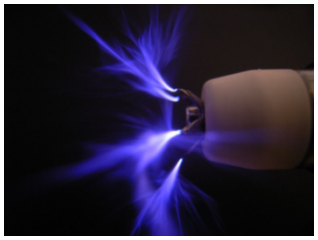
Diesel Particulate Filters for PM Control from Marine Engines

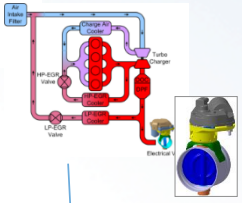
September 7, 2016
Vancouver, BC
Canada

MECA Portfolio Covers Criteria and GHG Emission Control Technologies

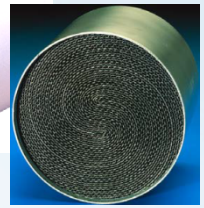
Fuel Combustion Controls



Air Handling

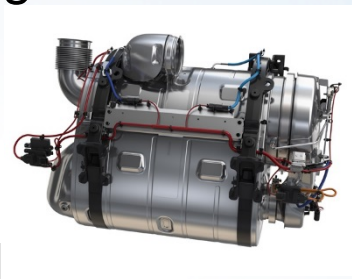


Filters & Substrates

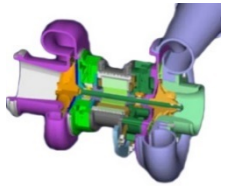


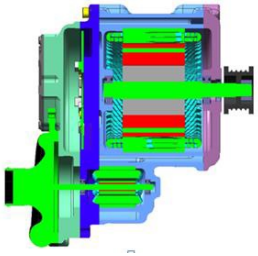
Evaporative Controls

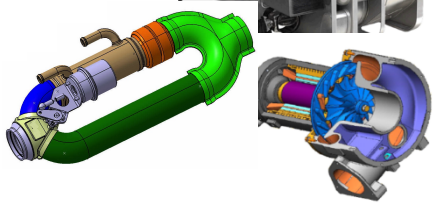
Exhaust System Integration



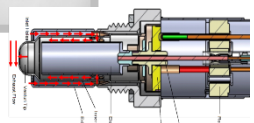
Powertrain Electrification







Waste Heat Recovery



OBD Sensors

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

U.S. EPA Tier 4 Emission Standards in Place for Commercial Marine Engines

Tier 4 Standards for Commercial Marine Diesel C1 and C2 (g/bhp-hr)

Rated kW	Model Year	PM	NOx	HC
3700 kW or above	2014[c]	0.09[a]	1.3	0.14
	2016[b,c]	0.04	1.3	0.14
2000≤ kW < 3700	2014[c,d]	0.03	1.3	0.14
1400≤ kW < 2000	2016[c]	0.03	1.3	0.14
600≤ kW<1400	2017[b]	0.03	1.3	0.14

[a] This standard is 0.19 for engines with 15-30 L/cylinder displacement.

[b] Optional compliance start dates are included within these model years.

[c] Option for C2 engines: Tier 3 PM/NOx+HC at 0.10/5.8 in 2012 and Tier 4 in 2015.

[d] Tier 3 PM standards continue to apply for these engines in 2014 and 2015.

Category 1: < 7 liters/cyl.;
Category 2: 7-30 liters/cyl.

15 ppm Marine Diesel Fuel Sulfur Limit Began in June 2012

Stage V EU Off-Road Standards

Stage V Emission Standards for Inland Waterway Vessels

Category	Net Power *kW*	Date	CO	HC[a]	NOx	PM	PN
			g/kWh				*1/kWh*
Propulsion Engines—Category IWP							
IWP-v/c-1	37 ≤P < 75	2019	5.00	4.70[b]		0.30[b]	-
IWP-v/c-2	75 ≤ P < 130	2019	5.00	5.40[b]		0.14	-
IWP-v/c-3	130 ≤ P < 300	2019	3.50	1.00	2.10	0.11	-
IWP-v/c-4	300 ≤ P < 1000	2020	3.50	0.19	1.20	0.02	1×10^{12}
IWP-v/c-5	P ≥ 1000	2021	3.50	0.19	0.40	0.01	1×10^{12}
Auxiliary Engines—Category IWA							
IWA-v/c-1	560 ≤ P < 1000	2020	3.50	0.19	1.20	0.02	1×10^{12}
IWA-v/c-2	P ≥ 1000	2021	3.50	0.19	0.40	0.01	1×10^{12}

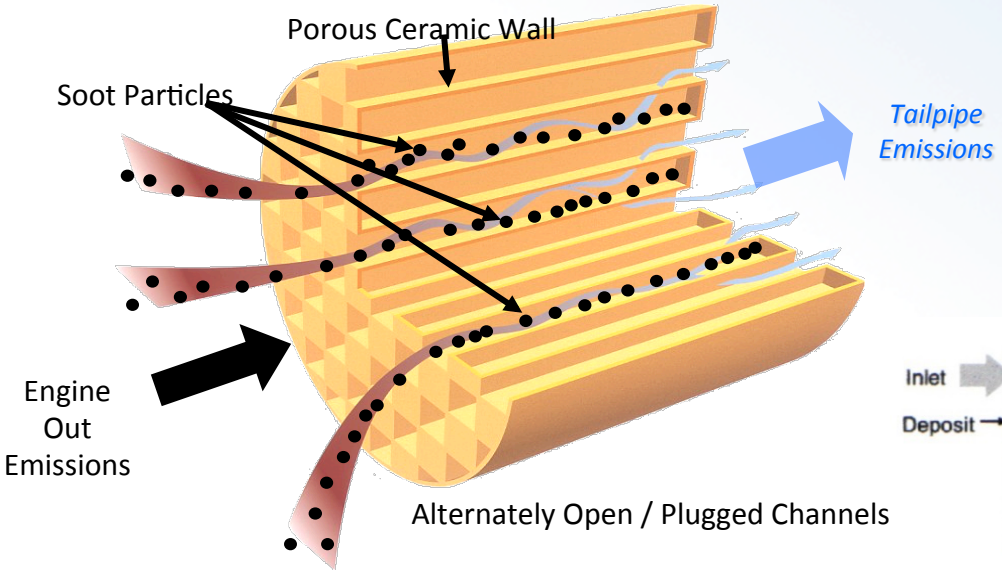
Stage V Emission Standards for Nonroad Engines

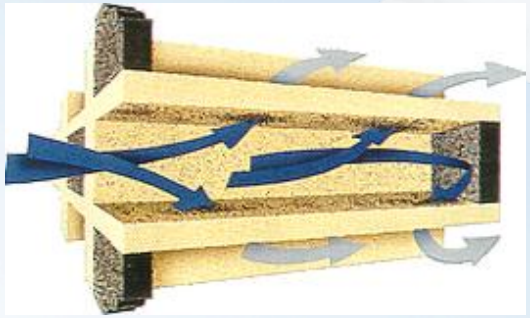
Category	Ign.	Net Power *kW*	Date	CO	HC	NOx	PM	PN
				g/kWh				*1/kWh*
NRE-v/c-1	CI	P < 8	2019	8.00	7.50[a,c]		0.40[b]	-
NRE-v/c-2	CI	8 ≤ P < 19	2019	6.60	7.50[a,c]		0.40	-
NRE-v/c-3	CI	19 ≤ P < 37	2019	5.00	4.70[a,c]		0.015	1×10^{12}
NRE-v/c-4	CI	37 ≤ P < 56	2019	5.00	4.70[a,c]		0.015	1×10^{12}
NRE-v/c-5	All	56 ≤ P < 130	2020	5.00	0.19[c]	0.40	0.015	1×10^{12}
NRE-v/c-6	All	130 ≤ P ≤ 560	2019	3.50	0.19[c]	0.40	0.015	1×10^{12}
NRE-v/c-7	All	P > 560	2019	3.50	0.19[d]	3.50	0.045	

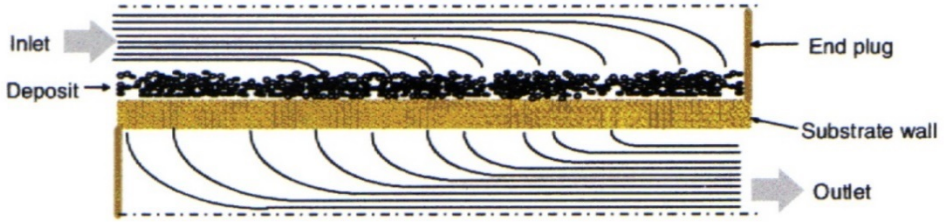
- PN standards for inland waterway vessel propulsion engines > 300 kW and aux engines > 560 kW
- Stage V will result in DPF use

Source: www.dieselnet.com

Diesel Particulate Filters (DPFs)





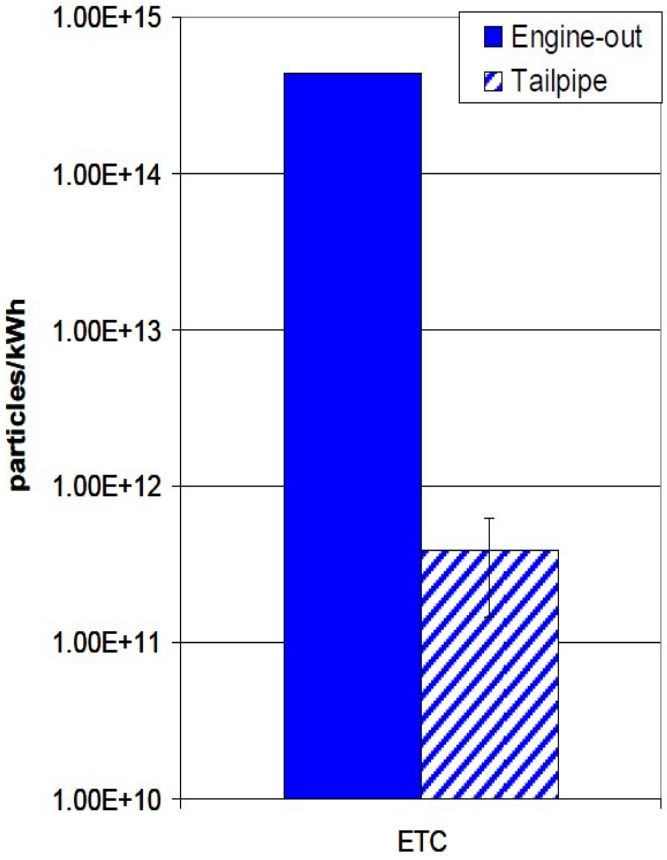


Source : Anforderungen an Partikelfiltersysteme für Dieselmotoren, A.Mayer, TTM

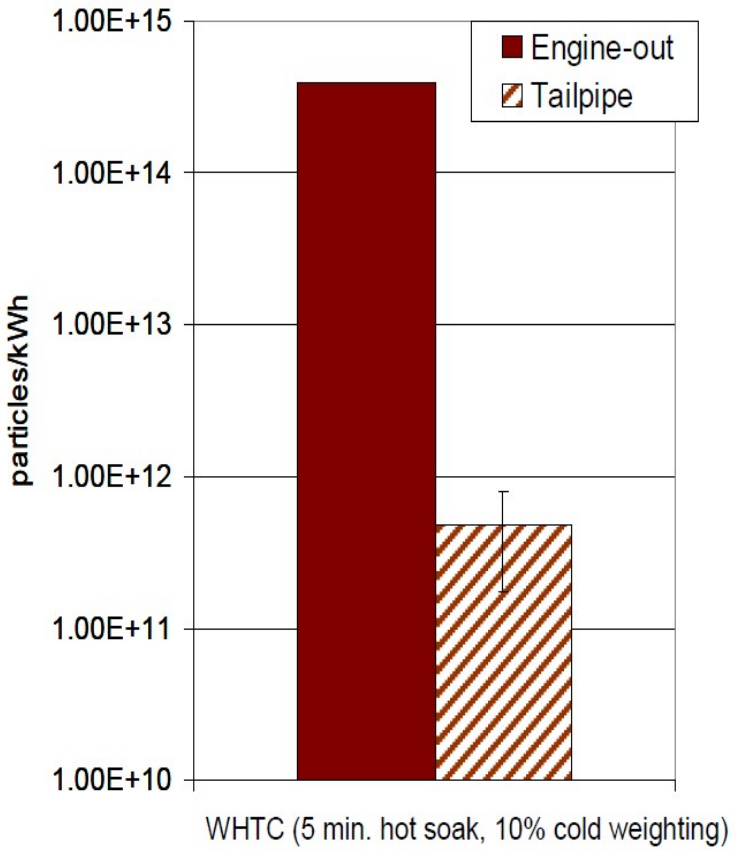
- Wall flow ceramic filter element with high capture efficiency for particulates over a broad size range (cordierite or SiC filter elements)
- Captured soot needs to be burned off (regenerated) at regular intervals to manage backpressure on engine (passive and active regen. options)
- Commercialized 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 ~ 4 x 10^{11}/kWh
- DPF Efficiency > 99.9%



- WHTC tailpipe emissions < 5 x 10^{11}/kWh
- DPF Efficiency > 99.8%



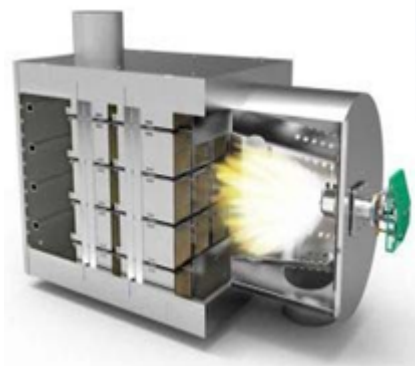
DPFs Capture Ultrafine Diesel Particulates

Clean Diesel Technology Expanding into U.S. Off-road Applications

Tier 4 Machines with DPFs

Locomotives with DPFs and/or SCR systems

Marine DPFs and/or SCR systems



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

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

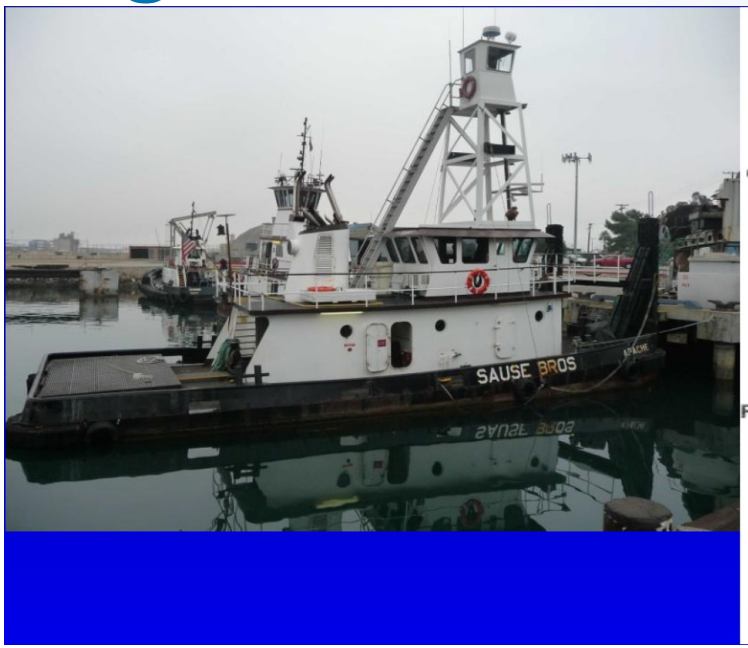
Applications

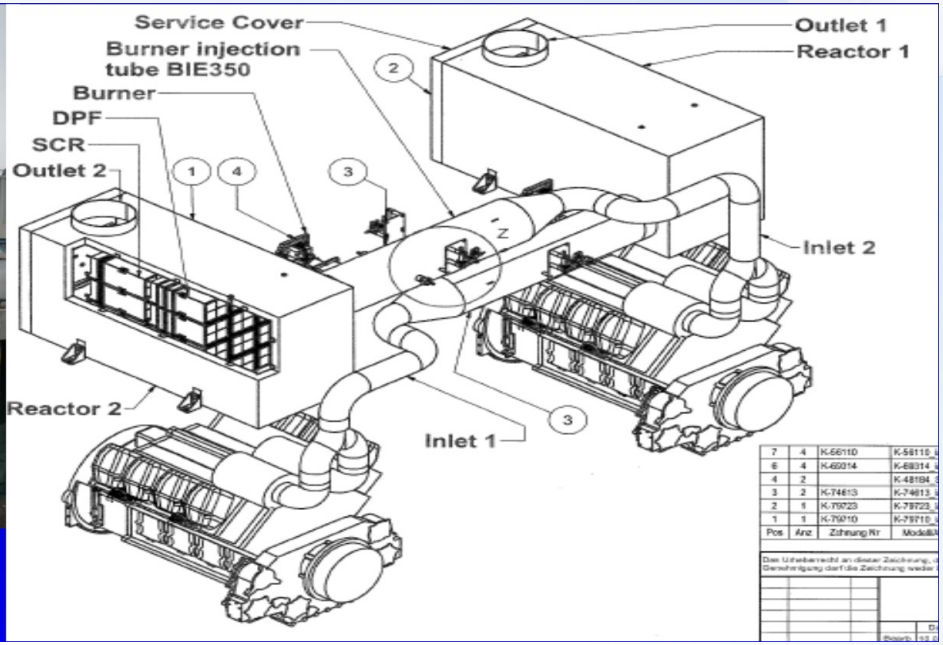
- Numerous large yachts: mostly auxiliary engines, some propulsion engines (100 – 1500 hp)
- Limited applications on harborcraft (tugs, ferries, pilot boats) & inland vessels (barges, ferries, excursion boats)
- DPF demonstration on OGV medium speed, auxiliary engine: relatively poor PM performance due 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, Queen Victoria 2014)

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

Tug Active DPF+SCR Retrofit at Port of LA



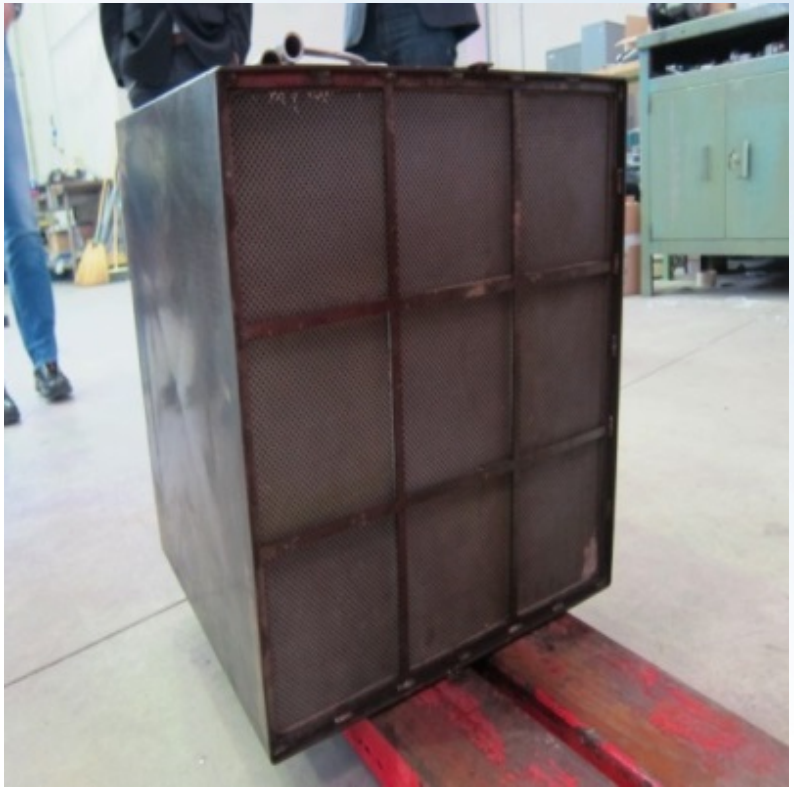


- Powered by two Detroit Diesel 525 hp, 14 liter, 2-stroke turbocharged & supercharged engines rebuilt to EPA Tier 2 emission levels
- Each engine retrofit with catalyzed DPF+SCR system; DPF regeneration managed by in-line diesel fuel burner
- With ULSD PM reduced by > 95% (ca. 5-7 mg/ kWh after ca.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

HFO DPF Challenge & Solution

Challenge

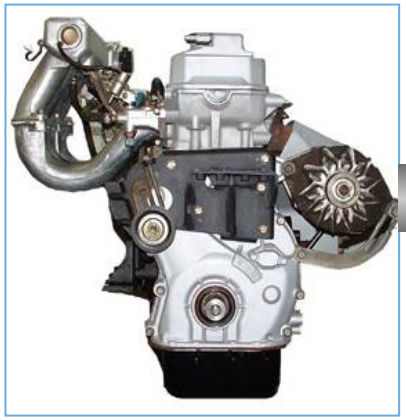
- Sulfur content in fuel up to 3.5% and no NO_2
- Ash content in HFO up to 0.2%
- Filter pressure drop max 25–60 mBar

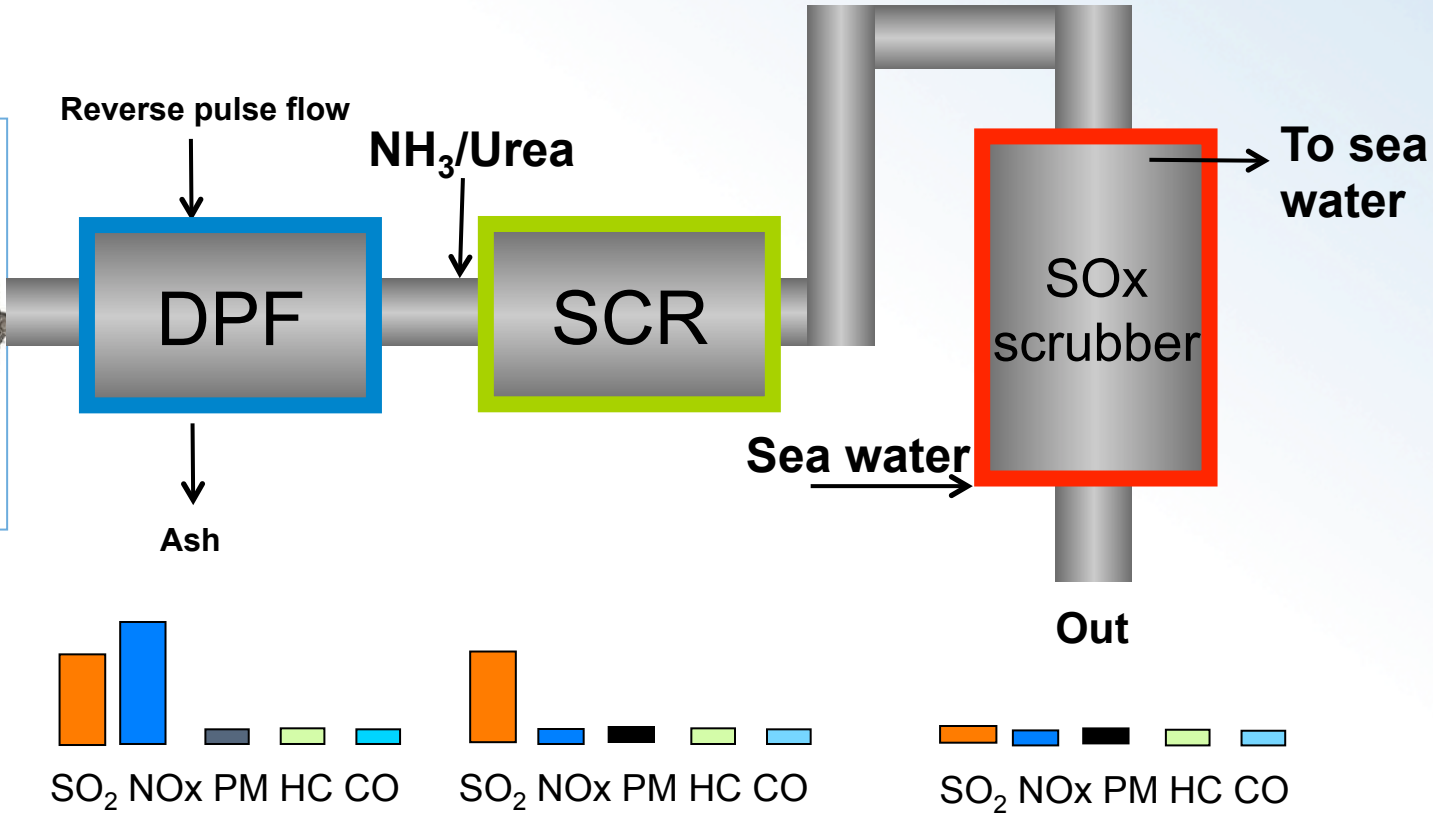


Solution

- SiC filter substrate coated with Pd/V_2O_5
- Passive soot combustion
- HC (PAH) conversion and CO conversion
- Ash removed by reverse pulse flow
- Sulfur-tolerant with low SO_2 oxidation

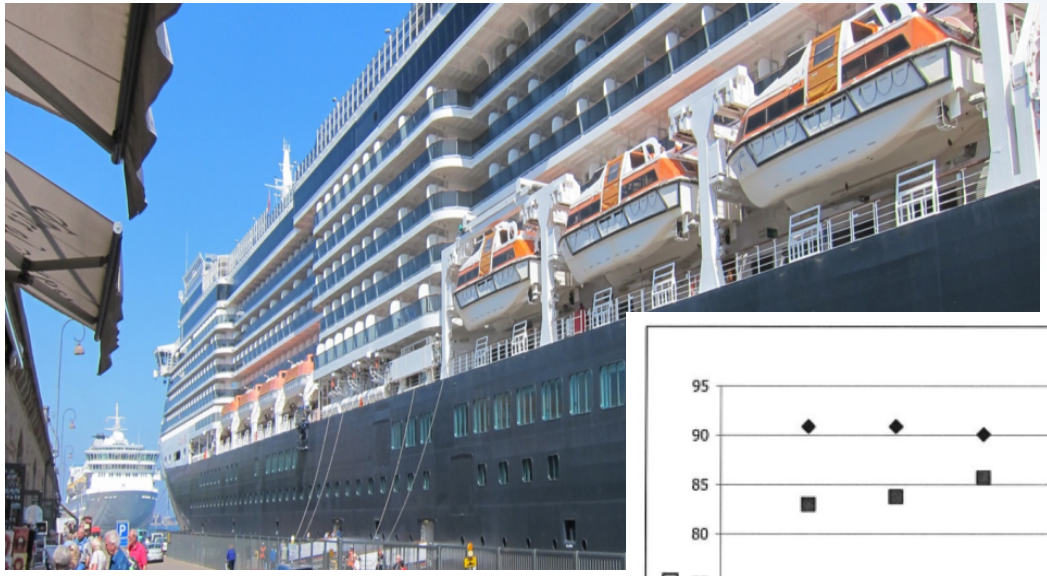
Particulate Removal Process with Passively Regenerated Catalyzed DPF





Johansen, Catalysis Today, 258 (2015): pp. 2-10

Queen Victoria Cruise Ship Soot Removal Summary



Soot removal: 80 – 92%

Δp_{max} = 40 mBar

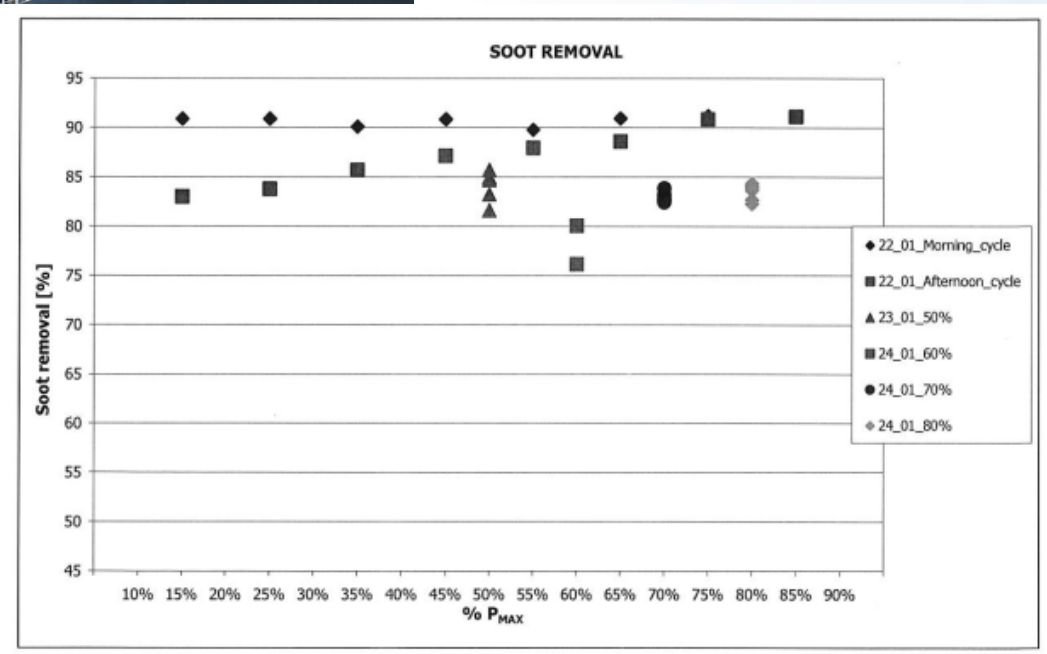


Figure 38: Summary of soot removal efficiencies achieved during the testing days

Johansen, Catalysis Today, 258 (2015): pp. 2-10

www.meca.org

Your emission control technology resources on the web

- Emission control technology white papers and fact sheets
- Retrofit technology descriptions
- Case study reports
- Regulatory info

Appendix

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

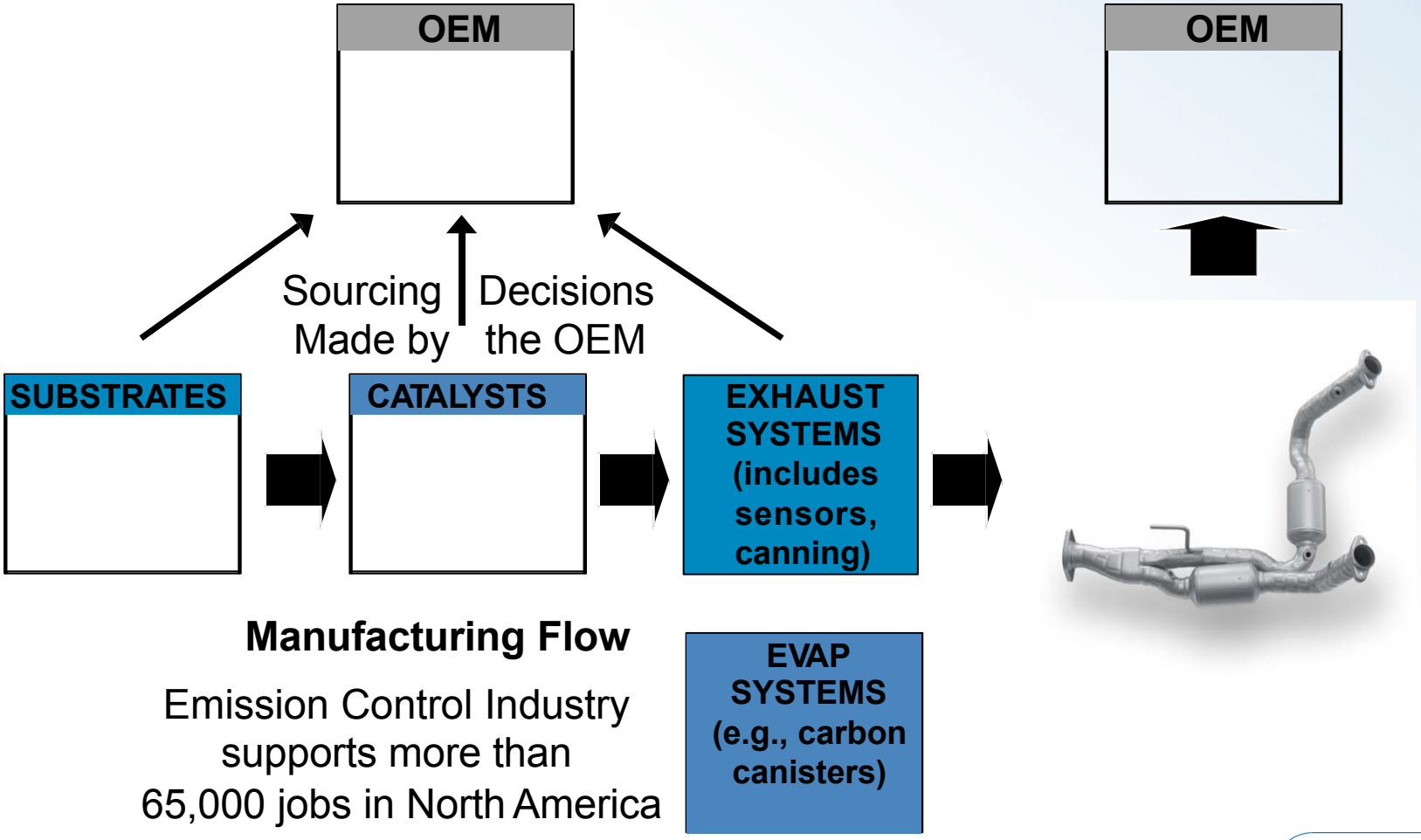
	2007 EPA Standard (g/hp-hr)	Average ACES Engine Emissions (g/hp-hr)	ACES Emissions % Reduction Relative to the 2007 Certification Standard
CO	15.5	0.33	98
NMHC	0.14	0.0064	95
PM	0.01	0.0011	89
NO_X	1.2 [a]	1.075	10

[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

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

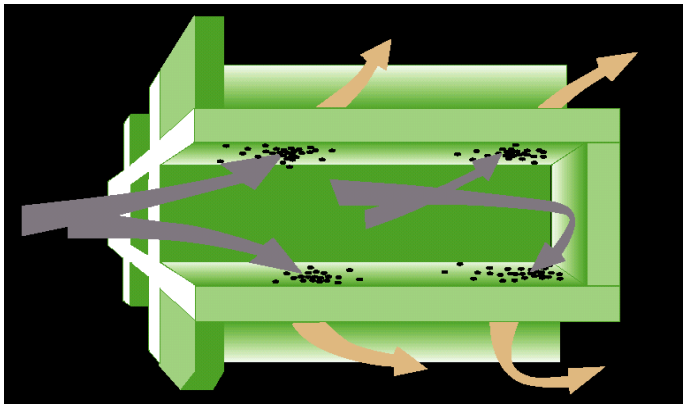


Manufacturing Flow

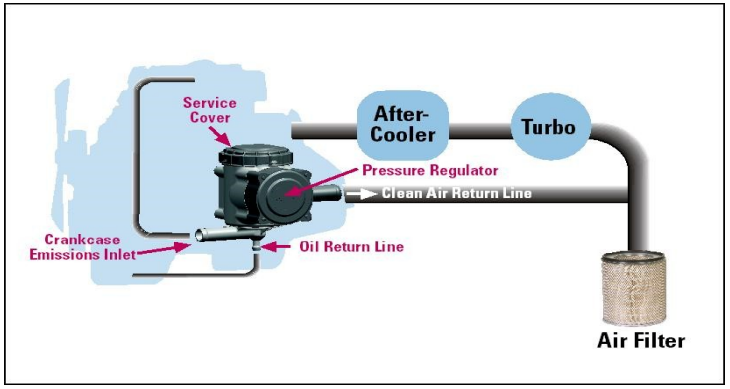
Emission Control Industry supports more than 65,000 jobs in North America

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

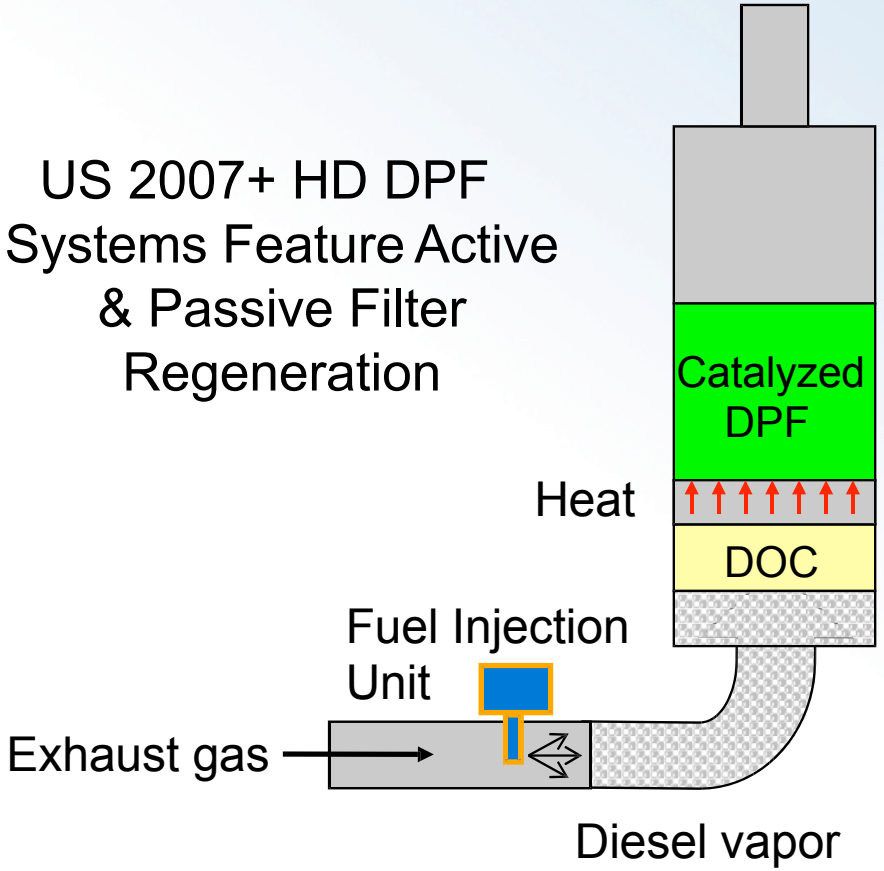
Diesel Particulate Filters



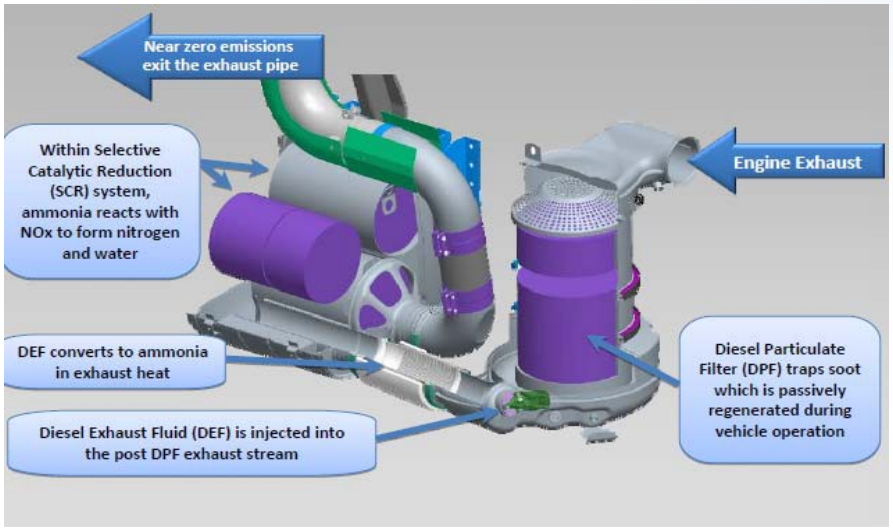
Crankcase Filters Provide Additional PM Control

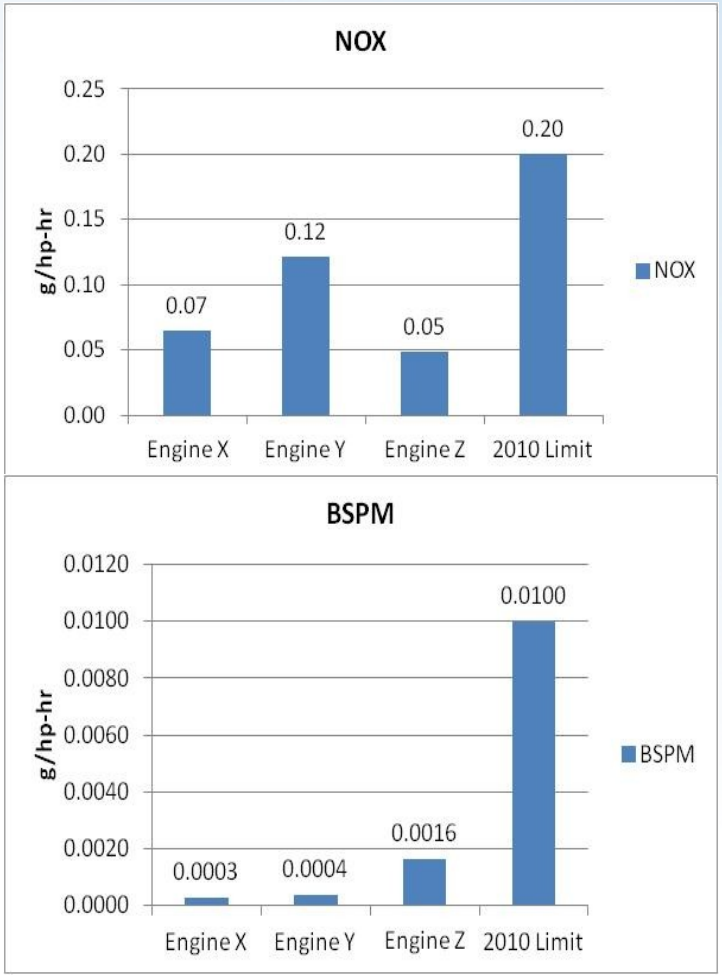


US 2007+ HD DPF Systems Feature Active & Passive Filter Regeneration



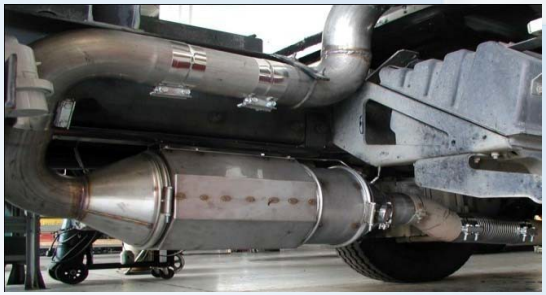
US 2010 Technologies Deliver Surplus Health Benefits





- 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

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/verdev/vt/cvt.htm)