Exhaust Aftertreatment Technologies for Curtailment of Diesel Particulate Matter and Gaseous Emissions

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Exhaust Aftertreatment Technologies for Curtailment of Diesel Particulate Matter and Gaseous Emissions

- Diesel particulate matter (DPM), total carbon (TC), and elemental carbon (EC):
  - Diesel particulate filter (DPF) systems;
  - Filtration systems (FS) with disposable filter elements (DPEs);
  - Flow through filter (FTF) systems.

- CO and hydrocarbons:
  - Diesel oxidation catalytic converters (DOC).

- NO and NO_2:
  - Selective catalytic reduction (SCR) systems;
  - Lean NO_x catalyst.

- Exhaust aftertreatment systems integrated with engine systems.

Implementation of retrofit aftertreatment technologies is perceived as important tool in reducing exposures in underground mines.

- **Current Trends (DOC OEM and DPFs retrofit)**
  - Diesel oxidation catalytic converters (DOCs) for CO and HC;
  - Flow trough filter (FTF) systems;
  - Diesel particulate filter (DPF) systems;
  - Filtration systems (FS) with disposable filter elements (DFE).
- **Future Trends (OEM and retrofit)**
  - DOC;
  - DPF or FTF systems;
  - Selective catalyst reduction (SCR).
  - Integrated engine/exhaust aftertretament systems

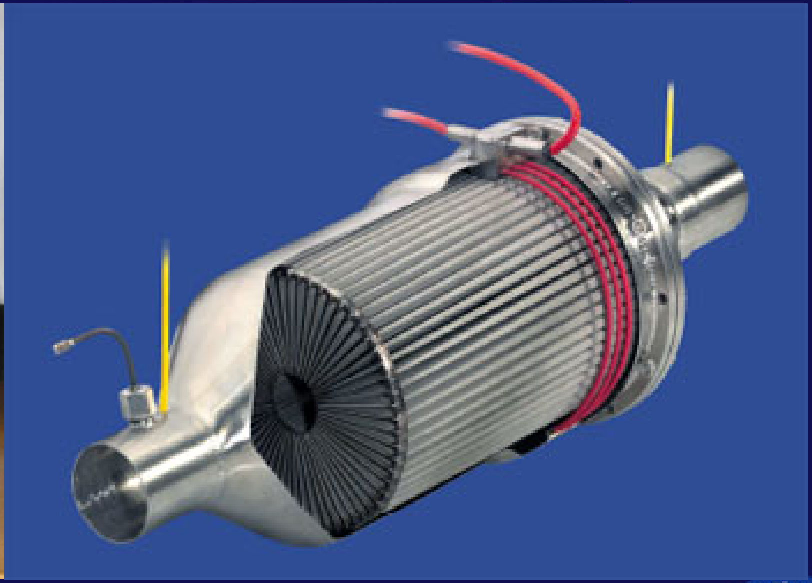
Diesel Particulate Filter (DPF) Systems

- **Design:**
  - Filtration media;
  - Catalyst;
  - Regeneration.
- **Performance:**
  - Effects on particulate emissions;
  - Effects on gaseous emissions.
- **Implementation:**
  - Selection;
  - Installation;
  - Maintenance.

Diesel Particulate Filters (DPFs) Filtration Media

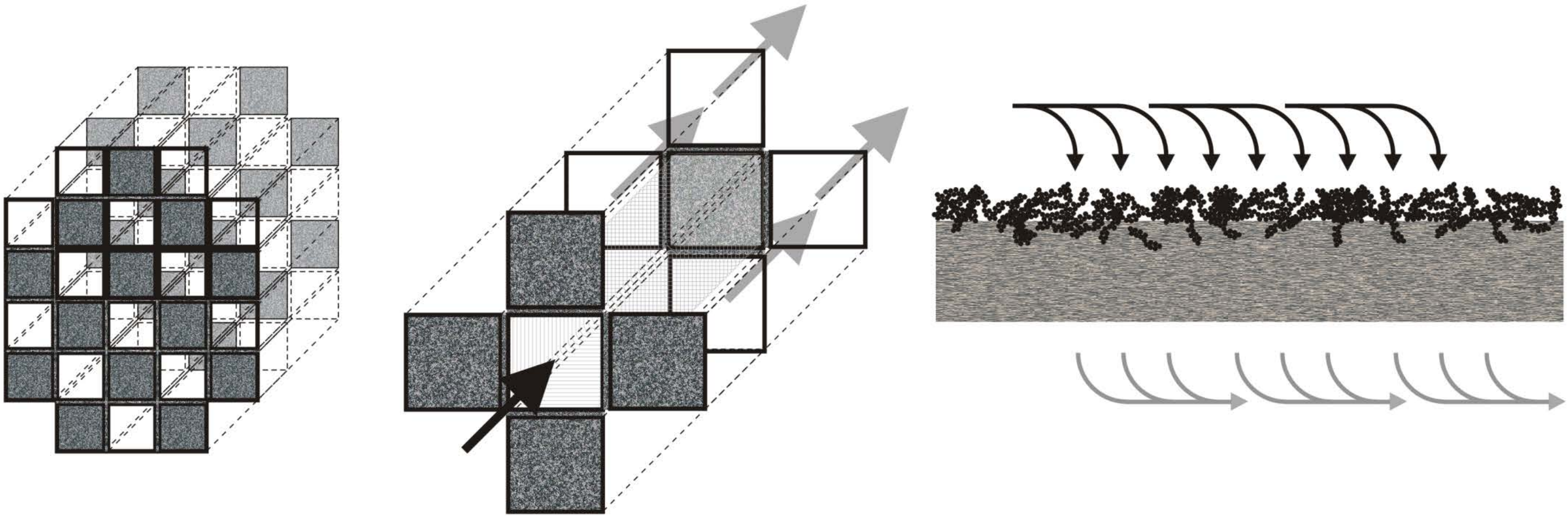
- wall flow monoliths (honeycomb)
  - Cordierite ($2MgO-2Al_2O_3-5SiO_2$);
  - Silicon carbide (SiC).

- sintered metal elements



silicon carbide   cordierite   sintered metal

Wall Flow Monolith DPF



- DPFs are primarily designed to reduce PM emissions.
- DPM cake improves filtration efficiency.

Diesel Particulate Filters (DPFs)
Catalyst

- Non-catalyzed DPF systems
- Catalyzed DPF systems
  - washcoated (Al_2O_3, SiO_2, CeO_2, TiO_2, ZrO_2, V_2O_5, La_2O_3 and zeolites) or impregnated with catalyst:
    - noble metals (platinum, palladium, rhodium)
    - base metals (vanadium, iron, cerium…)
  - fuel borne catalyst (FBC):
    - platinum, platinum-cerium, cerium, cerium-iron, iron, iron-strontium…

DPF Systems
Regeneration

- DPF regeneration – burning off carbon collected in a filter media:
  - oxidation by O_2;
  - oxidation by NO_2.
- Approximate minimum exhaust temperatures required to initiate regeneration process (O_2):
  - Non-catalyzed DPF – over 600 ^oC;
  - Base metal catalyst – over 390 ^oC;
  - Nobel metal catalyst – over 325 ^oC;
  - Continuously regenerated trap (CRT) type systems – over 250 ^oC.
- 25-30% or more of a vehicle/engine duty cycle should generate exhaust temperatures that exceed the regeneration temperatures shown above.

DPF Systems Regeneration

- Regeneration temperatures are function of:
  - Catalyst presence, formulation, and loading;
  - Contact between catalyst and DPM;
  - Type of the DPM;
  - NO_x/PM ratio in the exhaust.

- DPF regeneration systems are classified as:
  - **Passive;**
  - **Active**.

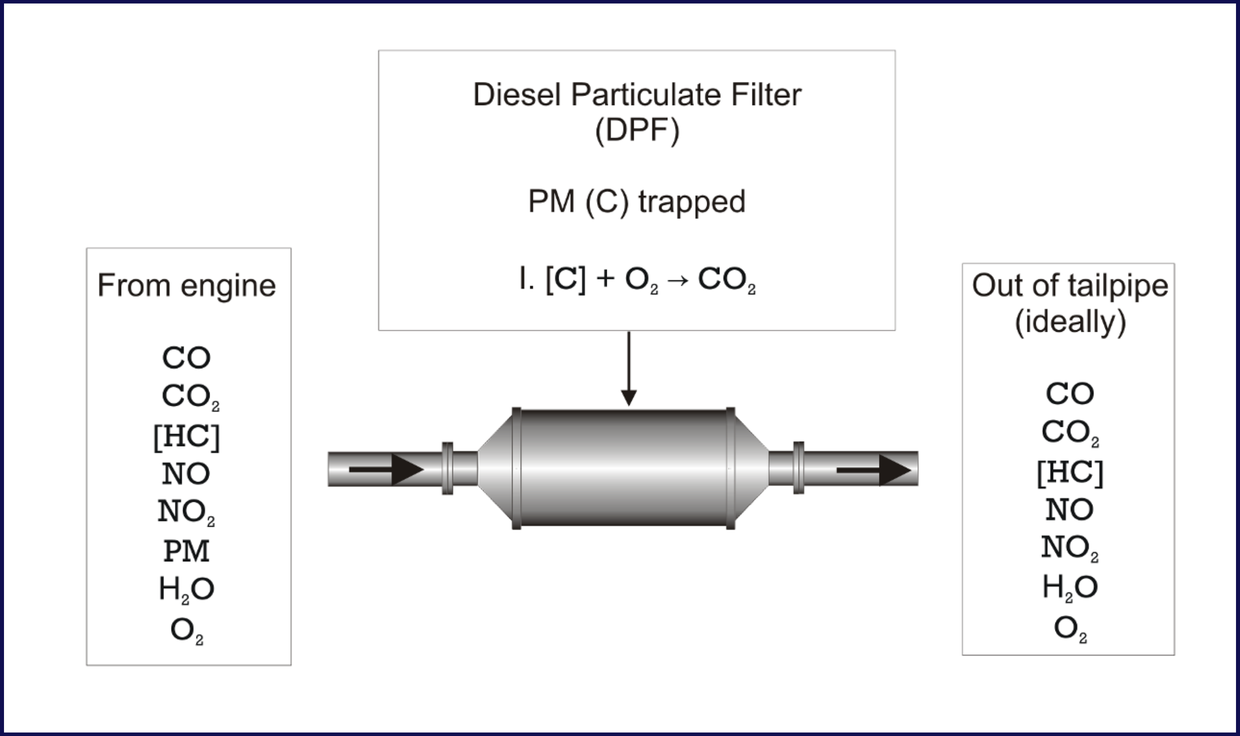
DPF Systems
Passive Regeneration

- The exhaust gas temperatures are favorable for regeneration of the DPF type and the process takes place during a duty cycle.
- The regeneration is typically supported by imbedded catalyst, use of fuel-borne catalyst, or fuel injection.
- 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:
  - On-board of vehicle
    - Electrical heater:
      - power and compressed air supply is on-board the vehicle;
      - power and compressed air supply is off-board the vehicle.
    - Fuel burner;
    - Fuel injection + DOC or catalyzed DPF.
  - Off-board of vehicle
    - electrical heaters.

Uncatalyzed DPF

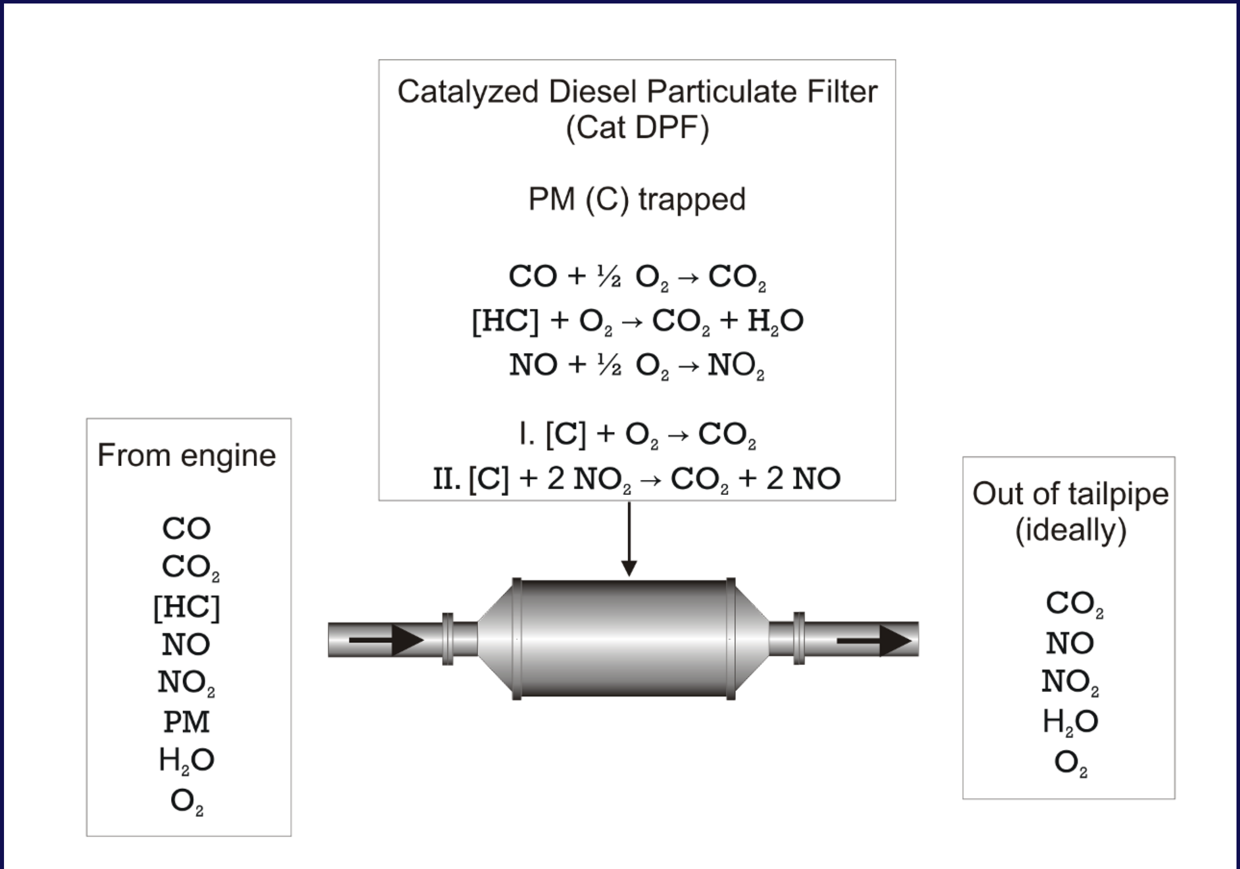


Regeneration temperature:

- > ~ 600 ºC

- Uncatalyzed DPFs reduce PM emissions.
- Uncatalyzed DPF has minor effects on gaseous emissions.

Catalyzed DPF

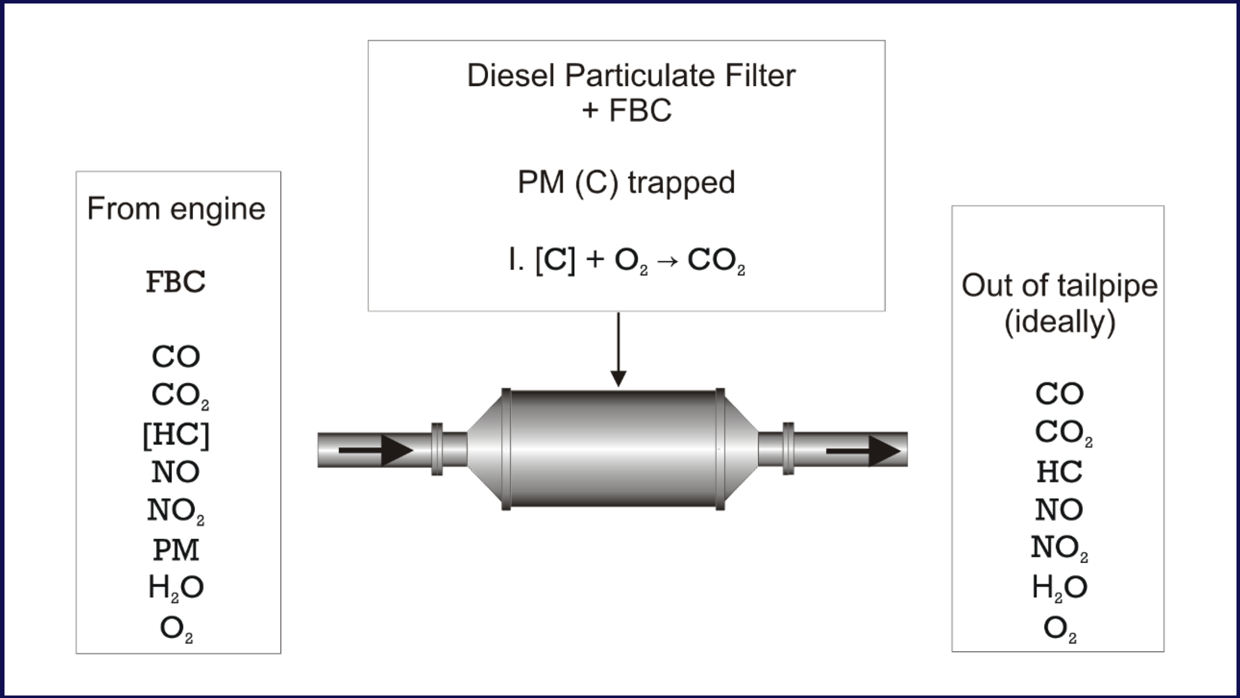


Regeneration temperatures:

- Nobel metal catalysts:
- >~ 325 ºC
- base metals catalyst
- >~ 390 ºC

- Pt catalyzed DPFs reduce PM, CO, HC emissions.
- Base metal catalyzed DPFs reduce primarily PM.
- Secondary NO_2 emissions are issue with Pt catalyzed DPFs.
- Base metal catalyzed DPFs do not tend to produce secondary NO_2 emissions.

DPF Regenerated with Help of Fuel Borne Catalyst (FBC)

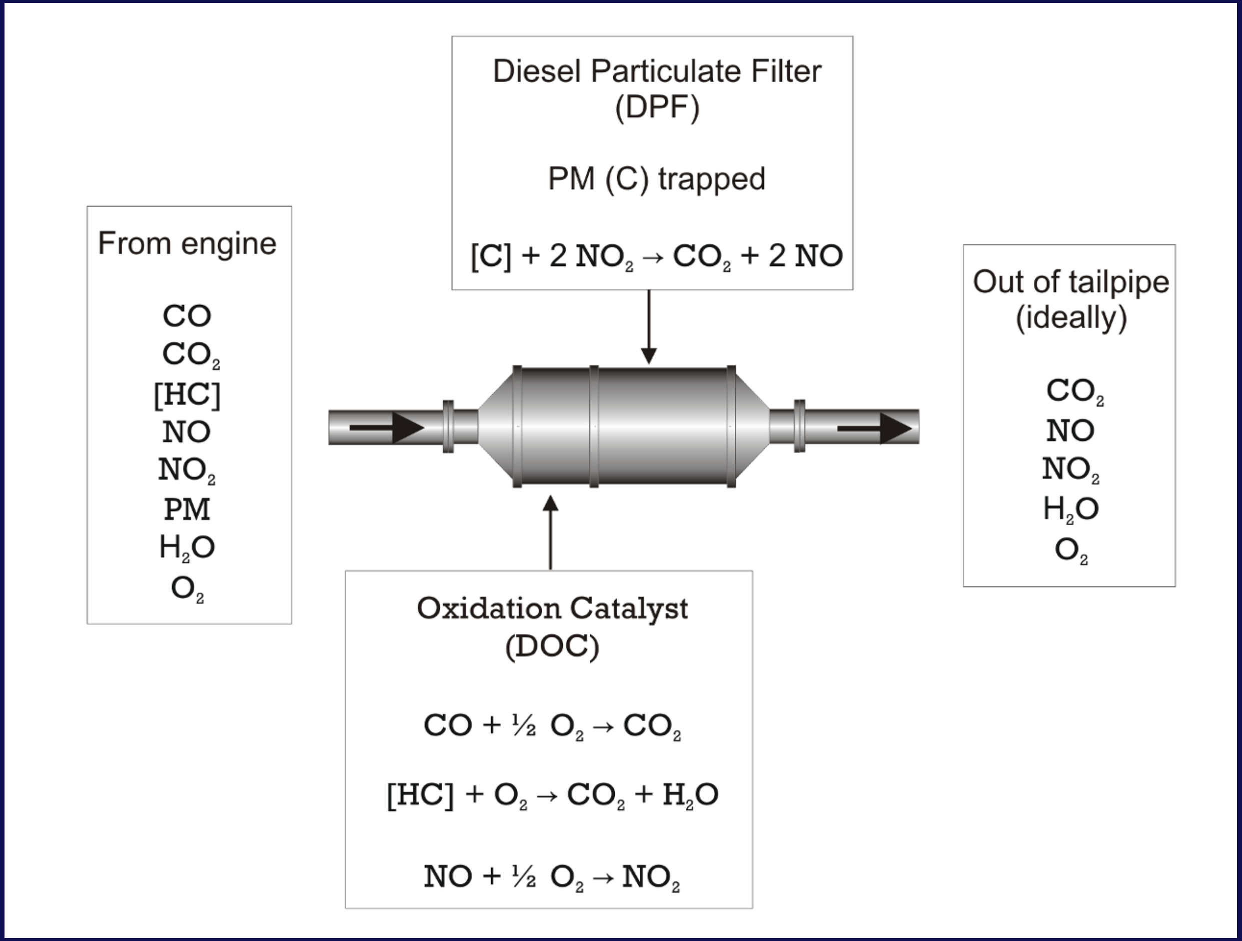


Regeneration temperature:

- Pt/Ce
- >~ 325 ºC

- More intimate contact between catalyst and DPM.
- Secondary NO_2 emissions are not issue with FBC.
- FBC doped fuel should not be used in the vehicles that are not equipped with DPFs.
- Larger amount of ash deposition in DPF.

Continuosly Regenerated Trap (CRT): DOC followed by DPF

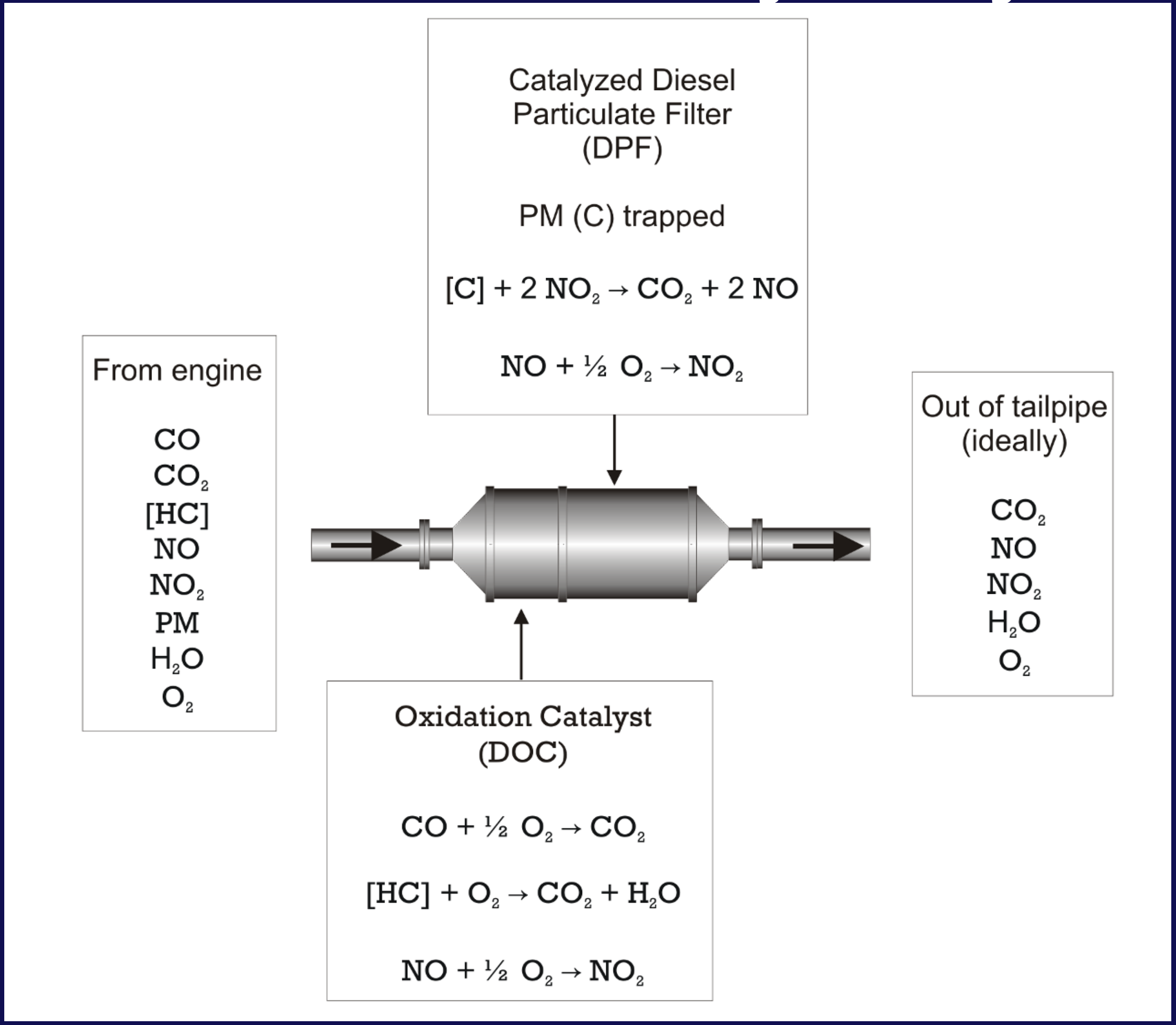


Regeneration temperature:

- > ~ 250 ºC

- Oxidation by NO_2.
- CRT system reduces PM, CO, HC emissions.
- Secondary NO_2 emissions are major issue with CRT systems.

Catalyzed Continuosly Regenerated Trap (CCRT): DOC Followed by Catalyzed DPF

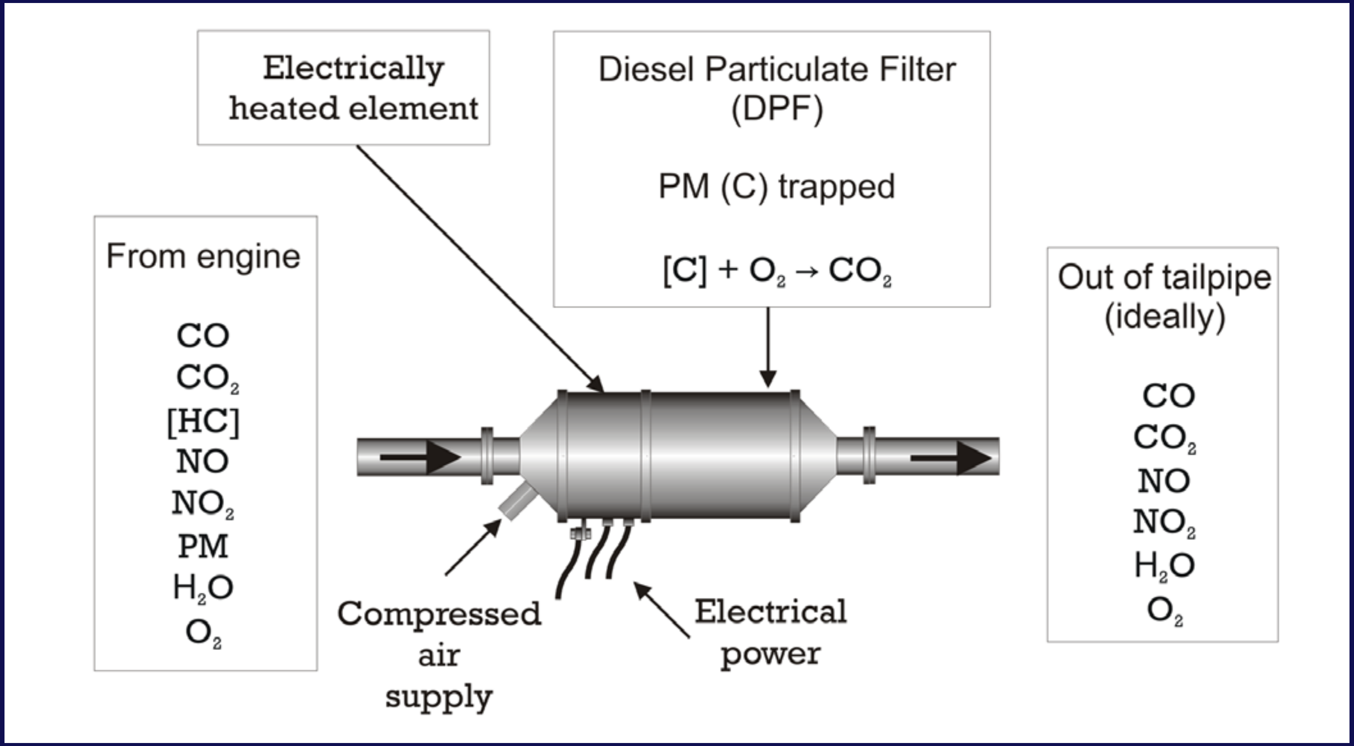


Regeneration temperature:

- >~ 200 ºC

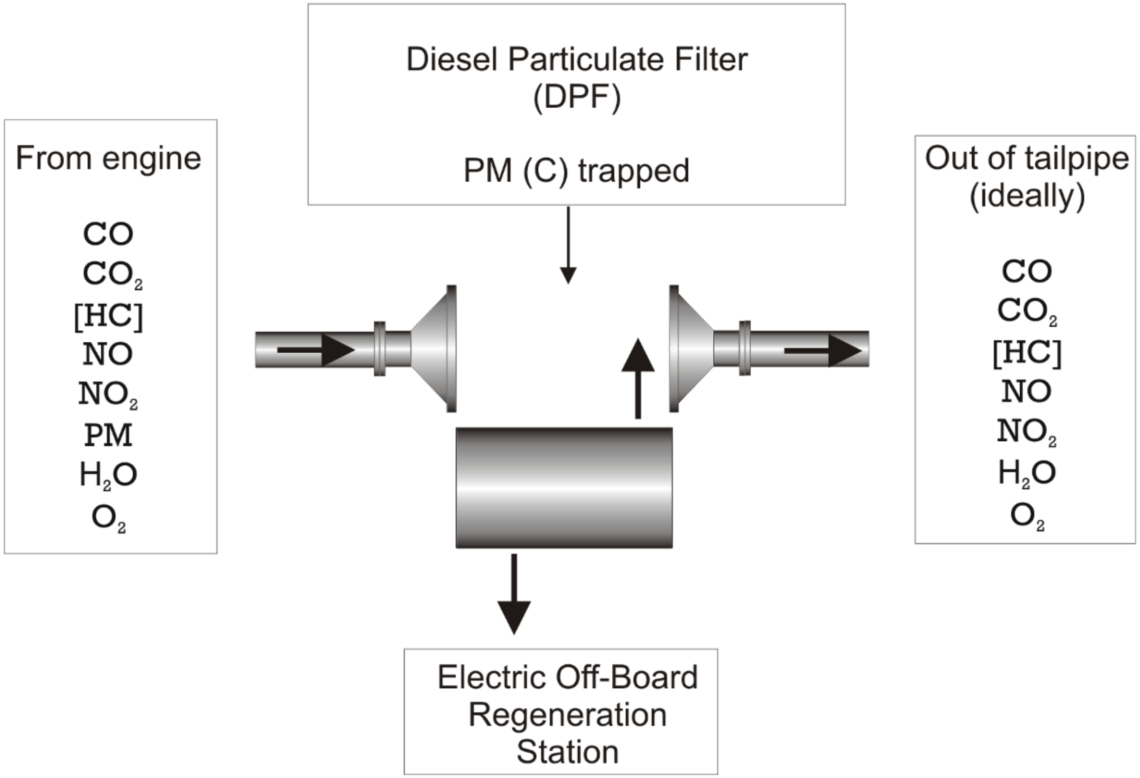
- CCRT has lower regeneration temperature threshold.
- Secondary NO_2 emissions are major issue with CCRT systems.

Electrically Regenerated DPF (on-board)



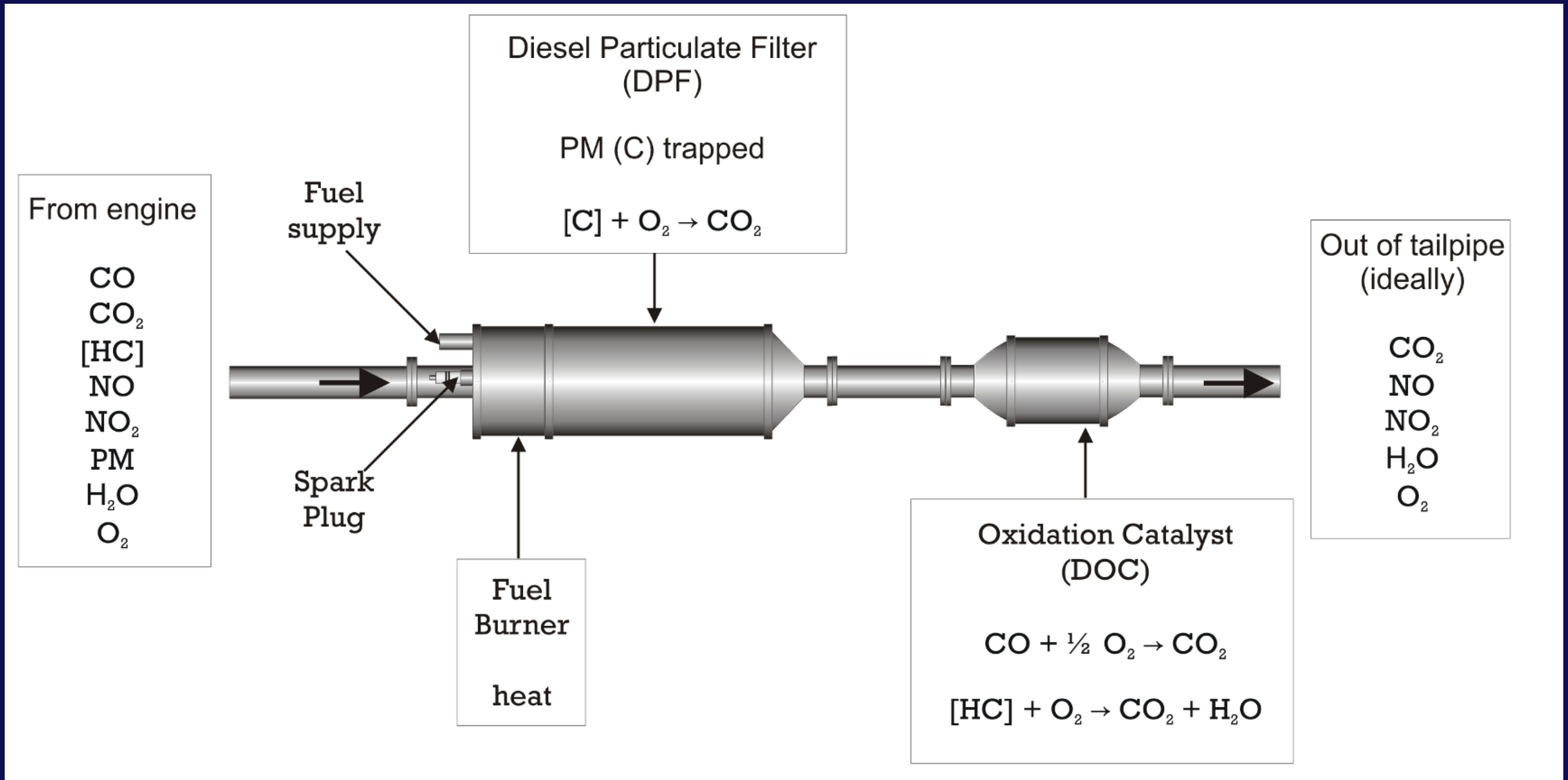
- Uncatalyzed DPF system reduces PM emissions.
- Secondary NO_2 emissions are not an issue with uncatalyzed DPFs systems.
- Source of power and compressed air:
  - On-board the vehicle;
  - Off-board the vehicle.

Electrically Regenerated DPF (off-board)



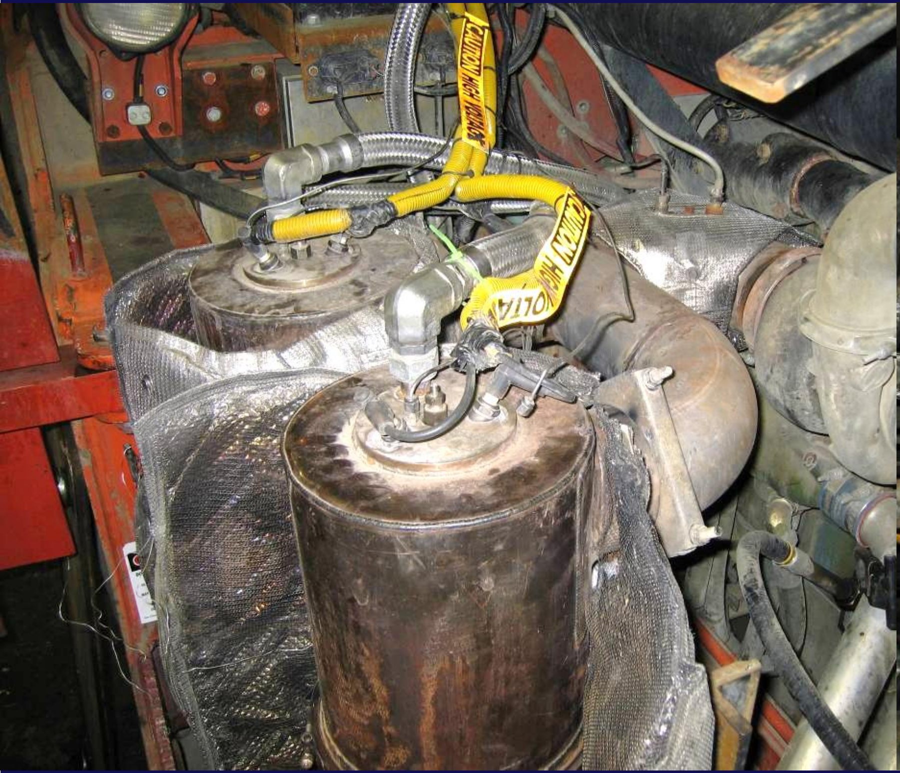
- Require removal of the filter from the system:
  - suitable for smaller units;
  - integrity of the system (the gaskets need to be replaced);
  - downtime for swapping filter elements.

DPF Regenerated with Help of Diesel Fuel Burner

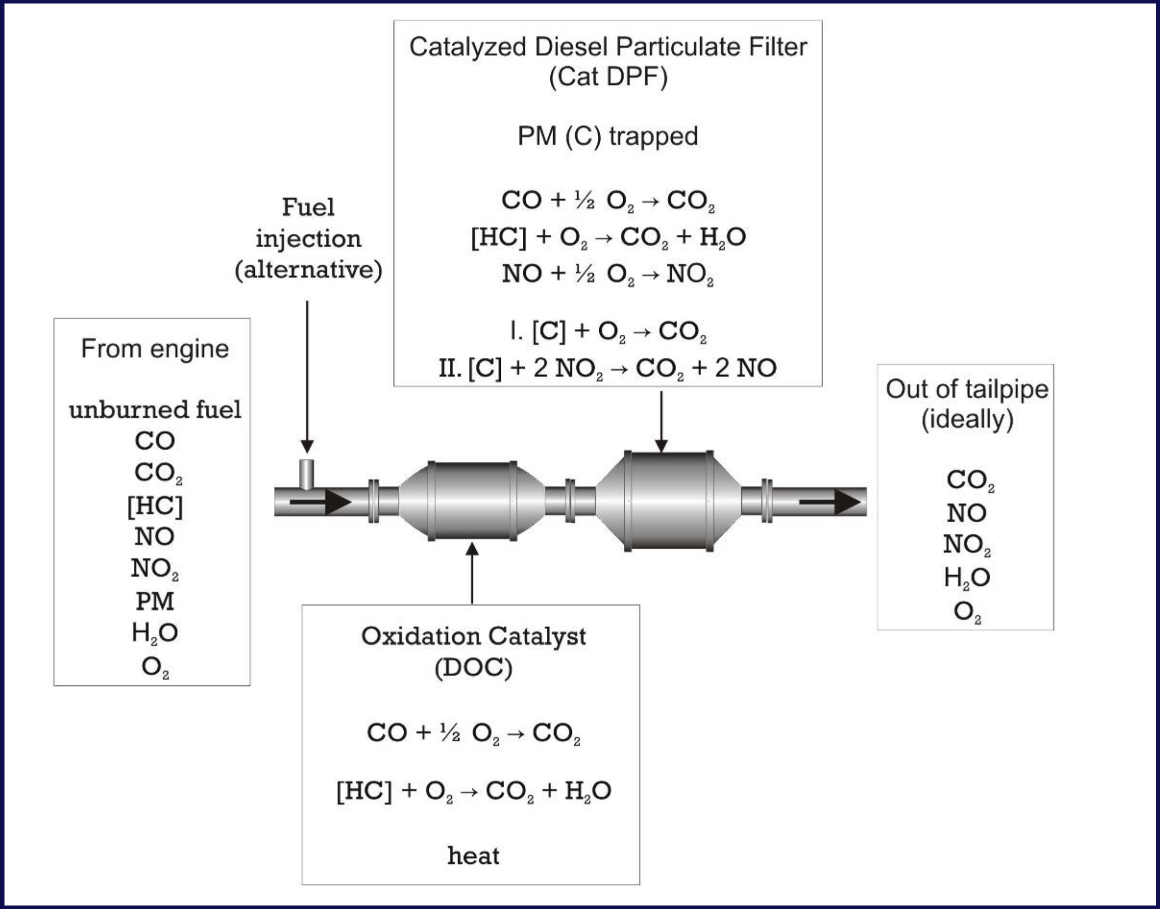


- Uncatalyzed DPF system reduces PM emissions.
- DOC is used to control CO and HC emissions during the regeneration.
- Secondary NO_2 emissions might be an issue with the systems that use DOC.
- Complexity and fuel penalty are major issues.

DPF System with Diesel Fuel Burner



DPF Regenerated with Help of Late Fuel Injection and Catalytic Combustion



- Common-rail fuel injection system is used to inject fuel in the late stage of compression and into expansion stroke.
- Catalytic combustion is used to increase exhaust temperature to app. 450 ºC.

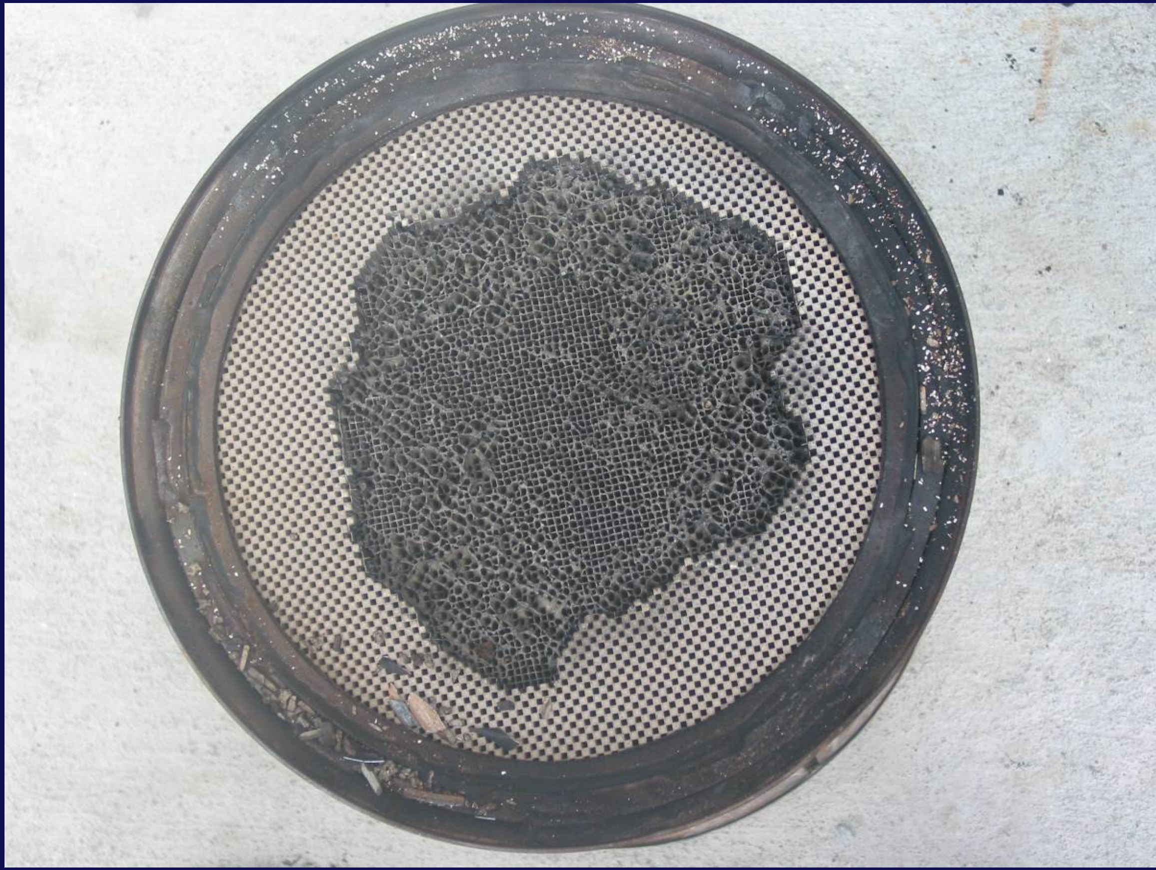
DPF Systems
Passive vs. Active Regeneration

- Passive DPF systems
  - 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.

- Active DPF systems
  - regeneration does not or is less dependent 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 – Uncontrolled Regeneration

- Thermal meltdown as result of uncontrolled regeneration.



Effects of DPF Systems and DFEs on DPM Emissions Verifications/Certifications

MSHA Verification (http://www.msha.gov/01-995/Coal/DPM-FilterEfflist.pdf):

Filtration System	Efficiency (TDPM)
Cordierite DPF	85%
Silicon carbide DPF	87%
Sintered metal DPF	81, 99%
DFE	80-83%

Effects of DPF Systems and DFEs on DPM Emissions Verifications/Certifications

VERT Filter List

(www.dieselnet.com/tech/text/ch_filterliste.pdf)

Filtration Rate	New	After 2000 hours
Solid Particle Count (20-300 nm)	> 95%	> 95%
EC mass conc.	> 90%	> 90%

CARB Verification

(http://www.arb.ca.gov/diesel/verdev/vt/vt.htm)

Reduction	Classification
< 25%	Not verified
> 25%	Level 1
> 50%	Level 2
> 85%, or < 0.01 g/bhp-hr	Level 3

Field Evaluations

DEEP

(http://www.deep.org/research.html)

- Field evaluation of diesel particulate filter systems in an underground mine – INCO;
- Field evaluation of diesel filter systems in an underground mine - Noranda Technology Centre.

NIOSH (http://www.cdc.gov/niosh/mining/pubs/

programareapubs8.htm

- Effectiveness of Selected Diesel Particulate Matter Control Technologies for Underground Mining Applications:
  - Isolated Zone Study, 2003;
  - Isolated Zone Study, 2004.

Laboratory Evaluations in Underground Environment

NIOSH Lake Lynn Laboratory Evaluations

- Laboratory evaluation of exhaust aftertreatment systems in an underground mine.

Secondary emissions of NO_2 have been major road block for implementation of passive DPF systems in underground mines.

- Effects of the aftertreatment system on NO_2 emissions is function of:
  - catalyst formulation and loading;
  - exhaust temperatures;
  - NO_x to PM ratio in the engine-out exhaust;
  - amount of soot in DPF system;
  - fuel sulfur content.

- Several studies showed that the systems with platinum based wash-coated catalysts promote NO to NO_2 conversion at the temperatures needed for DPF regeneration.

- Some DOC formulations tend to produce secondary NO_2 emissions.

The concern over NO_2 "slip" influenced selection of regeneration strategy for DPF systems for coal mining applications.

- MSHA advises against using platinum catalyzed passive DPF system in underground coal mines due to potential for increase in NO_2 emissions (PIB02-04).

- The popular choices of DPF systems in coal mining:
  - Passive systems regenerated with help of platinum/cerium fuel born catalyst;
  - Passive systems with wash-coated base metal catalyst;
  - Passive systems with wash-coated NO_2 suppressing catalyst;
  - Active systems with on-board electrical regeneration;
  - Active systems with off-board electrical regeneration.

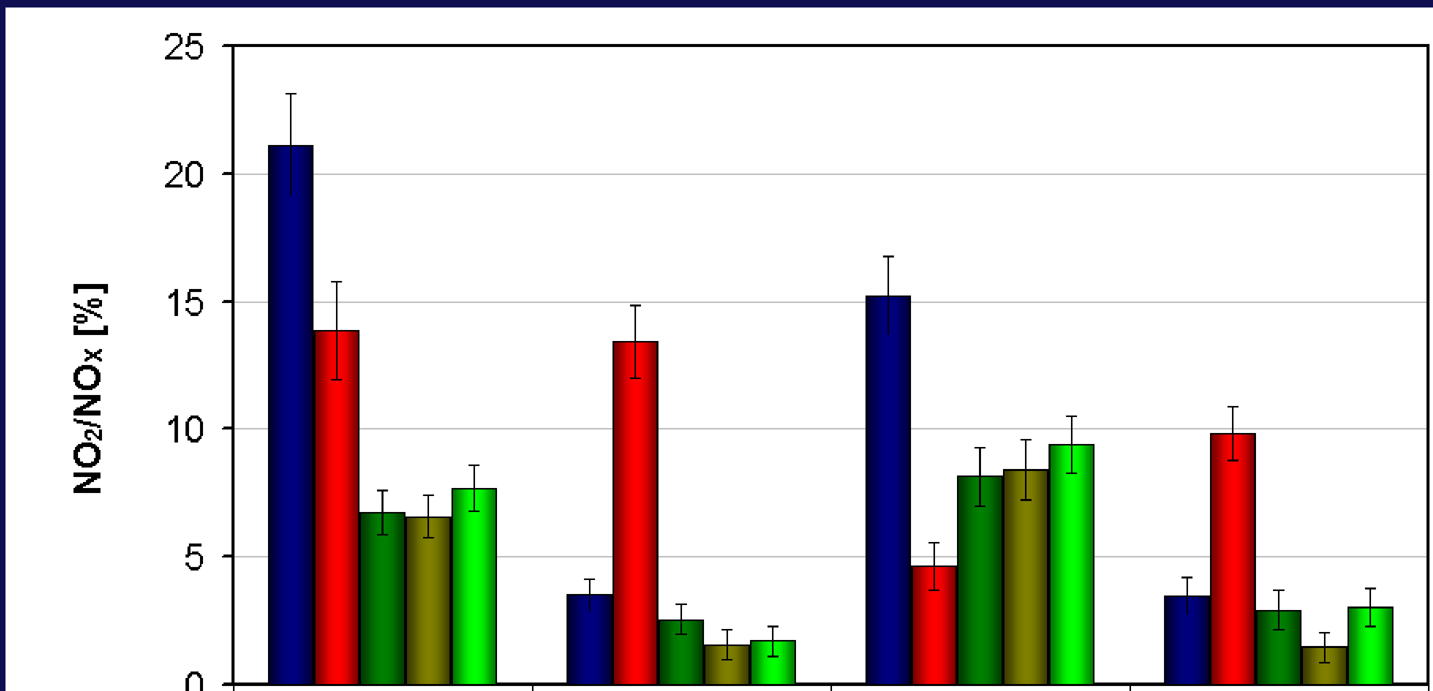
Not all catalyzed DPF systems promote NO to NO_2 conversion.

- Base metal wash-coated catalysts do not exhibit 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.
- The reaction between NO_2 and DPM in uncatalyzed filters may result is slight reduction in overall NO_2 concentrations.
- New formulations with NO_2 suppressant are marketed for underground mining industry.

Effects of aftertreatment technologies on fraction of NO_2 in NO_X were found to be dependent on engine operating conditions (exhaust temperature).

In the majority of cases, DPFs and DFEs decreased NO_2 fraction in NO_X.

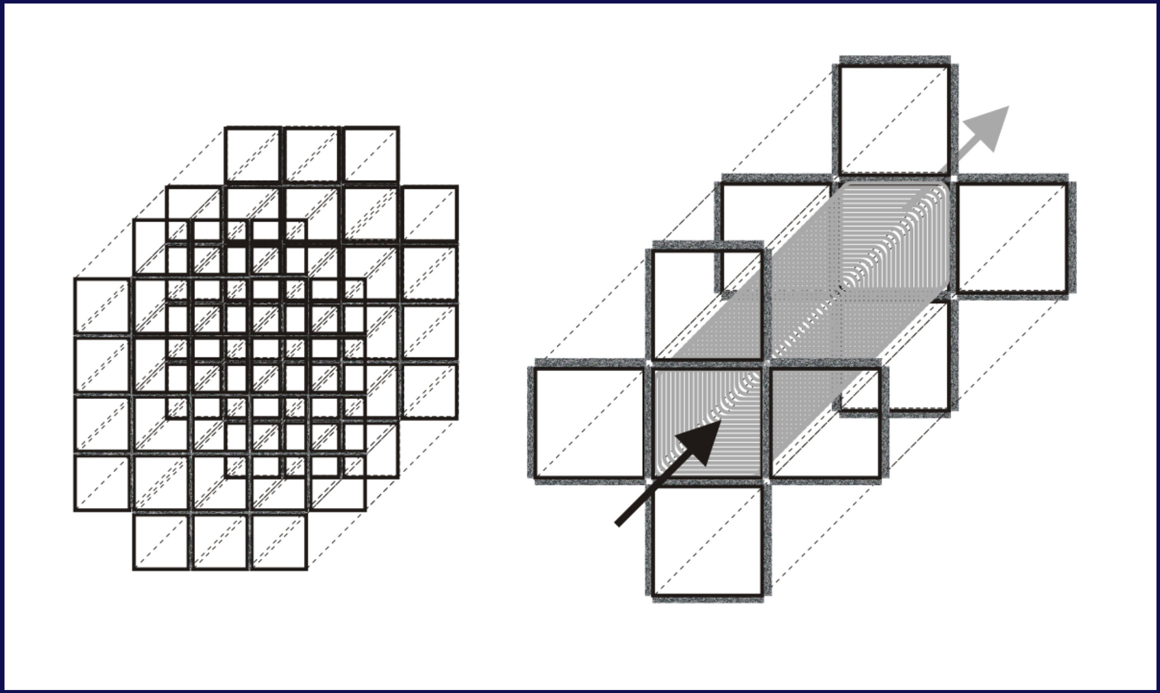
The DOC decreased NO_2 fraction in NO_X for the light-load conditions, but increased NO_2 fraction in NO_X for the heavy-load conditions.



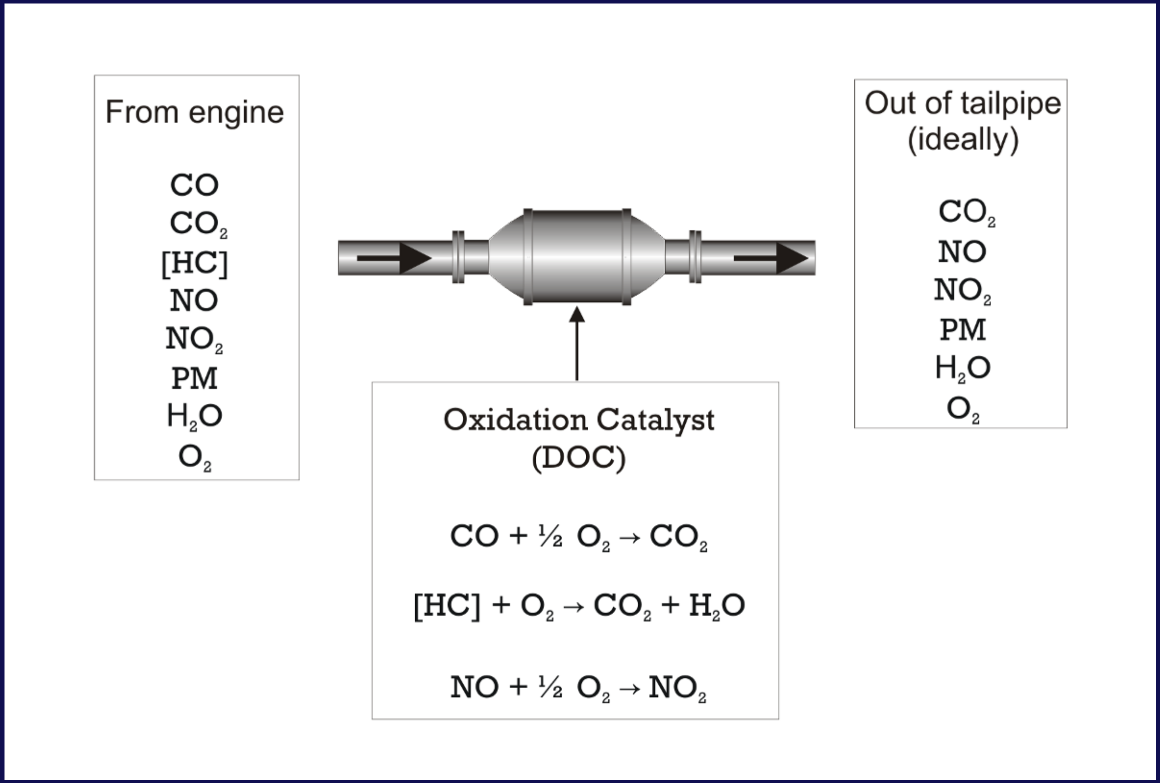
	M1	M2	M3	M4
Muffler	21.1	3.5	15.2	3.5
DOC	13.9	13.4	4.6	9.8
C DPF	6.7	2.6	8.1	2.9
SiC DPF	6.6	1.6	8.4	1.5
SM DPF	7.7	1.7	9.4	3.0

Diesel Oxidation Catalyst (DOC)

- Substrate (flow-through)
  - ceramic monolith honeycomb (Cordierite, $2MgO\text{-}2Al_2O_3\text{-}5SiO_2$);
  - Metal honeycomb (Fe-Cr-Al).
- Washcoat (Al_2O_3, SiO_2, CeO_2, TiO_2, ZrO_2, V_2O_5, La_2O_3 and zeolites) containing catalyst:
  - Platinum (Pt);
  - Palladium (Pl).

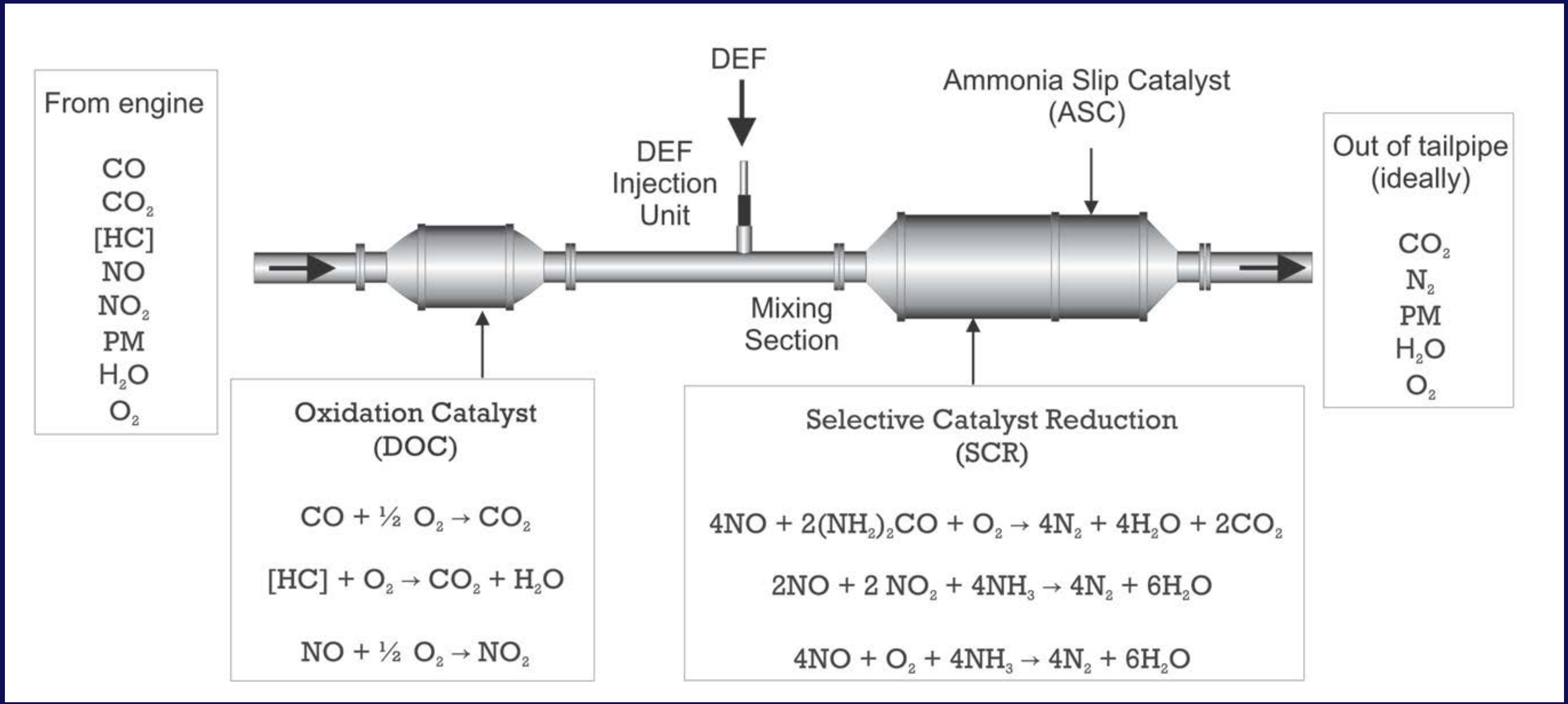


Diesel Oxidation Catalyst (DOC)



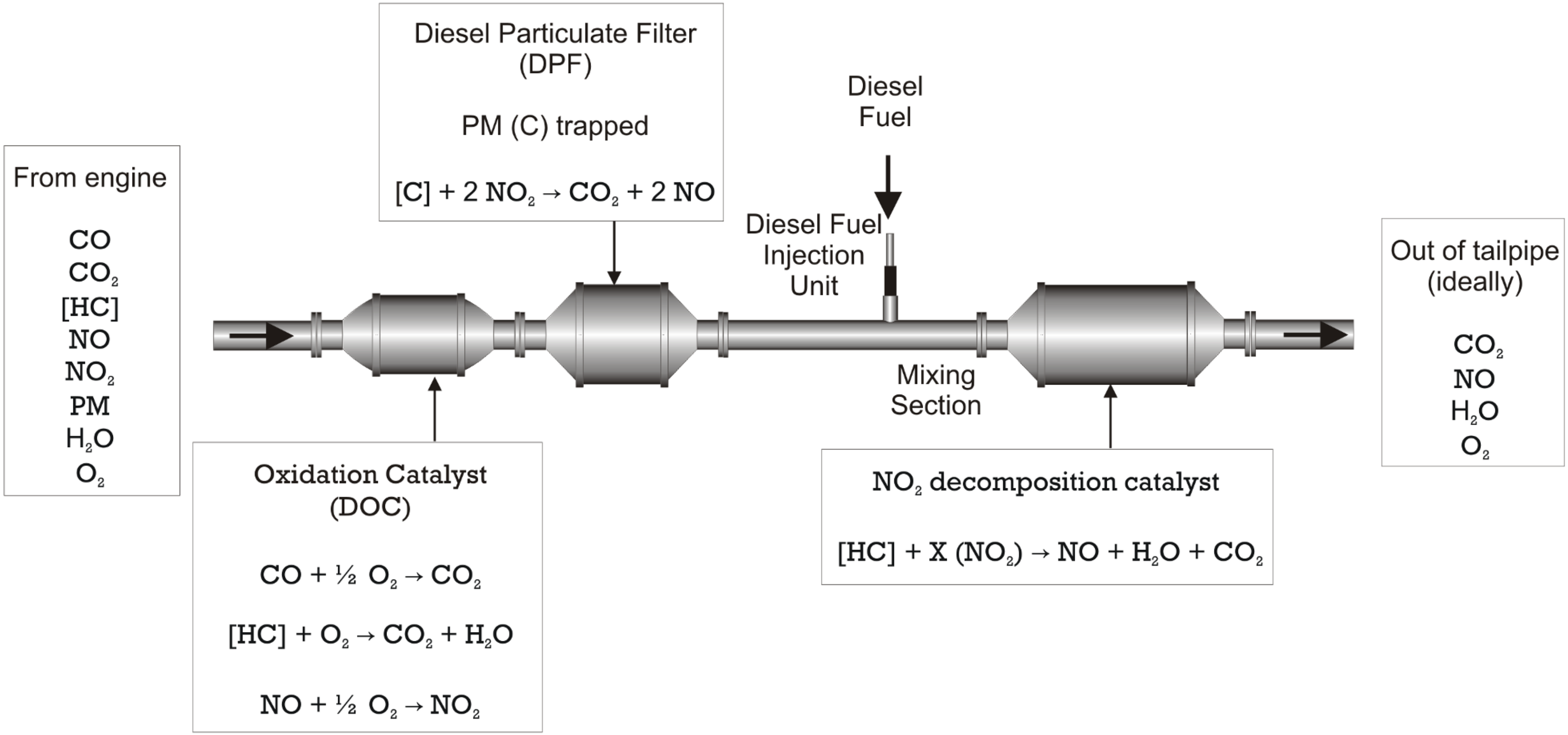
- DOCs are primarily designed to reduce CO and HC emissions.
- DOCs can reduce organic fractions of PM.
- Unwanted reaction might be one producing NO_2.

Selective Catalytic Reduction (SCR) Systems



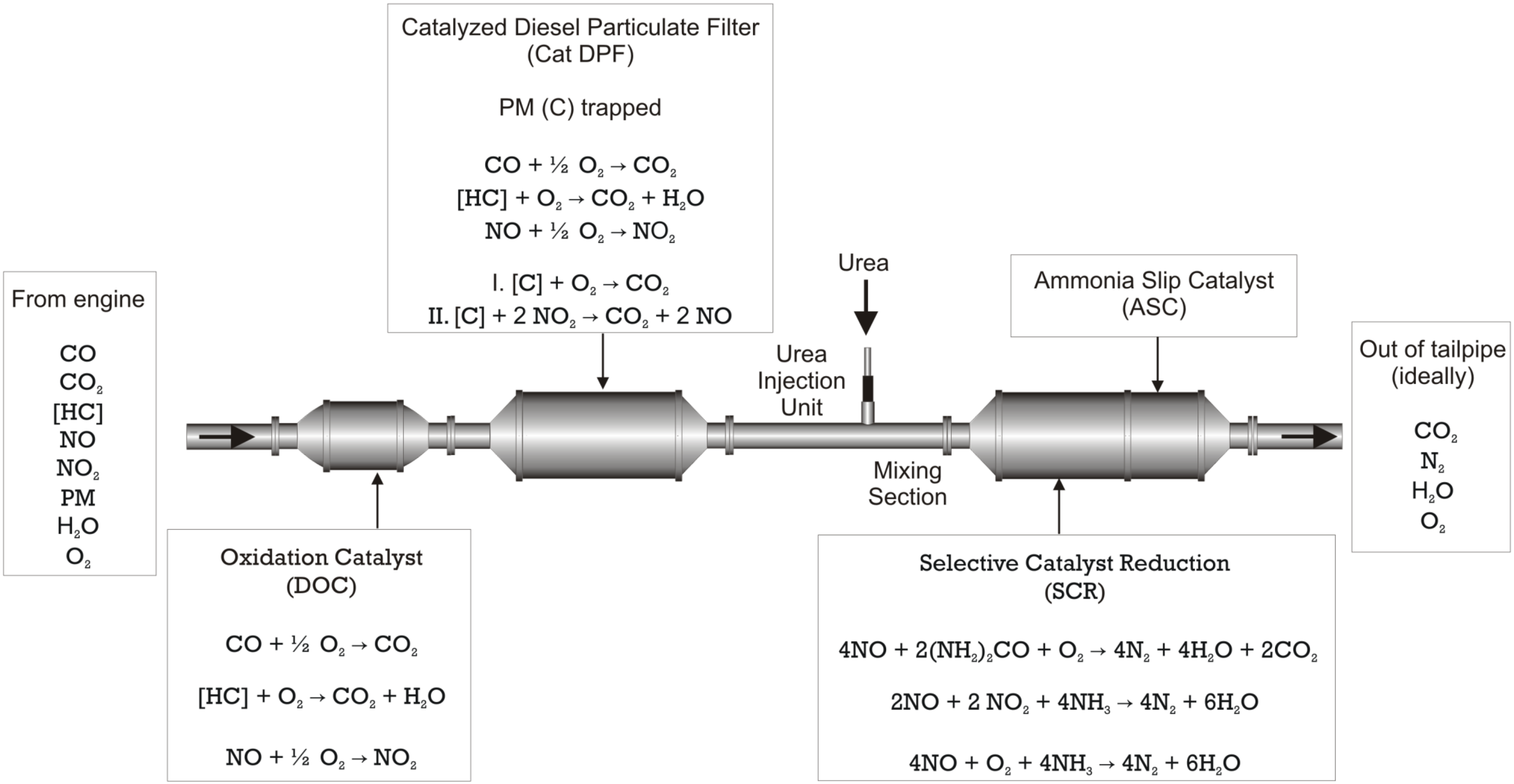
- SCR systems are primarily designed to reduce NO_X emissions to inert molecular nitrogen.
- Diesel exhaust fluid (32.5% high-purity urea) is used as reducing agent.

Integrated Systems for DPM and NO_2 Control



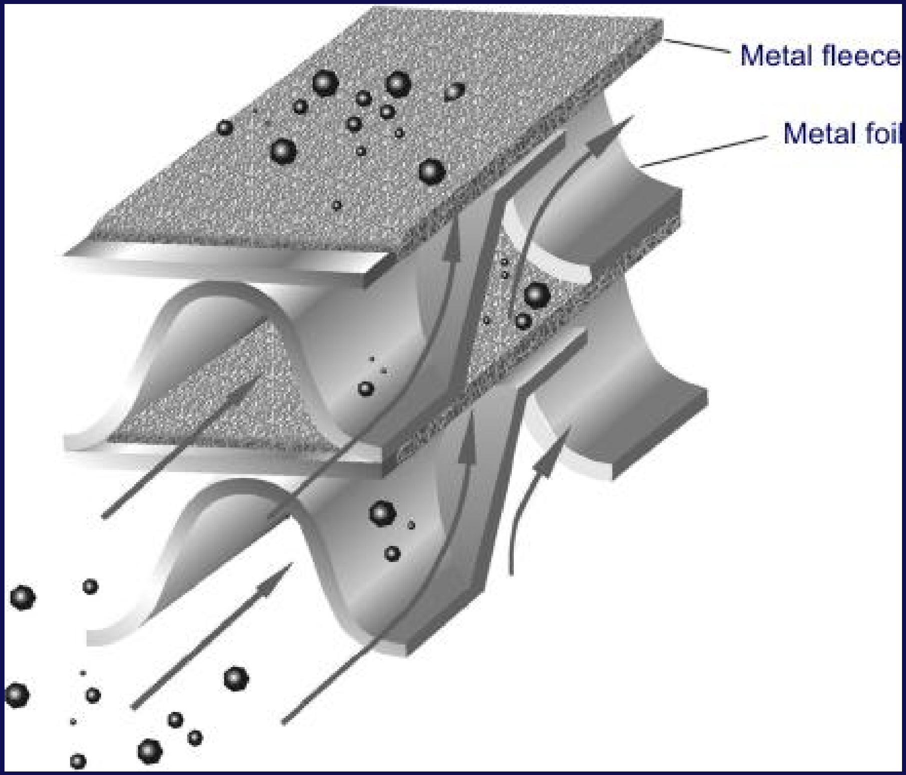
- DOC + Cat DPF + NO_2 decomposition catalyst.
- NO_X neutral.
- Control of NO_2 slip from CRT system.

Integrated Systems for DPM and NO_X Control



- DOC + Cat DPF + SCR.
- Control of both DPM and NO_X emissions.

Flow-Through-Filters (FTF)



- Theoretically, over 50% removal (CARB Level 2).
- Absence of regeneration and DPM buildup affects FTF performance.
- Storage and release (blow-off) phenomenon.
- Secondary NO_2 emissions.

Selection of Exhaust Aftertreatment Systems for Underground Mining Applications

- Selection of system type.
- Effects of systems on:
  - concentrations of DPM (EC);
  - concentrations of regulated and unregulated gases.
- Regeneration/disposal.
- Installation, implementation, and maintenance issues.
- Cost benefit analysis.

System Approach toward Selection and Optimization of Engine/Aftertreatment/Fuel system

- Exhaust aftertreatment should not be afterthought:
  - Selection of the engine for the application;
  - Selection of the aftertreatment;
  - Optimization.

- Identify hierarchy of solutions
  - Exhaust aftertreatment is not method for cleaning “dirty” engines and overcoming poor maintenance practices.
  - Exhaust aftertreatment systems are not equally effective in controlling all emissions of all pollutants, adequate ventilation will be required.

Aftertreatment System Installation and Survival

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 like 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.
- API CJ4 lubricating oil.

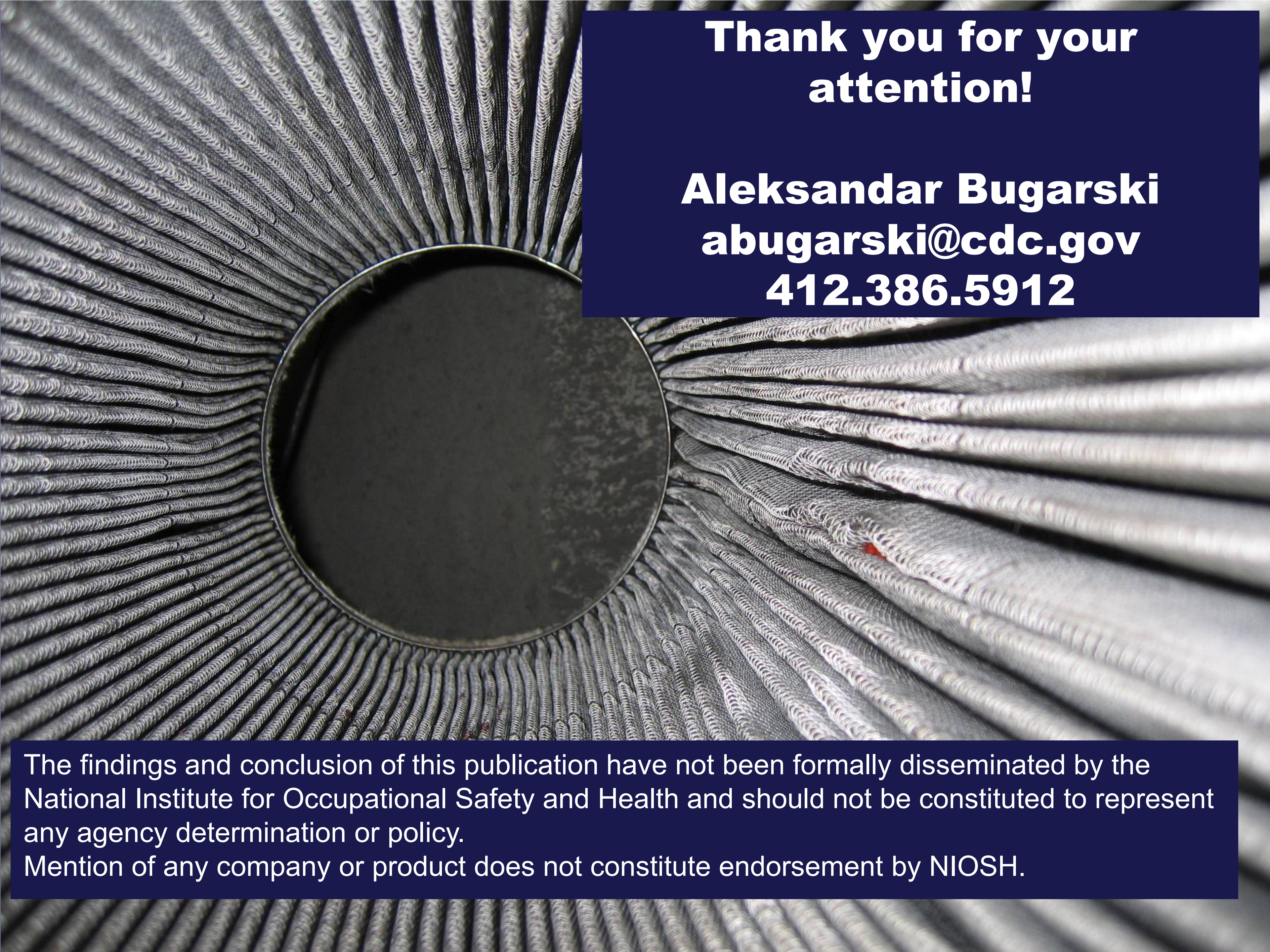
DPF Systems
Backpressure Monitoring

- 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 as part of the filtration system.

Other Parameters that Can Potentially Affect Effectiveness and Performance of DPF System

- Exhaust system integrity:
  - Internal leaks;
  - External leaks.

- Avoid operating the system outside of design parameters.



Thank you for your attention!

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