# Overview of Diesel Emissions Control Technologies Available to Underground Mining Industry

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## Diesel Emissions and Occupational Health Standards

- Gaseous emissions
  - **Carbon Dioxide ($CO_2$), ACGIH TLV-TWA is 5000 ppm**
  - **Carbon Monoxide (CO), ACGIH TLV-TWA is 50 ppm**
  - **Nitric Oxide (NO), ACGIH TLV-TWA is 25 ppm**
  - **Nitrogen dioxide ($NO_2$), ACGIH TLV-TWA is 3 ppm, ACGIH TLV-STEL is 5 ppm**
  - **NOTE: MSHA adopted 1973 ACGIH standards**
- Particulate emissions
  - **Total Carbon (TC) = Elemental Carbon (EC) + Organic Carbon (OC), (interim standard for U.S. underground M/NM mines is 400 µg/m$^3$ )**

## Controlling Emissions at the Source

- Well-maintained low emitting engines
- Alternative fuel formulations and fuel additives
- Aftertreatment technologies
  - Curtailment of gaseous emissions
  - Curtailment of particulate emissions
  - Combination of technologies



## Engines

- As of November 25, 1999 all diesel engines introduced in U.S. coal mines must be approved by MSHA [30 CFR Part 7 Subpart E]
  - List of MSHA approved engines (Category A and B) is available on: http://www.msha.gov/s&hinfo/deslreg/appeng.htm
  - Ventilation Rate and Particulate Index
  - Suppliers should be able to provide you with emissions data for certified models.
- Replace old technology with new technology
  - Alternative engines are only available in Category B

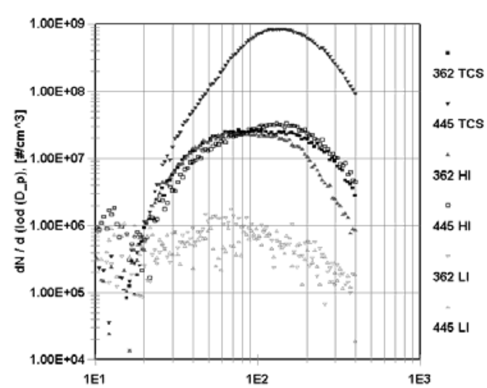
# Engine

- **Engine-out emissions control strategies**
  - Charge air cooling
  - Fuel injection pressure, patterns and multiple injection
  - Injection timing
  - Exhaust gas recirculation
  - Control of air-to-fuel ratio



# Engine Deration

- High altitude
- Ventilation requirements
- Example
  - engine rated at 325 hp
  - engine rated at 285 hp



## Engines

- System approach
  - Engine is integral part of the system:
    - vehicle/engine/aftertreatment
    - ventilation
    - duty cycle
    - economics…



## Fuel

- Fuel effects on DPM emissions
  - sulfur content:
    - Sulfates, $SO_2$ to $SO_3$ + $H_2O$ to $H_2SO_4$
    - < 500 ppm (avg. 350 ppm) sulfur
    - < 15 ppm by mid-2006 (EPA),
    - affects performance of catalyst based technologies
    - competing with NO for the $O_2$
  - cetane number
  - aromatic content

# Alternative Fuels

- **Biodiesel**
  - oxygenated fuel, virtually no sulfur
  - $NO_2$ issue
  - soy been oil, yellow grease, …
  - DEEP study (www.deep.org)
    - Blend with 58% of biodiesel, diesel oxidation catalyst
    - 43% increase in $N0_2$
    - 29% reduction in elemental carbon emissions
  - EPA : B20 reduce DPM by 10%, neat B100 by 47%
  - fuel economy penalty up to 11%
  - expensive
    - used primarily blended with regular diesel (B20, B50,…)
  - www.biodiesel.org



# Alternative Fuels

- **Synthetic diesel**
  - virtually no sulfur
  - low on aromatics
  - significant reductions in regulated emissions
    - Schaberg et al. [1997]
      - HC (49%), CO (33%), NOx (27%), PM (21%)
  - expensive and not readily available
- **Ultra low Sulfur Fuel (<15 ppm)**
  - Should be widely available by mid-2006

## Fuel Additives

- **Fuel additives**
  - Combustion enhancers
  - DPF regeneration aid
- Fuel additives used in U.S. underground mines should be approved by EPA
- **Secondary emissions**
  - Fuel with additives for stimulating filter regeneration should not be used in the engines that are not equipped with DPFs



## Aftertreatment Technologies

- Gaseous Emissions
  - Diesel Oxidation Catalytic Converters (DOC)
  - Control of Nitric Oxide ($NO_x$) Emissions
- Particulate Emissions
  - Diesel Particulate Filter (DPF) Systems
  - Disposable Diesel Particulate Filter Systems

## Diesel Oxidation Catalytic Converters (DOC)

- CO to $CO_2$
  - 70-90% reductions in CO
- Hydrocarbons to $CO_2$
  - 70% reduction in HC
- Reduce organic portion or soluble organic fraction (SOF) of DPM
  - 20-30 % reductions in total DPM



## Control of Nitric Oxide ($NO_x$) Emissions

- Selective catalyst reduction (SCR)
  - Up to 80% reduction
  - Relatively complex system
    - Urea injection
  - Commercially available for stationary systems
- Lean $NO_x$ traps (LNT)
  - 30-50 % reduction
  - Relatively complex system
    - Fuel injection
  - Not commercially available

# Diesel Particulate Filters (DPFs)

- Diesel Particulate Filters Systems (DPFs)
- Disposable Diesel Particulate Filter Systems



# Diesel Particulate Filters (DPFs) Media

- wall flow monoliths
- deep bed filters

## Diesel Particulate Filters (DPFs) Catalyst

- Non-Catalyzed DPF
  - no regeneration aid
- Catalyzed DPF
  - wash coat catalyst:
    - platinum, palladium, rhodium, vanadium, magnesium, strontium …
  - fuel borne catalyst:
    - platinum, cerium, iron, strontium, …



## Efficiency of DPF Systems

- DPM = Elemental Carbon + Organic Carbon+ Sulfates + Water + Ash
  - Composition is function of engine design, engine operating conditions, aftertreatment…
- DPFs are primarily designed for curtailment of DPM emissions. The effects on gaseous emissions depend on a catalyst formulation.

# Efficiency of DPF Systems

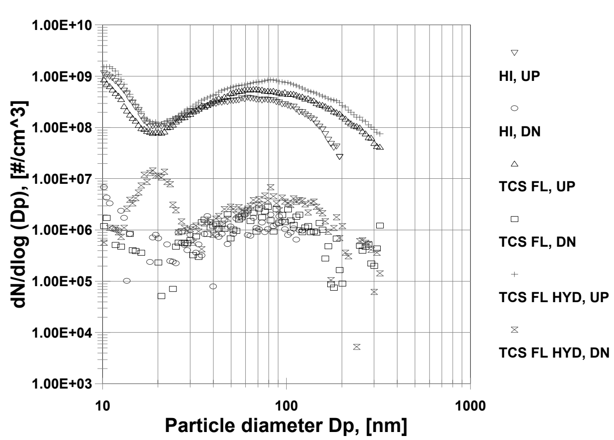
- **Mass**
  - Cordierite 85% (www.msha.gov)
  - Silicon carbide 87% (www.msha.gov)
  - VERT 90% (new), 85% (after 2000 hours)
- **Carbon**
  - Occupational standards based on total (U.S.) or elemental carbon (Germany, U.S. in future)
  - Over 95% on EC.



# Efficiency of DPF Systems

- **Number**
  - Potential for forming a large number of ultrafine and nanosize particles from semi-volatile hydrocarbons, sulfates, and ash
  - Potential for forming large number of transition metals particles when fuel additive are used
  - VERT 95% (new), 90% (after 2000 hours)
- **Surface area**
  - Ultrafine particles (<100 nm) have a very larger surface area per unit mass, bioavailability
  - Currently there is no standards
- **Chemical composition**
  - Transition metals
  - PAH

## Size Distribution of DPM in the Tailpipe of Engine Retrofitted With SiC DPF




Legend:

HI - rated speed no load

TCS FL -
  torque converter stall

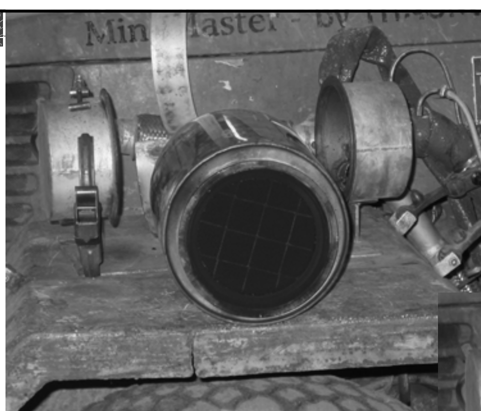
TCS FL HYD -
  torque converter stall and hydraulics engaged

UP - upstream

DN - downstream



## Filter Efficiency- Visual Inspection




## Secondary Emissions

- Filter effects on $NO_2$ emissions:
  - The filters washcoated with platinum based catalysts have tendency to increase $NO_2$ emissions. Function of:
    - catalyst formulation
    - exhaust temperatures
    - $NO_x$ to PM ratio
    - fuel sulfur content…
  - Wascoated base metal catalysts do not have tendency to increase $NO_2$ emissions.
  - The systems using fuel borne catalysts, even those that are based on platinum, were not found to increase significantly $NO_2$ emissions.



## Secondary Emissions

- nanoparticles:
  - Evident when fuels with higher sulfur content are used in the catalyzed systems,
  - when fuel borne catalysts are used to stimulate DPF regeneration…
- sulfates:
  - Remedy is ultra low sulfur fuel
- transitional metals:
  - The major source are fuel borne catalysts, engine wear, and lubricating oil. Avoid using fuel borne catalyst with engines that are not equipped with DPF system.
- dioxins, nitro-PAHs…

## DPF Systems Regeneration

**DPF Regeneration – burning off carbon collected in a filter media**

- Approximate minimum exhaust temperatures required to initiate regeneration process:
  - Non-catalyzed DPF – over 550 $^oC$
  - Base metal catalyst – over 390 $^oC$
  - Nobel metal catalyst – over 325 $^oC$
- 25-30% or more of a duty cycle an vehicle/engine should be operated at loads generating exhaust temperatures exceeding aforementioned regeneration temperatures.



## DPF Systems Regeneration

- Regeneration temperatures are function of:
  - Catalyst loading
  - Contact between catalyst and carbon
  - $NO_x$/PM ratio in the exhaust…
- Regarding the regeneration concept DPF systems can classified as
  - **Passive**
  - **Active**

# DPF Systems - Passive Regeneration

- The exhaust gas temperatures are favorable and a DPF is regenerated during a duty cycle.
- The regeneration is enhanced by catalyzing filter media.
- Establishing exhaust temperature profile crucial for success of selection process.
- Engine idling should be minimized.



# DPF Systems Active Regeneration

- Accumulated DPM is removed using external source of energy (electrical heaters and fuel burners)
- ON-BOARD: A heating element or fuel burner is on-board of a vehicle. In the case of electrical systems regenerations station with power and compressed air supply is off-board of a vehicle:
  - no need to remove filter
  - suitable for most engines and applications
  - downtime associated with regeneration (electrical)
  - regeneration station requirements (electrical)
    - space, power, compressed air
  - higher maintenance requirements for electrical systems mostly associated with electrical heaters.
  - regeneration intervals can be extended with use of catalyst in the system…

## DPF Systems
## Active Regeneration

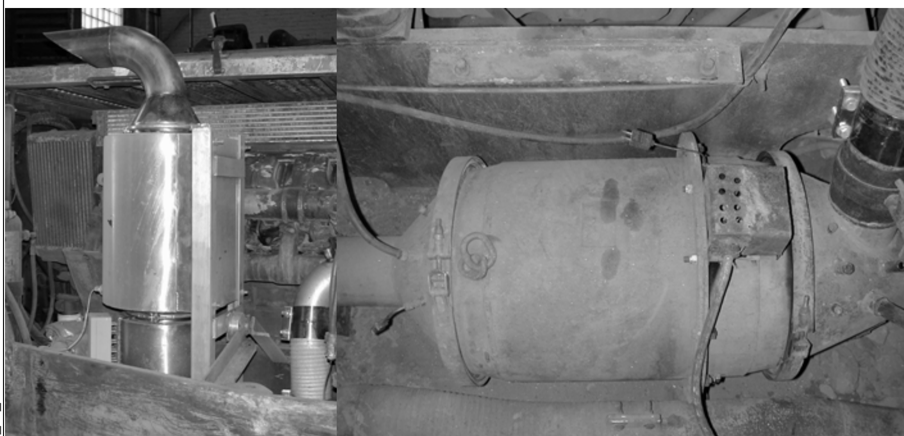
- OFF-BOARD (ELECTRICAL SYSTEMS): heating element is integral part of off-board regenerations station.
  - require removal of the filter from the system
    - suitable for smaller units
    - risk associated with handling the units
    - costs associated with replacement of the gaskets
    - downtime for swapping filter elements
  - problem of maintaining integrity of the system
  - regeneration station requirements



## DPF Systems
## Active Regeneration

- Filter should be sized to accumulate DPM between two active regenerations.
  - Engine PM emissions over selected test cycles are available from engine certification process!!!
- Media has to be compatible with selected regeneration scheme
  - Silicon carbide for express regeneration
  - Cordierite for slow regeneration

# DPF Systems
# Electrical On-board Regeneration





# DPF Systems
# Passive vs. Active Regeneration

- Passive DPFs
  - low operational requirements
  - low maintenance requirements
  - relatively inexpensive, depending on catalyst formulation
  - regeneration depend on exhaust heat!!!
  - potential for increase in $NO_2$, sulfates emissions

## DPF Systems
## Passive vs. Active Regeneration

- Active DPFs
  - regeneration does not depend on exhaust heat
  - no effects on secondary emissions
  - require changes in way vehicles are operated
  - higher maintenance requirements
  - require change in operator's attitude
  - relatively expensive



## DPF Systems Operational Issues
## Ash Accumulation

- Ash originates from fuel, lubricating oil, engine wear or fuel additives.
  - up to 1% of DPM
- Ash can not be regenerated as carbon. Accumulation of the ash in the filter results in continuous increase in base backpressure.
- Periodic cleaning of the filter is required, usually every 1000-2000 hours.

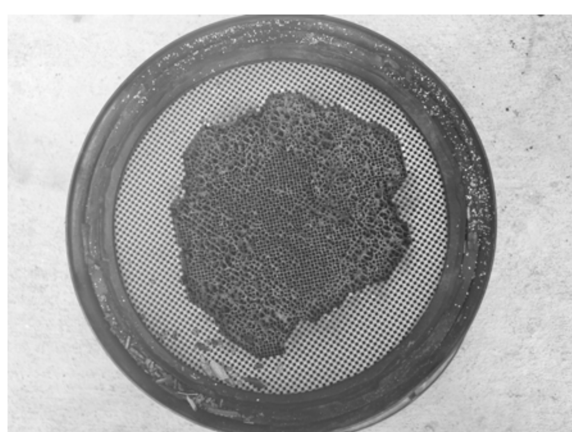
# DPF Systems Backpressure Monitoring

- Sizing of the system is critical
  - Engine backpressure – engine limitations
    - Caterpillar 3306 PCNA - 34 in $H_20$
    - DDEC Series 60 – 42 in $H_20$
- Reliable backpressure monitoring and logging capabilities are essential for performance of the filtration system.
- Pressure gage and alarm should be included in the filtration system.



# DPF Systems – Uncontrolled Regeneration

- Thermal meltdown as result of uncontrolled regeneration



# Selection of DPF Strategy

- **Ultimate goal is to reduce exposure of the miners to harmful gases and particulate matter**
  - Production vehicles (heavy-duty)
  - Support vehicles (light-duty)
- **DPF is integral part of the vehicle/engine/filter system**
  - Maintenance
    - Significant lube oil consumption jeopardizes filter performance and life. Filter can not substitute maintenance.
  - Right size of the engine for the application



# Selection of DPF Strategy

- List of the diesel particulate filter systems end disposable elements: http://www.msha.gov/01-995/Coal/DPM-FilterEfflist.pdf
- Underground mining applications require additional considerations:
  - confined space;
  - no sunlight;
  - occupational exposure limits;
  - application specific duty cycles;
  - different set of the mind.
- Uniqueness vs. “one size fits all”

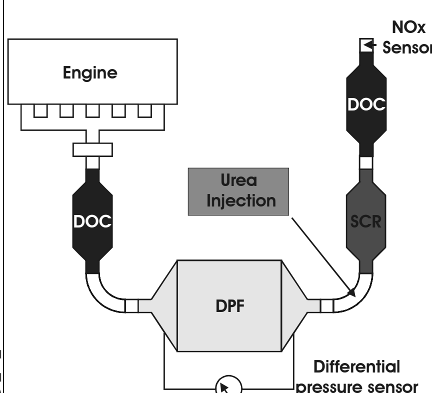
# DPF systems Considerations

- Integrity of a filtration system from an engine to the end of a tailpipe is crucial for reducing concentrations of DPM in mine air.
- Filter crankcase breather emissions
  - Closed crankcase filtration system
- The exhaust pipe insulation should reduce heat loss and increase possibility for passive regeneration. Insulation should to be removable so integrity of a system can be periodically inspected.

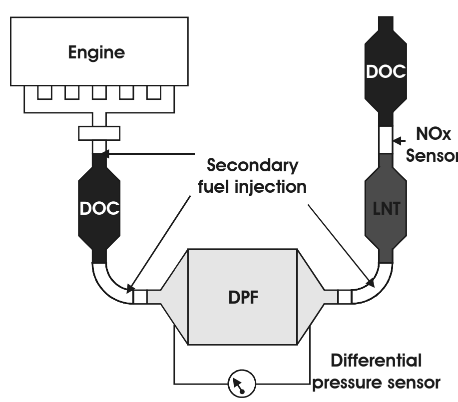


# Combination of technologies

- DOC + DPF + SCR




- DOC + DPF + LNT



# Questions

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