Summary and Outline

“DPFs are becoming as much a part of the modern diesel engine as direct injection and turbocharging.” Ulrich Dohle, President Bosch Diesel, 2006.

- Diesel system trends described
- Sophisticated regeneration control strategies emerging
- Materials and filter design optimization in progress
  - Three major DPF materials in the market
  - Pore size effects on filtration efficiency (~ 20 μm threshold)
  - Wall attributes, cell structure, and cell density
  - Ash management
- NOx aftertreatment trends and complexity being addressed
Light-Duty Diesel Vehicle Production & Filter Demand

CAGR 07-11
- 9.6%
- 5.3%
- 23.3%

Non Filter OEM's: India & China Local

Filter Penetration
- 2006: 29%
- 2007: 37%
- 2008: 44%
- 2009: 53%
- 2010: 63%
- 2011: 69%
- 2012: 71%

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Light-Duty Diesel Systems Trend
Close-Coupled Filters

• **Drivers**
  – Potential for fewer components → cost, space considerations
  – More continuous regeneration due to higher temperatures
  – Less post-injection fuel penalty and oil dilution

• **Enablers**
  – Smaller filters
    • More ash-storage capacity (→ ACT)
  – Integration of catalyst function on the filter (CSF) with optimal pressure drop performance
    • Optimized porosity & washcoat interaction

*Asymmetric Cell Technology*
Summary of LDD Trends for PM and NOx Aftertreatment

- Clear majority of systems include a DOC with the DPF
- Two major architectures are emerging
  - Close-coupled filter
    - AT and SiC optimized for higher SML applications
    - Cordierite applicable with proper controls
  - Under-floor filter with secondary fuel injector or vaporizer
    - Allows long oil-change intervals (oil dilution addressed)
- Interest in combining functionality is strong, but modular systems are the norm for the near term
  - DOC + DPF + LNT/SCR (as needed)
Global OEM System Forecast: On-road & Non-road

Key Assumptions

- EUVI timing: '12-13 w/ some pull ahead
- US10/EUVI systems
  - LHD Chassis: SCR + DPF
  - LHD Engine: DPF + SCR
  - M/HHD: DPF + SCR
- Brazil: SCR and DOC+DPF
- China: SCR
- India: IPR and SCR
- 75-750 HP Non-road: DOC+DPF

Growth of filter systems continues with tightening global HDD regulations

Source: Corning Forecast
Potential System Configurations for Future L-HD, MD and HD On-road Legislation (US2010 and EUVI)

Most common L-HD Layout

Most common HD and MD SCR Layout

Trends:
- Typical soot loads 3-5g/l
- Some applications might require higher soot loads
Sophisticated Regeneration Control Strategies

DPF bed temperature is controlled by oxygen level.

Oxygen control is very good in transient conditions.

Adaptive learning tightens A/F control and allows better soot estimation.
# Key Properties of Diesel Particulate Filter Materials

<table>
<thead>
<tr>
<th>Property</th>
<th>DuraTrap® AC</th>
<th>DuraTrap® AT</th>
<th>SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material (assuming ~ 50% porosity)</td>
<td>Cordierite</td>
<td>Stabilized Aluminum Titanate</td>
<td>Silicon Carbide</td>
</tr>
<tr>
<td>Structure</td>
<td>Monolith</td>
<td>Monolith</td>
<td>Segmented</td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion</td>
<td>&lt;6</td>
<td>&lt;9</td>
<td>~ 45</td>
</tr>
<tr>
<td>(x10^-7/°C) (22-1000°C)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal Conductivity @ 500 °C (W/mK)</td>
<td>~1.0</td>
<td>~1.0</td>
<td>10-20*</td>
</tr>
<tr>
<td>Specific Heat Capacity @ 500 °C (J/cm³ °C)</td>
<td>2.79</td>
<td>3.60</td>
<td>3.63</td>
</tr>
<tr>
<td>Thermal Shock Parameter (°C) a</td>
<td>&gt;800</td>
<td>&gt;900</td>
<td>&lt;300</td>
</tr>
<tr>
<td>Strain to Failure (%) (bending strength/elastic modulus)</td>
<td>~0.05</td>
<td>~0.10</td>
<td>~0.05</td>
</tr>
<tr>
<td>Allowable Thermal Gradient</td>
<td>high</td>
<td>very high</td>
<td>low</td>
</tr>
</tbody>
</table>

a: MOR/(E_mod x CTE)  

* Dependent upon bonding type
General Material and Design Interactions

<table>
<thead>
<tr>
<th>Influencing Parameters</th>
<th>Strength</th>
<th>Bulk Heat Capacity</th>
<th>Soot Mass Limit</th>
<th>Pressure Drop</th>
<th>Filtration Efficiency</th>
<th>Catalyst Storage Space</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Porosity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(constant cell density &amp; wall thickness)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Bulk density, $\rho_{\text{bulk}} = \rho_{\text{material}} \times (1-P) (1-OFA)$

- Bulk heat capacity, $c_p^{\text{bulk}} = c_p^{\text{material}} \times \rho_{\text{bulk}}$

<table>
<thead>
<tr>
<th></th>
<th>200/12</th>
<th>300/15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall Porosity</td>
<td>50%</td>
<td>60%</td>
</tr>
<tr>
<td>Bulk Density - Matrix</td>
<td>394 g/l</td>
<td>315 g/l</td>
</tr>
<tr>
<td>OFA - Total</td>
<td>68.5%</td>
<td>53.0%</td>
</tr>
<tr>
<td>OFA - Inlet Channels</td>
<td>34.3%</td>
<td>26.4%</td>
</tr>
</tbody>
</table>

$\rho = \text{density, } P = \text{wall porosity, } c_p = \text{heat capacity, } \text{OFA} = \text{open frontal area} = (L-T)^2/L^2$
Cordierite DPF reaches soot burning temperatures in about half the time of SiC. Attributed to lower thermal conductivity.
Oxides exhibit higher regeneration efficiencies at the same inlet temperatures.

For oxides (low thermal conductivity), slightly lower filter inlet temperatures are desirable to initiate regeneration (higher safety & lower fuel penalty to regenerate).
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PMP: Mass-Based Measurements

mean PM emissions (all vehicles)

Jon Andersson et al., PMP LD Interlab. Final Report January ‘07
PMP: Number-based Measurements

mean N emissions (all vehicles)

High Porosity and MPD Filter

$5 \times 10^{11}$/km

Jon Andersson et al., PMP LD Interlab. Final Report January ‘07
Filtration efficiency drops significantly if DPF has significant number of pores >20 \( \mu \text{m} \). Balancing porosity and catalyst loading is important for optimum performance.

<table>
<thead>
<tr>
<th>Material</th>
<th>SiC.A</th>
<th>SiC.B</th>
<th>SiC.C</th>
<th>SiC.D</th>
<th>Cd.A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity</td>
<td>58%</td>
<td>52%</td>
<td>48%</td>
<td>43%</td>
<td>50%</td>
</tr>
<tr>
<td>MPS</td>
<td>23( \mu \text{m} )</td>
<td>21( \mu \text{m} )</td>
<td>14( \mu \text{m} )</td>
<td>18( \mu \text{m} )</td>
<td>14( \mu \text{m} )</td>
</tr>
</tbody>
</table>

Cell Structure: (Wall Thickness: 0.31mm, Cell Pitch: 1.47mm)

Catalyst: Coated

Pressure drop at 4 g/l soot loading is not improved with larger pores, but is more affected by total porosity.

All filters meet the Euro 5 PM requirements (3 mg/km) on the NEDC test cycle.

Initial filtration efficiency drops for DPFs with pores >20 \( \mu \text{m} \).

NGK, SAE 2007-01-0923
Soybean biodiesel blends produce less soot, drop balance point temperature, and result in faster burn rate. Diesel PM production rates using diesel, B20 and B100 fuel at 2000 rpm and 20 ft-lbs. torque. Cummins 5.9 liter ISB engine, MY2002.

Balance point temperature results at 1700 rpm.

Soot combustion temperature is 550-580°C for biodiesel blends, and 650-680°C for diesel fuel. Difference is due to carbon structure.
Asymmetric cell design results in lower lifetime backpressure

- Symmetric
- Asymmetric

Source: Corning
DPF ash accumulation tracks lube oil consumption. Some ash goes back to the sump.

Ash accumulated on the DPF tracks lube oil consumption quite well. Only 50-56% of the total ash in the consumed oil ends up on the DPF.

Back pressure – ash accumulation behavior is explained. With soot, early ash accumulation prevents deep bed filtration, which increases back pressure. Then, loss of filtration area by ash causes pressure increase. Later, loss of hydraulic diameter causes rapid increase. Asymmetric cell geometry gives +30% ash capacity.
Regulations Differ by Region

Note the advantage given to diesel in Europe relative to NO\textsubscript{x}

This partially explains the clear difference in market share of diesel vehicles in these two regions

Source: Michael P. Walsh

<table>
<thead>
<tr>
<th></th>
<th>2005 Tier 2, MDPV*</th>
<th>2005 Tier 2, Bin 9*</th>
<th>US Tier 2 Bin 5</th>
<th>CA Lev2, ULEV</th>
<th>Euro 4</th>
<th>Euro 5**</th>
<th>Euro 6***</th>
<th>Japan ’05</th>
<th>Japan ‘09</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO\textsubscript{x} g/km</td>
<td>0.9</td>
<td>0.3</td>
<td>0.03</td>
<td>0.07</td>
<td>0.25</td>
<td>0.18</td>
<td>0.08</td>
<td>0.14/0.15</td>
<td>0.08</td>
</tr>
</tbody>
</table>

* MDPV Medium Duty Passenger Vehicles (>8,500 lb) must comply with Bin 5 standards beginning with 2009 model year
** Euro 5 standards (model years 2009/10+)
*** Euro 6 standards recently fixed (model years 2014/15+)
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