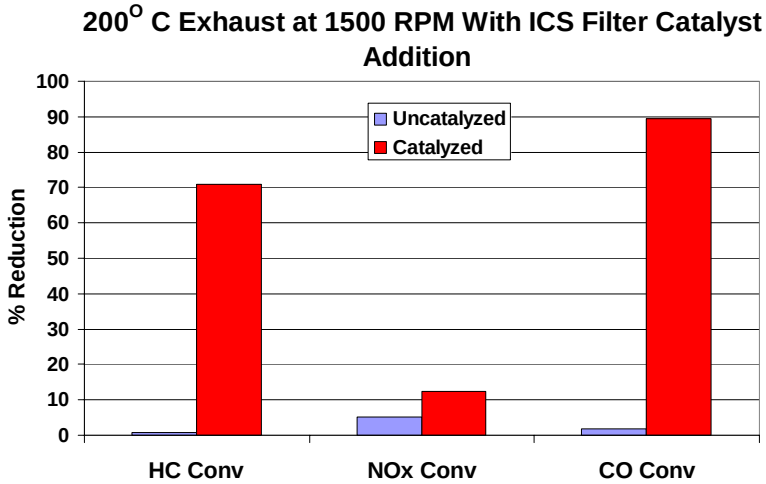
Fuel Economy – Engine backpressure of the pleated cartridge is 1/5th that of competitive systems. This means lower fuel penalty & potentially higher ash loading.

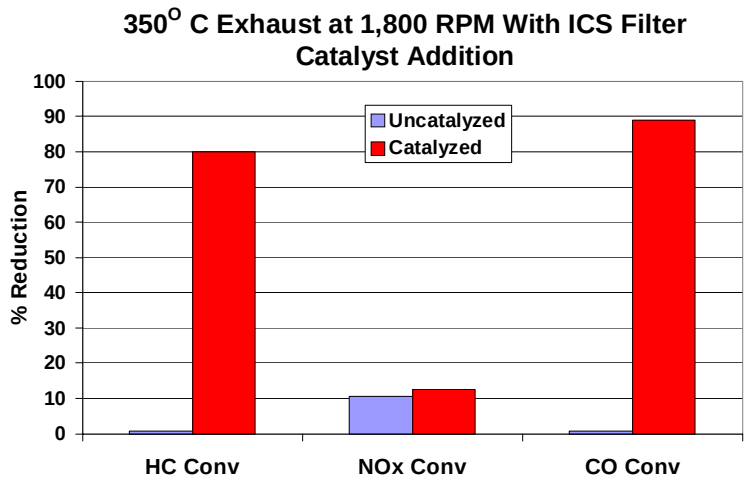
Regeneration Time – Thermal mass of the DPF cartridge affects the regeneration time and energy input required. The ICS filter is ½ that of cordierite and 1/3rd that of silicon carbide.

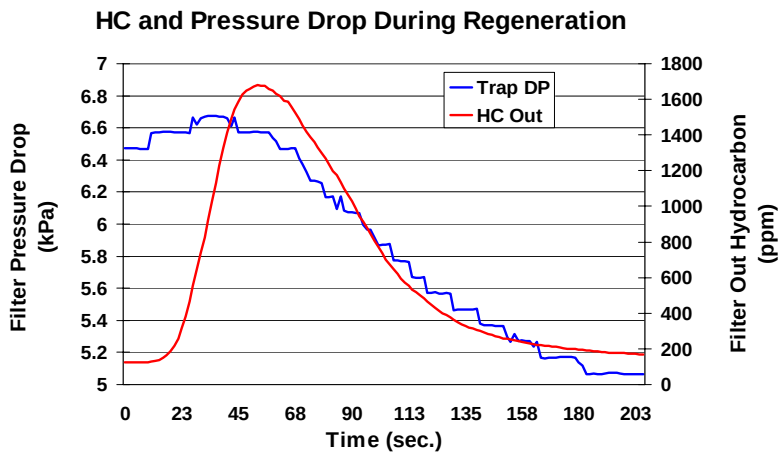
Heat Transfer – Soot combustion heat in 0.070” wall is immediately transferred to exhaust and can with no thermal excursions.

Catalysts – Catalysts can be directly applied to the fibers without a wash coat. A manufacturing step is removed with no reduction in porosity (or increased pressure drop).

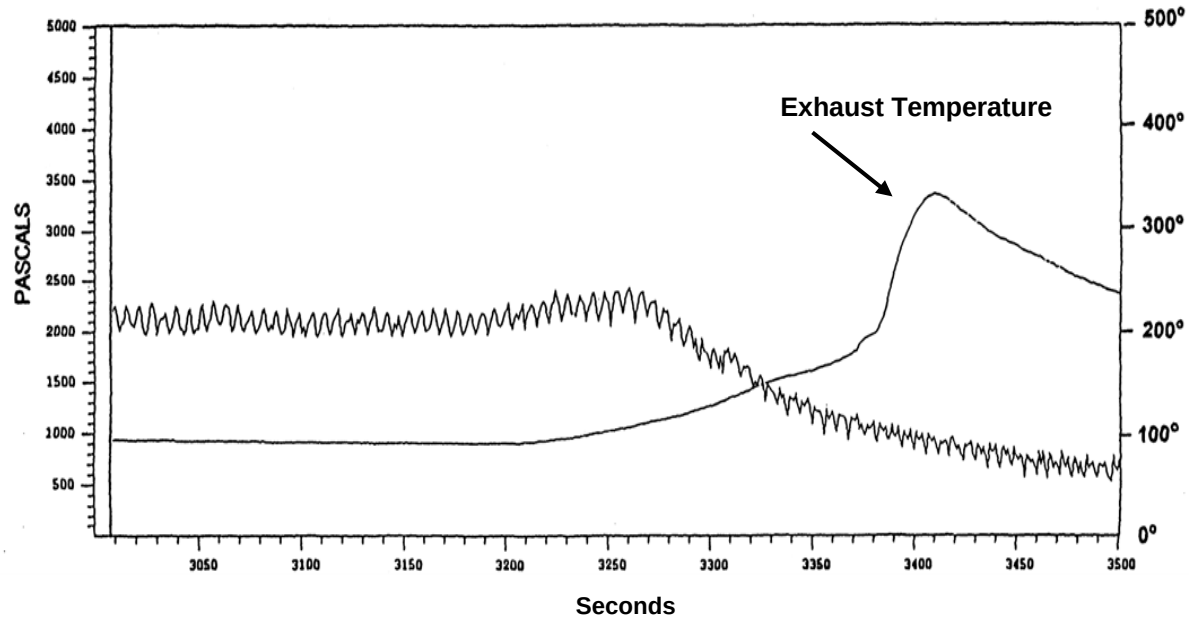
1.9-L Volkswagen CIDI Stationary Engine Testing
Preparation for Jetta Vehicle Road Testing

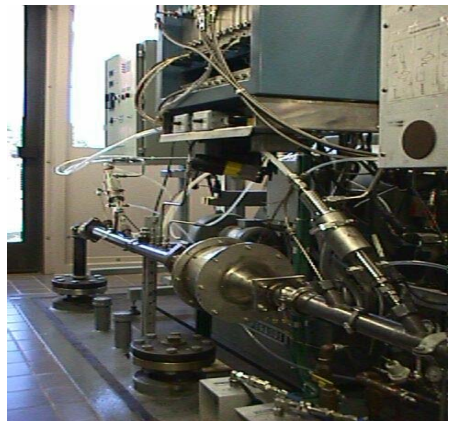






Vehicle and Engine Testing
1.2-Liter DIATA at Ford SRL in 2000





Microwave regeneration at 1,000-RPM high-idle speed after 1 hour operation at 2,600 RPM

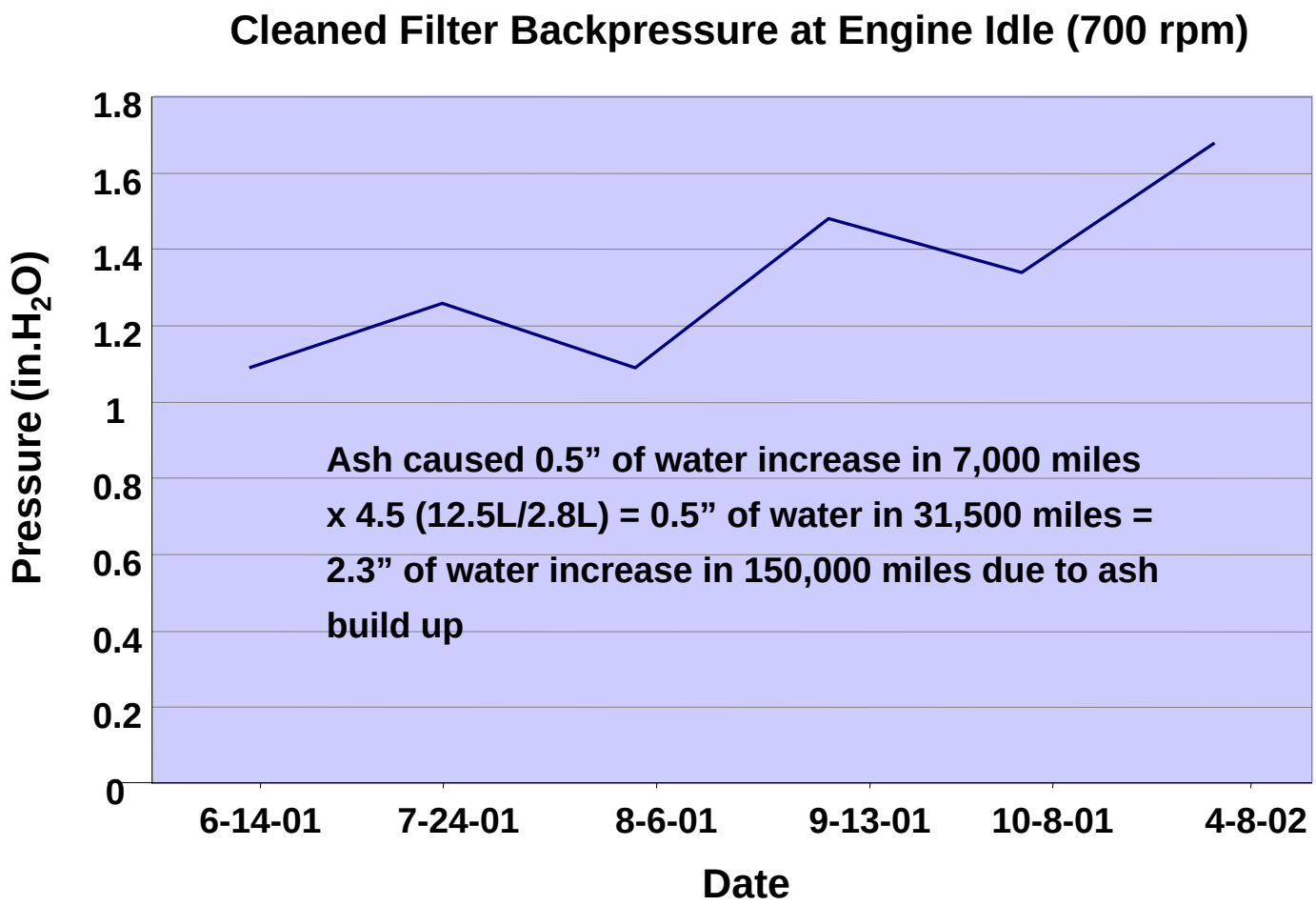
89% PM efficiency and 97% regeneration efficiency

Durability Testing of Ceramic Filter
on the 7.3-Liter Ford F-250 Truck (2001-2002)

- **Needed 10-Liter**
- **Exhaust noise quieter than muffler**

- **Cartridge removable from can for lab furnace regen**
- **Recorded continuous pressure and temperature at filter**

Durability Testing of a Ceramic Filter on the 7.3-Liter Ford F-250 Truck



2003 Vehicle and Engine Testing

1998 Volkswagen Jetta

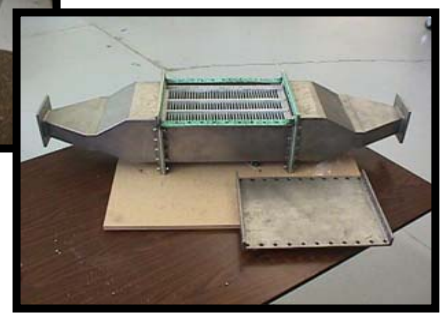
- **Equipped with ICS DPF and microwave regeneration system**
- **Test abandoned due to previous engine damage in DOE EGR testing**

University of Wisconsin Future Truck Entry

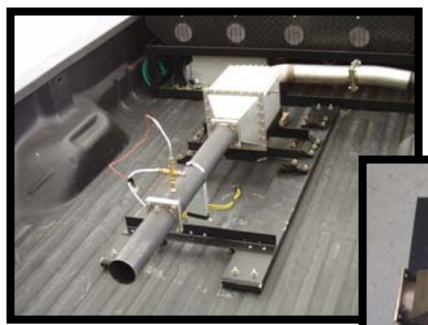
- **Equipped with ICS filter**
- **Team won competition in emissions**

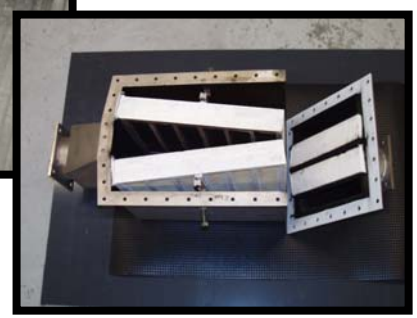
2004-06 Microwave Development Stopped for Commercialization of Pleated Filter Concept

- **DOE PNGV funding directed concentrated effort on the pleated fiber filter**
- **ICS redesigned F250 truck equipment to test pleated filters**
- **Pleated filter prototypes were test at ORNL on the Mercedes 1.7-liter engine for PM efficiency and durability**
- **Continuous road testing was initiated on the Ford F250 to improve DPF durability and soot loading capacity**



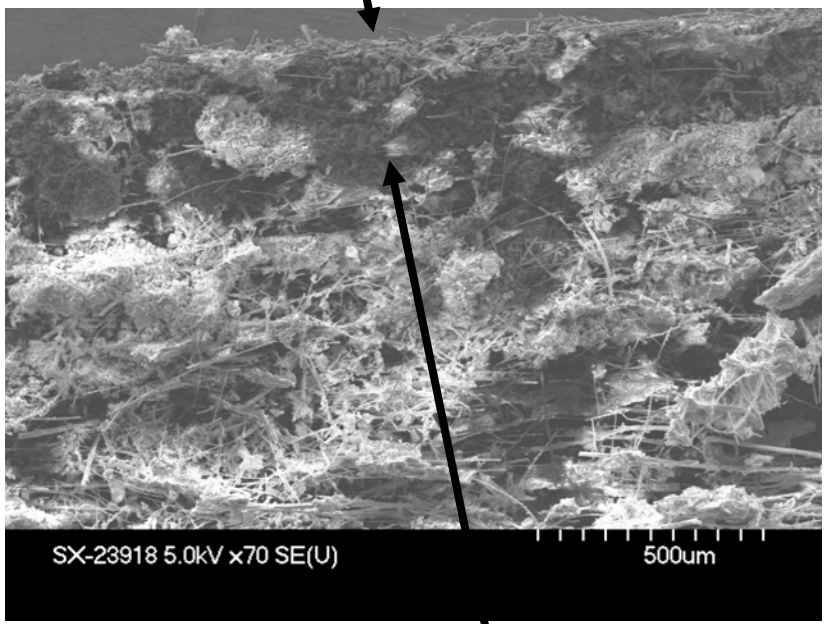
Mercedes testing

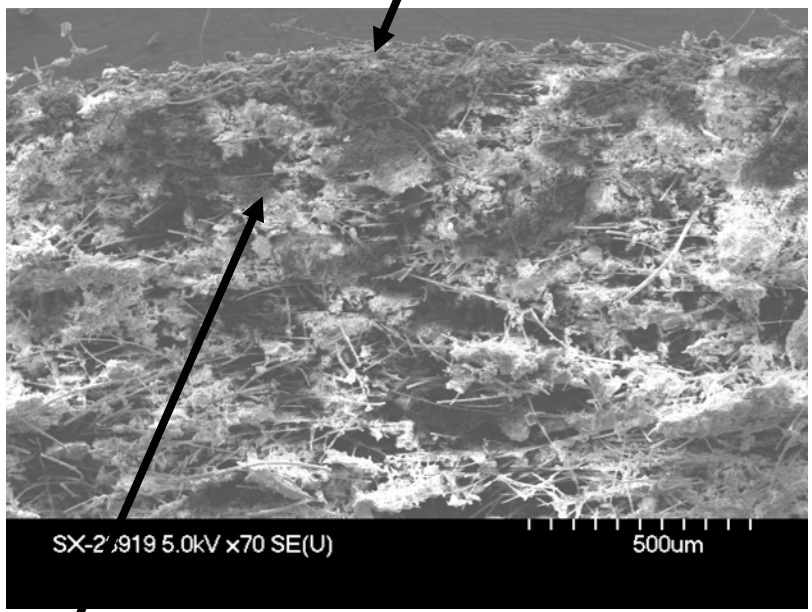




Ford F250 testing

Electron Microscopy Shows Media Exhibiting Depth Filtration Rather Than Surface Filtration

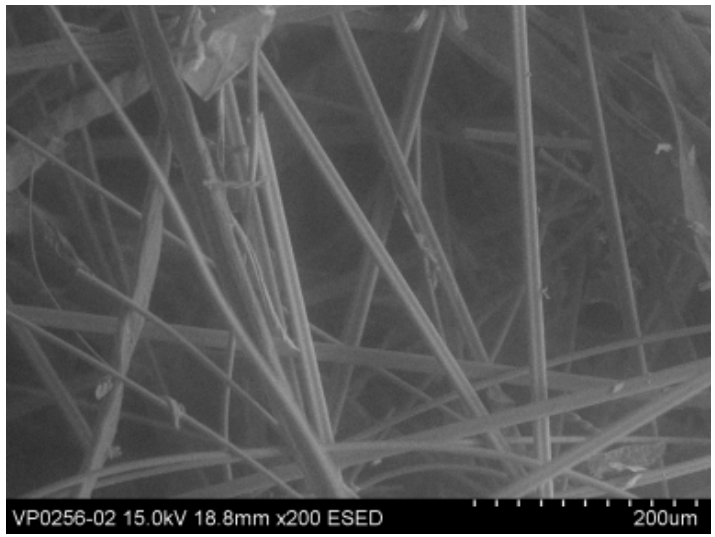




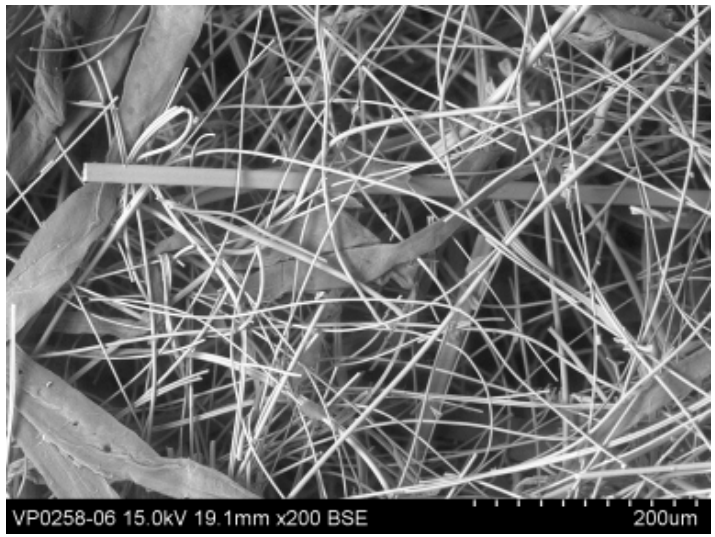
Soot penetrated approximately 20% of media thickness with media yielding approximately 3 gms/liter soot capacity. Media is now being fabricated in two layers to achieve 50% soot penetration.

New Patent-Pending Dual-Layer Media

Soot will penetrate approximately 50% of media thickness.
Media yields approximately 8 gms/liter soot capacity.

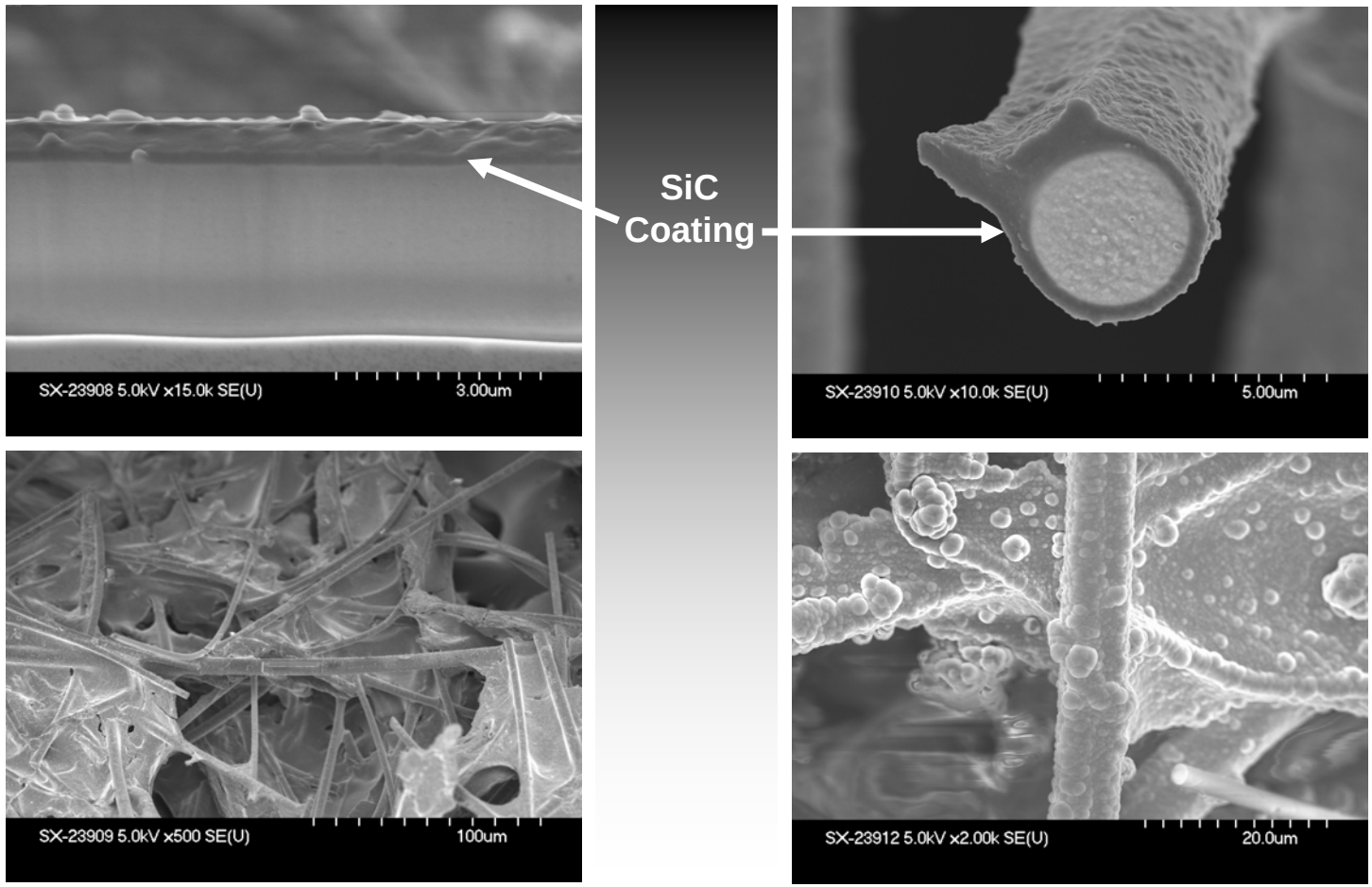


Open entry to dual-layer at 200X



Closed exit to dual-layer at 200X

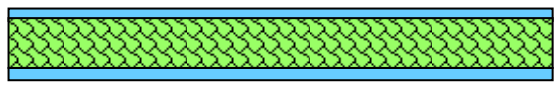
Optional CVI Silicon Carbide Coating Can Double Filter Media Strength and Increase Durability



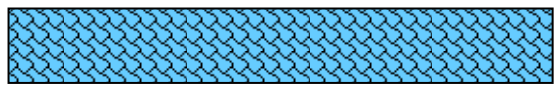
On-Going ThermaPore Media Improvements

	Burst Strength	Permeability
FY 2000	1.0 psi	10 scfm/ft^2
FY 2002	6.0 psi	20 scfm/ft^2
FY 2006	22.0 psi	15 scfm/ft^2

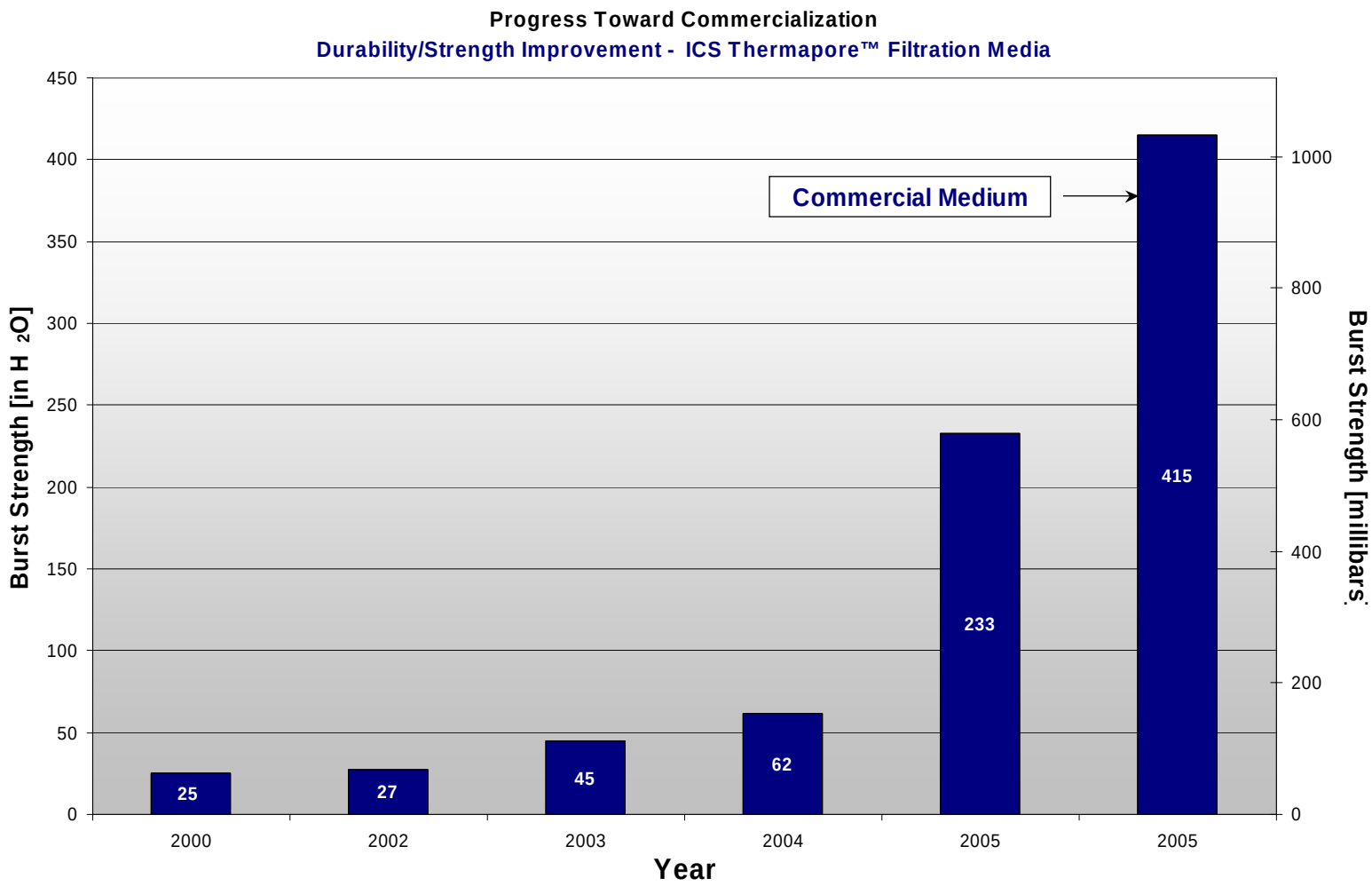
Binder migrated to paper surface in drying.



Improving binder addition, chemistry, and drying techniques yielded uniform binder distribution in the filter media.



Six Year Progress Toward Media Durability

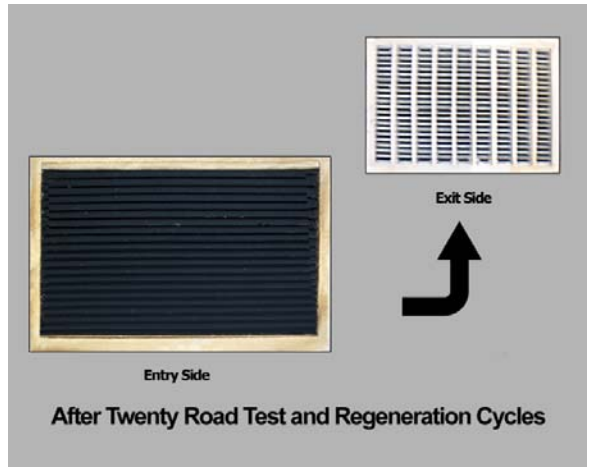


Potential Partnership with Honeywell Consumer Products Division

- **ICS pleated ceramic fiber DPF offers significant performance and price advantages.**
- **Provides no value to the diesel industry without a source of volume production and high automotive QA standards**
- **May 2005, ICS signed a joint development agreement with Honeywell to investigate use of the pleated DPF in Honeywell automotive products**
- **Honeywell funded testing of milestone goals relating to filter durability, soot-holding capacity, and vibration testing. Goals were set at competitive levels for participation in the commercial marketplace.**
- **ICS has surpassed the durability and soot-capacity goals by significant margins. Vibration testing was completed with no filter failures.**

Potential Partnership with Honeywell Consumer Products Division

- **Conclusion of the Honeywell/ICS JDA in May 2006 will give Honeywell the option to commercialize the pleated DPF.**
- **Honeywell will then operate a pilot production line, scalable to large volume quantities to supply DPF's.**
- **Prototype test samples will be available for customer testing by the 3rd qtr 2006.**
- **ICS will assist Honeywell with product improvements, customer testing, and marketing.**



GE/ICS Joint Development Agreement
Diesel Locomotive Emissions Control

- **Full-load diesel locomotive exhaust flow is approximately 24,000 cfm.**
- **Fuel efficiency and back pressure are critical factors in the operation of locomotive engines.**
- **The weight and low-backpressure performance of the ICS DPF make it ideal for this application.**
- **GE has selected ICS as its technology development partner for the 2012 system.**
- **A system currently being tested on a 6-liter diesel engine will be scaled up to accommodate a full-sized locomotive.**

The ICS DPF is unique in its flexibility to accommodate various engine geometries and sizes.

The Microwave Regeneration Option

- **ICS stopped work on microwave regeneration when interest and funding from DOE and industry was curtailed in 2003.**
- **Honeywell is only interested in manufacturing and selling the pleated ceramic fiber DPF – not the microwave option.**
- **ICS is resuming work on microwave regeneration for special applications.**
- **Ferrite Company, Inc., the worlds largest manufacturer of industrial microwave systems and components, is negotiating a joint development agreement with ICS to move the technology into commercial products. Ferrite's management is particularly interested in automotive applications.**
- **Active microwave regeneration of a DPF system has some special advantages when coupled with the ICS ceramic fiber DPF.**

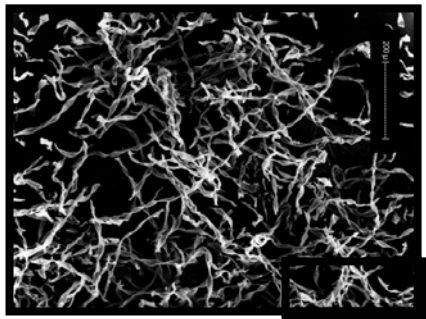
Advantages of the ICS DPF and Microwave-Regeneration

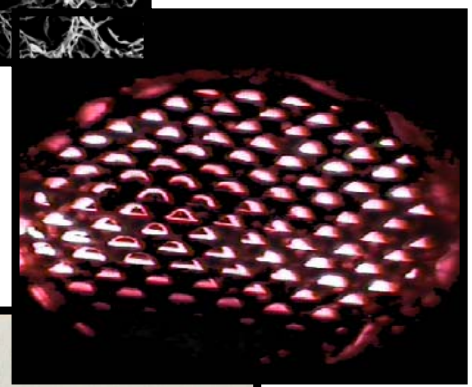
- **The patented SiC fibers are unique in their ability to heat quickly in a low-energy microwave field.**

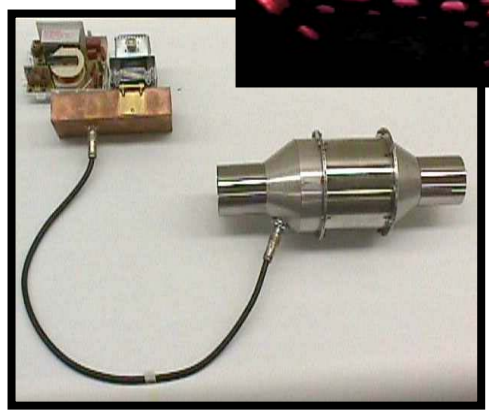
- **Filters can be regenerated with one of more 1 KW microwave sources available on the world market for $15 each.**

- **Microwave regeneration is ideal for diesel hybrids where electric power is available and regens at zero exhaust flow are preferable.**

- **Due to the microwave coupling of the ICS SiC fibers, the microwaves heat the filter first, not the surrounding exhaust gas and can. All energy is used for the combustion of soot .**

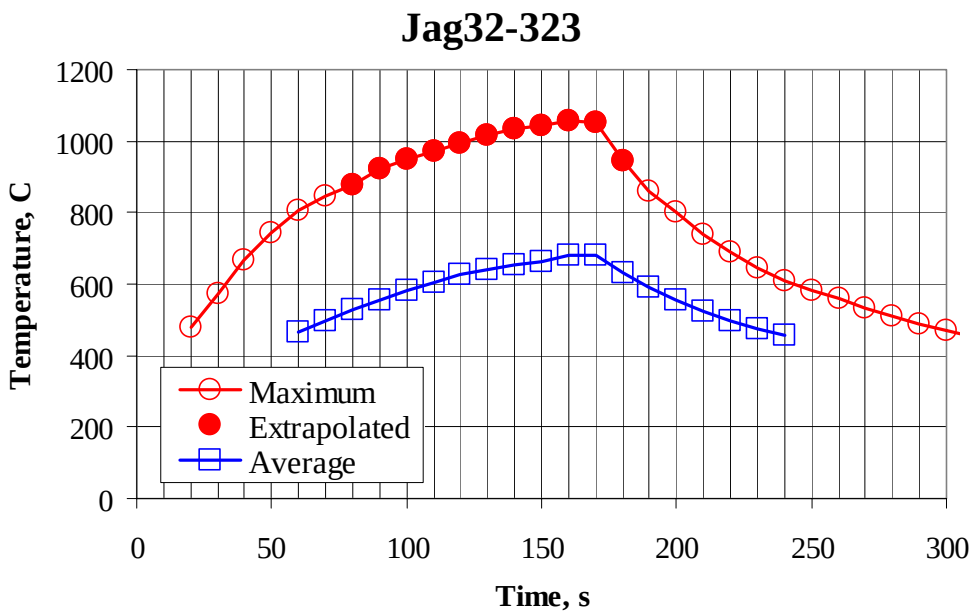


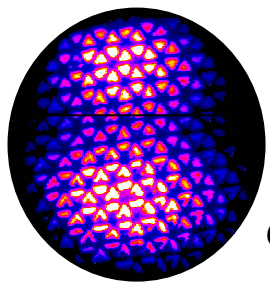




Jaguar/ICS 2003 and 2004 JDA on DPF Microwave-Regeneration

- **Jaguar needed a ceramic coupling agent that would heat in a microwave field.**
- **The ICS microwave-coupling SiC fiber successfully met this requirement.**
- **Jaguar used the ICS fiber filter as an igniter to replace the DOC in current regen designs, placing it directly upstream of a SiC Wall-Flow filter.**
- **Some success in regenerating the wall-flow filter with the ICS igniter was achieved.**





ORNL Infrared Thermography

ICS Pleated Ceramic Fiber DPF Cartridge
Why Is It Competitive in the World Market ?

Uniform Filter Heating

Honeycomb filters fail because a thermal excursion in the center of the filter does not allow heat to be conducted to the outside of the cylinder. The ICS pleated filter does not accumulate heat. All surfaces are directly exposed to the exhaust, and heat from thermal excursions is instantly released.

Filter Cartridge Cost

A Corning wall-flow filter for a medium-duty truck cost $785, and an Ibiden silicon carbide filter cost $1,000. ICS can sell a equivalent silicon carbide cartridge for $500 in production volumes.