
Diesel Particulate Filter Experience on Marine Engines

Marine Black Carbon Workshop

Ottawa, CANADA

September 2014

Dr. Joe Kubsh

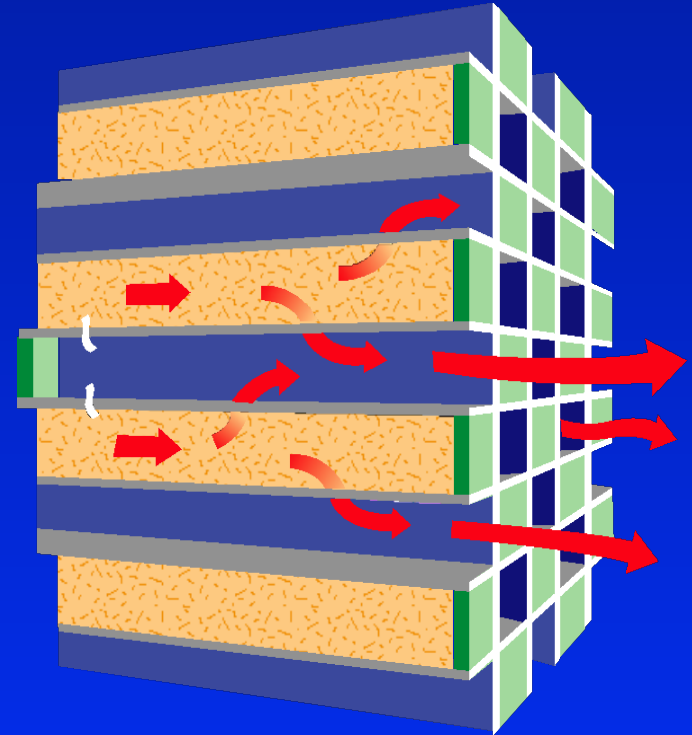
Manufacturers of Emission Controls Association

www.meca.org



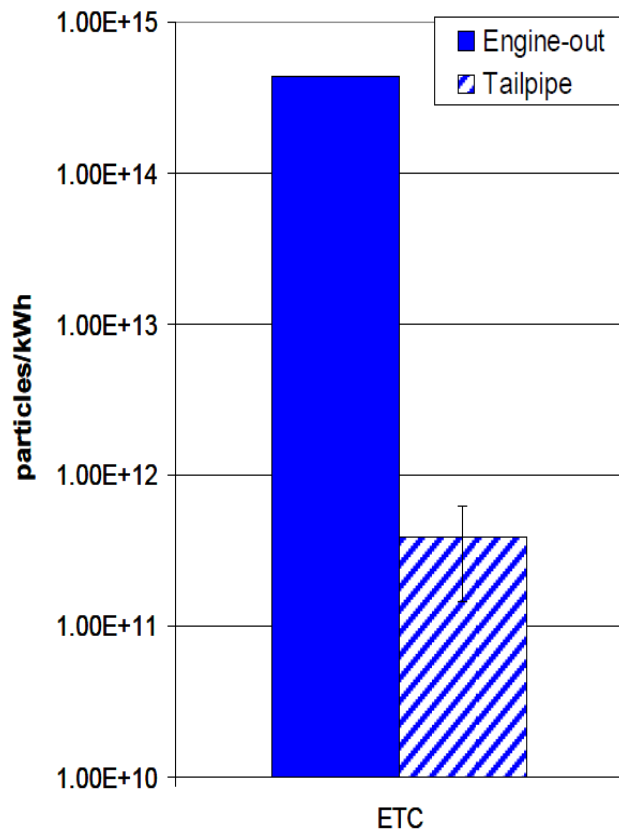
Diesel Particulate Filters (DPFs)

- Wall flow ceramic filter element with high capture efficiency for particulates over a broad size range (cordierite or SiC filter elements)
- Captured soot needs to be burned off (regenerated) at regular intervals to manage backpressure on engine (passive and active regen. options)
- Commercialized on light-duty diesels in Europe in 2000, on US LDD starting in 2006; standard on US 2007+ trucks/buses, on 2013+ Euro VI trucks/buses – 10s of millions in-use worldwide
- Capture soot and inorganic-based particles associated with engine wear, lubricant consumption: regular maintenance required (filter cleaning)

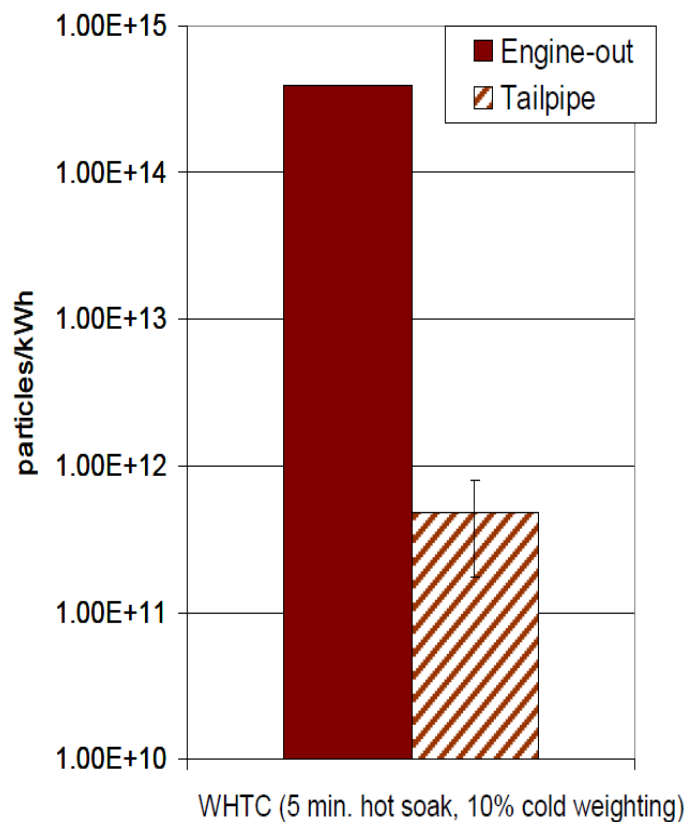


DPFs Have High BC/PN Filtration Efficiency: Heavy-duty Diesel Engine Example

- ETC tailpipe emissions $\sim 4 \times 10^{11}/\text{kWh}$
- DPF Efficiency $> 99.9\%$



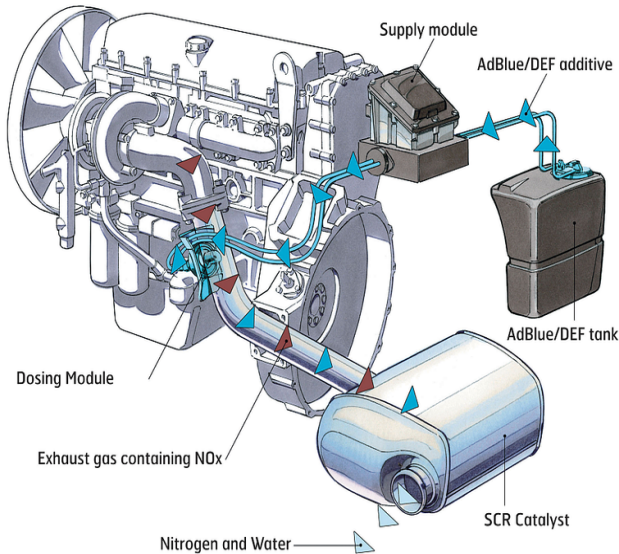
- WHTC tailpipe emissions $< 5 \times 10^{11}/\text{kWh}$
- DPF Efficiency $> 99.8\%$



DPFs Capture Ultrafine Diesel Particulates

Clean Diesel Technology Expanding into U.S. Off-road Applications with & without DPFs

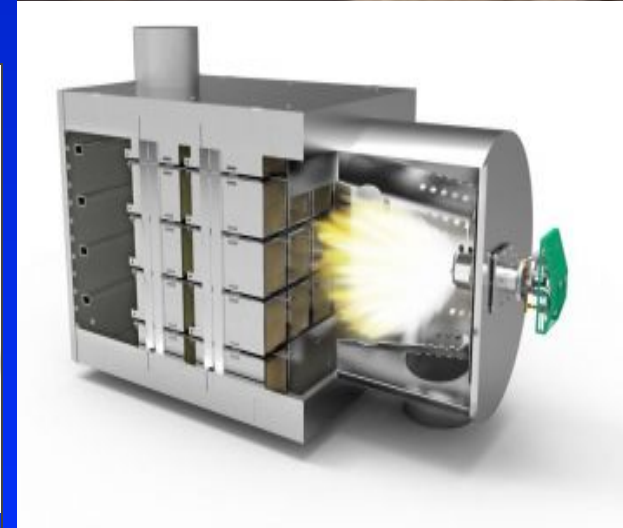
Tier 4 Tractors with SCR



Tier 4 Machines with DPFs



Locomotives with DPFs and/or SCR systems



Tier 4 U.S./Stage IV EU Off-road Diesels Offering a Wider Range of Emission Controls

EPA Tier 4 Interim / EU Stage IIIB
 EPA Tier 4 Final / EU Stage IV

| KW | EPA | HP | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | |
|----------|-----|---------|------------------------------|------|------|------|-------------------------|--------------------|--------------------------|------|-------------------------|------|--|
| 0-18* | | 0-24 | (7.5) / 6.6 / 0.40 | | | | | | | | | | |
| 19-36 | | 25-48 | (7.5) / 5.5 / 0.30 | | | | | (4.7) / 5.0 / 0.03 | | | | | |
| 37-55 | | 49-74 | (4.7) / 5.0 / 0.30 Option 1) | | | | | | (4.7) / 5.0 / 0.03 | | | | |
| 56-129* | | 75-173 | | | | | 3.4 / 0.19 / 5.0 / 0.02 | | 0.40 / 0.19 / 5.0 / 0.02 | | | | |
| 130-560* | | 174-751 | | | | | 2.0 / 0.19 / 3.5 / 0.02 | | 0.40 / 0.19 / 3.5 / 0.02 | | | | |
| >560 | | >751 | | | | | | | 3.5 / 0.40 / 3.5 / 0.10 | | 3.5 / 0.19 / 3.5 / 0.04 | | |

| KW | EU | HP | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | | |
|---------|----|---------|------------------------------|------|------|------|--------------------------|------|--------------------------|------|------|------|--|--|
| 18-36 | | 24-48 | Stage IIIA (7.5) / 5.5 / 0.6 | | | | | | | | | | | |
| 37-55 | | 49-74 | | | | | | | (4.7) / 5.0 / 0.025 | | | | | |
| 56-129* | | 75-173 | | | | | 3.3 / 0.19 / 5.0 / 0.025 | | 0.4 / 0.19 / 5.0 / 0.025 | | | | | |
| 130-560 | | 174-751 | | | | | 2.0 / 0.19 / 3.5 / 0.025 | | 0.4 / 0.19 / 3.5 / 0.025 | | | | | |

(NOx + HC) / CO / PM (Oxides of Nitrogen + Hydrocarbons) / Carbon Monoxide / Particulate Matter (g/kW-hr)
 NOx / HC / CO / PM Oxides of Nitrogen / Hydrocarbons / Carbon Monoxide / Particulate Matter (g/kW-hr)

* Combines regulatory powerbands with same emission levels

50%+ higher off-road limits:

PM (g/kWh)
 0.020 off-road
 (0.04-0.06 for Tier 4 marine)
 vs.
 0.013 on-road

NOx (g/kWh)
 0.40 off-road
 (1.8 for Tier 4 marine)
 vs.
 0.26 on-road

Tier 4 Final includes a variety of emission control solutions including: EGR+DOC, DOC+SCR, EGR+DPF, DPF+SCR

EU considering a Stage V standard that could be similar to Euro VI, including a PN limit; EU Stage IIIB/IV and U.S. Tier 4 Standards utilize the Nonroad Transient Cycle (NRTC)



Marine DPF Experience Includes Filters with Passive & Active Regeneration; Little Experience with OGVs

Applications

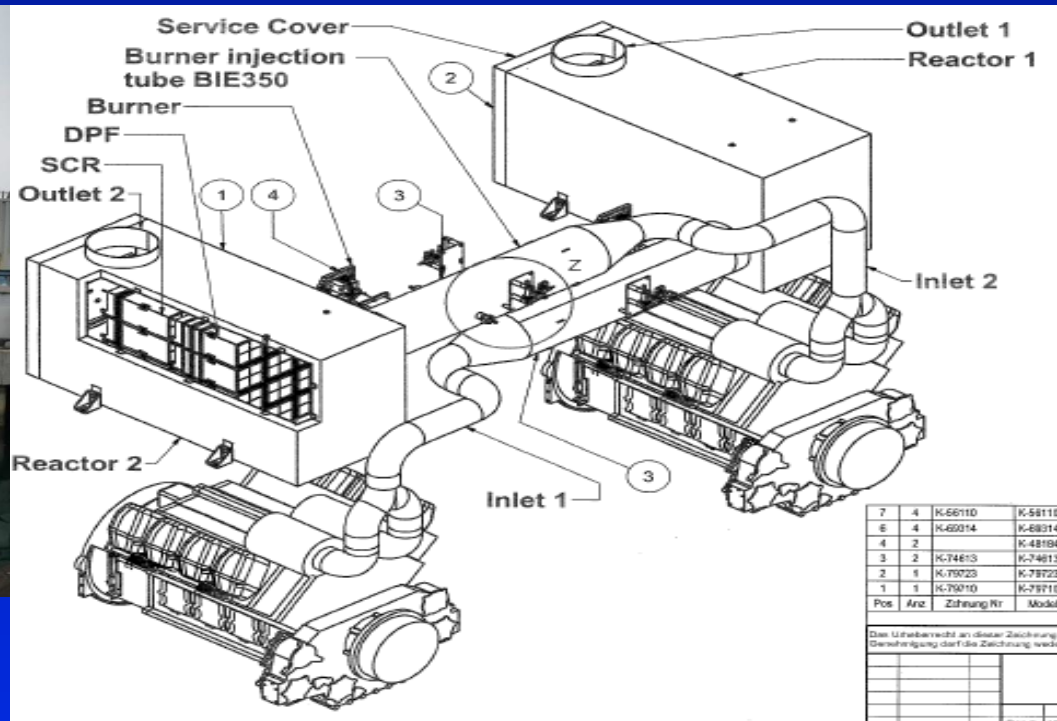
- Numerous large yachts: mostly auxiliary engines, some propulsion engines (100 – 1500 hp)
- Limited applications on harborcraft (tugs, ferries, pilot boats) & inland vessels (barges, ferries, excursion boats)
- DPF demonstration on OGV medium speed, auxiliary engine: relatively poor PM performance due to use of high sulfur fuel/high ash lube (700 ppm S fuel, PM dominated by organic carbon)
- Few reports of OGV filter demos (Mitsui OSK Lines 2010 coastal ferry trial/2012 OGV trial)

Experience/Issues

- LSD/ULSD provides best PM performance
- Installations designed for marine environment (stainless steel housings, exclude water intrusion, insulated, creative packaging in a limited space)
- Filter also provides sound attenuation
- Engine backpressure issues need to be addressed (filter design, bypass loop, monitor)
- Filter maintenance friendly installations



Tug Active DPF+SCR Retrofit at Port of LA



- Powered by two Detroit Diesel 525 hp, 14 liter, 2-stroke turbocharged & supercharged engines rebuilt to EPA Tier 2 emission levels
- Each engine retrofit with catalyzed DPF+SCR system; DPF regeneration managed by in-line diesel fuel burner
- With ULSD PM reduced by > 95% (ca. 5-7 mg/ kWh after ca. 200 h service) NOx reduced by > 90%
- Report available at: <http://www.arb.ca.gov/msprog/aqip/demo.htm>



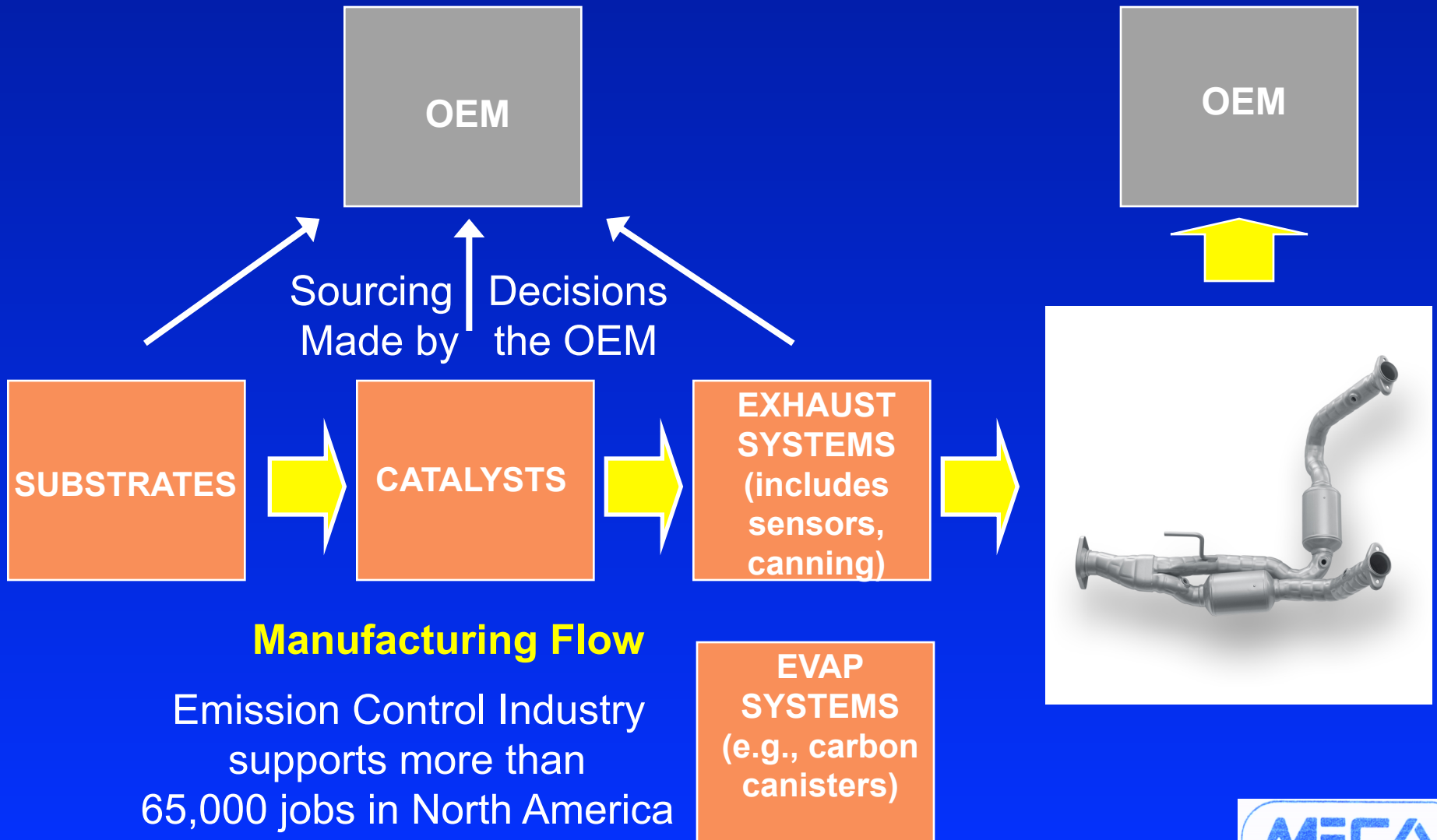
Passive DPF Locomotive Retrofit Completed in California



- Tier 2 locomotive powered by three 19 liter, 522 kW Cummins gen-sets each retrofit with a DOC+catalyzed DPF (passive regeneration)
- Operated 3000 hours in switcher rail service with ULSD
- PM levels reduced by ca. 80% (19 mg/bhp-hr PM measured after 3000 h of service; below EPA Tier 4 PM limit of 30 mg/bhp-hr); HCs: 90%, CO: 99% reduced vs. baseline
- Report available at: <http://www.arb.ca.gov/msprog/aqip/demo.htm>

Back-up Slides

Emission Control Industry Has Long Standing Relationships with CARB, EPA, Vehicle and Engine Manufacturers



Clean Diesel Technology Driven By a Decade of U.S. EPA Mobile Source Emission Regulations

Average Benefit:Cost = 20:1

Tier 2 Light-Duty

final rule 1999

fully phased in 2009

Diesels held to same standards as gasoline vehicles

Diesel sulfur now 15 ppm



Ocean-going Vessels

final rule 2009; IMO ECA in 2010

**ECA: 1000 ppm Sulfur by 2015;
80% lower NOx by 2016**



Heavy-Duty Highway

final rule 2000

Sulfur now 15 ppm

fully phased in 2007-2010



Locomotive / Marine Tier 4

final rule 2008

Sulfur now 15 ppm

fully phased in 2017



Nonroad Diesel Tier 4

final rule 2004

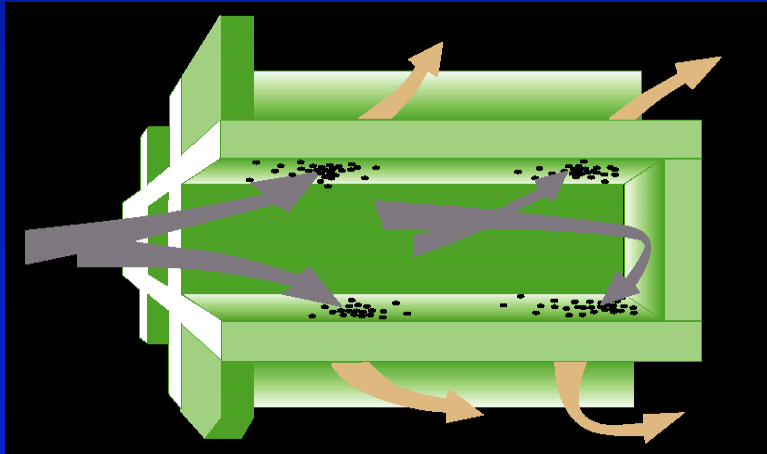
Sulfur now 15 ppm

fully phased in 2015

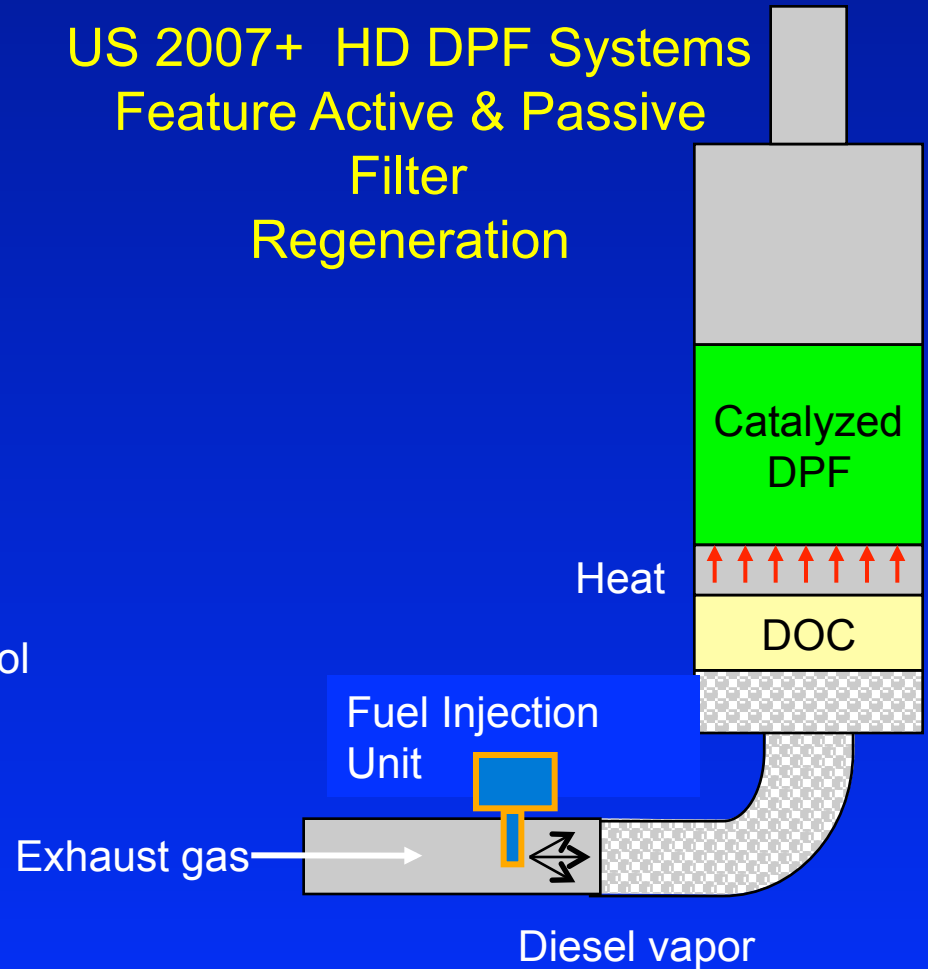


DOCs and DPFs Form the Technology Base for Reducing PM Emissions from US 2007 Diesel Engines

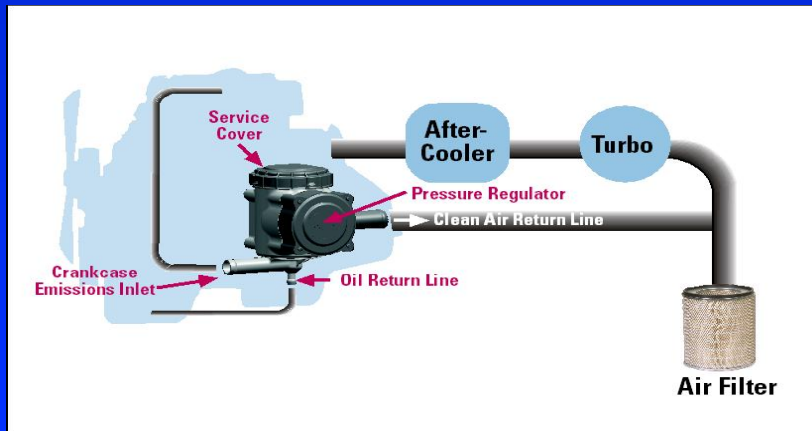
Diesel Particulate Filters



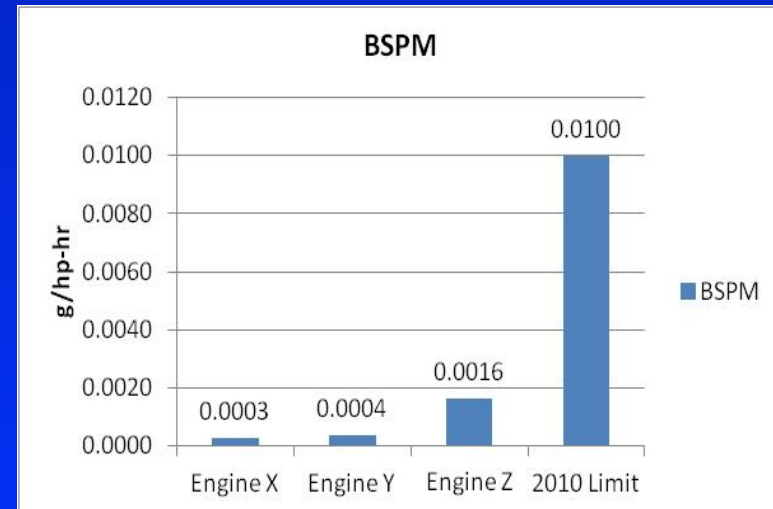
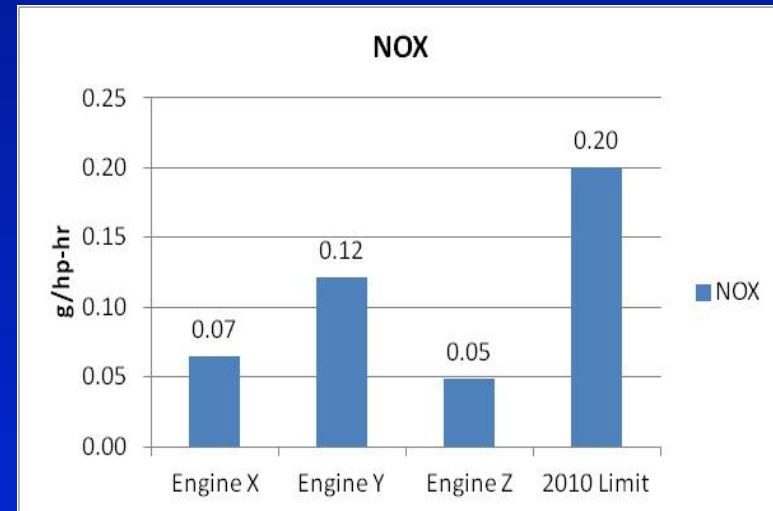
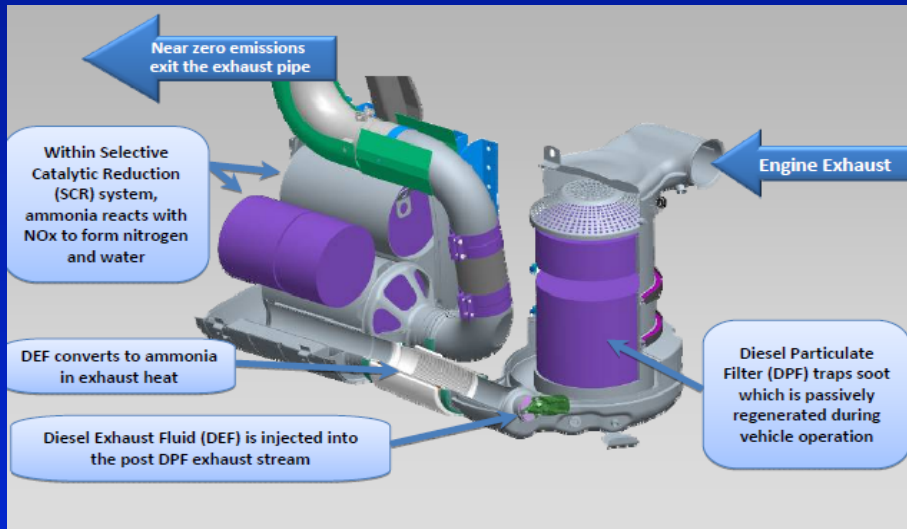
US 2007+ HD DPF Systems Feature Active & Passive Filter Regeneration



Crankcase Filters Provide Additional PM Control



US 2010 Technologies Deliver Surplus Health Benefits



- 2010 on-highway emission controls employing Cu and Fe based SCR catalysts have evolved into 2nd generation technologies.
- U.S. ACES study shows that 2010 commercial emission control technology significantly exceeds the standards, esp. on PM.
- > 3 million DPF equipped trucks & buses operating on U.S. highways

U.S. 2007 HD Emission Performance Provides Significant Reductions in PM, CO, Air Toxic HCs

| | 2007 EPA Standard (g/hp-hr) | Average ACES Engine Emissions (g/hp-hr) | ACES Emissions % Reduction Relative to the 2007 Certification Standard |
|-----------------|--------------------------------|--|---|
| CO | 15.5 | 0.33 | 98 |
| NMHC | 0.14 | 0.0064 | 95 |
| PM | 0.01 | 0.0011 | 89 |
| NO _x | 1.2 ^a | 1.075 | 10 |

^a Average value between 2007 and 2009, with full enforcement in 2010 at 0.20 g/hp-hr

| Compounds | % Lower Than 2004 Engine Technology | |
|-----------------------------|--|-----------|
| | 16-Hour Cycle | CARBx-ICT |
| Single Ring Aromatics | 82% | 69% |
| PAH | 79% | 26% |
| Nitro-PAH | 81% | 49% |
| Alkanes | 85% | 84% |
| Polar | 81% | 12% |
| Hopanes/Steranes | 99% | 99% |
| Carbonyls | 98% | 78% |
| Inorganic Ions | 38% | 100% |
| Metals and Elements | 98% | 90% |
| Organic Carbon | 96% | 78% |
| Elemental Carbon | 99% | 100% |
| Dioxins/Furans ^a | 99% | N/A |

^a Relative to 1998 Engine Technology

Source: CRC Phase 1 ACES Report;
2010+ Engines Delivering Even Lower
Toxic HC Emissions than 2007 Engines

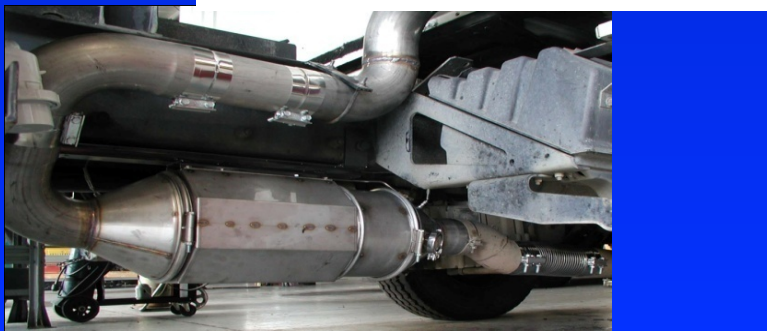
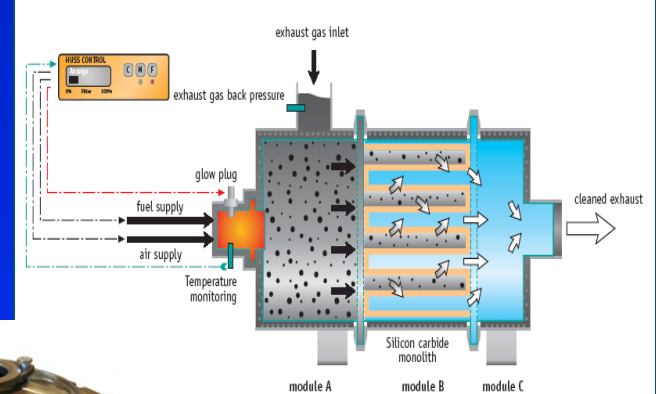
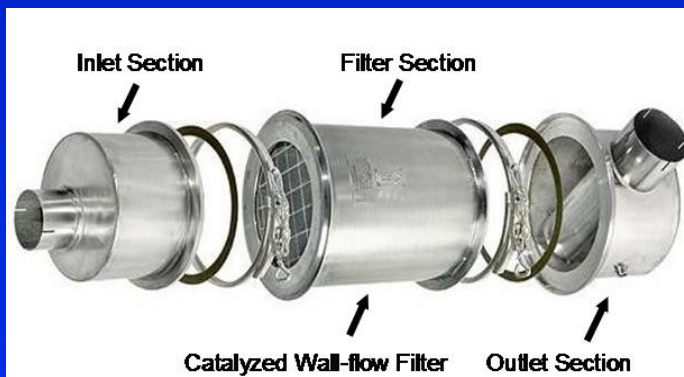


Off-Road Heavy-Duty Engines – Marine Vessels and Locomotives

- Current EPA standards, which are still being phased-in, do not require the use of exhaust emission controls
- EPA finalized Tier 4 standards for locomotive and marine diesel (C1, C2) engines in 2008; requires ULSD
 - Tier 4 PM (0.04 g/kWh) and NOx (1.8 g/kWh) technology forcing standards included:
 - Line haul, switcher locomotives: 2015 for PM & NOx
 - Commercial marine 600 kW and larger: 2014-2017 for PM & NOx (phase-in based on power rating; 3700 kW & larger Tier 4 PM limit is 0.06 g/kWh)
- North American ECA established, effective August 2012 (consistent with IMO limits)
 - 1% sulfur limit, lowers to 0.1% sulfur max. in January 2015 (scrubbers are also allowed)
 - Tier 3 NOx limits within ECA for new ship starts in 2016 (SCR, EGR, LNG all options)

Availability of ULSD Enables Variety of CARB/EPA Verified Diesel Retrofit Technologies

- On-Road & Off-Road DPFs with Active Soot Regeneration
- On-Road & Off-Road DPFs with Passive Soot Regeneration
- Retrofit DPFs for Stationary Diesel Engines
- SCR Retrofits for On-Road & Off-Road Engines
- U.S. EPA (epa.gov/cleandiesel/verification/verif-list.htm)
- California ARB (www.arb.ca.gov/diesel/verde/vt/cvt.htm)



www.meca.org – Newly redesigned Your emission control technology resources on the web

The screenshot shows the MECA website homepage. At the top, there is a navigation bar with links for 'about us', 'contact us', 'sitemap', 'Intranet', and 'You are logged in'. Below this is a secondary navigation bar with 'MECA' logo and links for 'technology', 'regulation', 'diesel retrofit', 'resources', and 'newsroom'. A search bar is also present. The main banner features a blue sky with white clouds and the text 'Technology for Clean Air'. Below the banner, there is a paragraph: 'The member companies of the Manufacturers of Emission Controls Association (MECA) include leading manufacturers of emission control technology for a variety of sources, including:'. To the right, there is a 'Recently Posted' section with tabs for 'News' and 'Other Updates'. The main content area is a grid of featured articles with images and titles: 'Passenger Cars, SUVs, and Light-Duty Trucks', 'Heavy-Duty Trucks and Buses', 'Off-Road Diesel Equipment', 'Off-Road Spark-Ignited Equipment', and 'Alternative Fuel / Advanced Tech. Vehicles'. A 'View All Technologies' link is also visible. The 'Recently Posted' section lists several news items with dates and titles, such as 'Retrofit Sales for Trucks and Buses in California Remain Lower Than Projected' and 'MECA Releases New Report on Health Impacts of Ultrafine Particulates, Importance of Advanced Emission Control Technology'.

- New Ultrafine particulate report with Executive summary in Mandarin
- Emission control technology white papers and fact sheets
- Retrofit technology descriptions
- Case study reports
- Regulatory info

