Effects of sintered metal filter systems on emissions from light-duty diesel powered underground mining vehicles

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The objective of the study was field evaluation of in-use sintered metal diesel particulate filter (DPF) systems supplied by Mann+Hummel (Model SMF® -AR) and installed on two light-duty vehicles from Vale's Creighton Mine.

5109	
vehicle type	forklift
vehicle manufacturer	Kubota
vehicle model	R520SF
engine manufacturer	Kubota
engine model	V2203-M-ES
number of cylinders	4 (inline)
engine displacement	2.2 l
engine type	liquid cooled, naturally aspirated
engine output	36 kW (49 hp)

368	
vehicle type	10 ton locomotive
vehicle manufacturer	Clayton Equipment Ltd.
engine manufacturer	Deutz Corporation.
engine model	F6L912W
number of cylinders	6 (inline)
engine displacement	6.1 l
engine type	air cooled, naturally aspirated
engine output	60 kW (80 hp)

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Mann+Hummel SMF ® -AR is actively regenerated system.

- These systems are built around filter elements made of sintered metal plates.
- When needed, the electrical heater mounted at the back of the filter element can be used to actively regenerate the system.
- Iron-based fuel additives (currently DT8i) supplied by on-board dosing system play important role in regeneration process and operation of the system.

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Two SMF ® -AR systems (used with DT7 and DT8i) have been subjected to long-term evaluation at Vale's Creighton Mine.

- The results of 1500+ hours of evaluation of the SMF systems installed on the forklift 5109 and loco 368 (operated with DT7 fuel additive) were previously reported in the literature and at the MDEC conference:
  - Stachulak JS, Hensel V [2010]. Successful application of DPF system at Vale Inco's Creighton Mine. In: Hardcastle S and McKinnon DL Eds. Proceedings of 13th U.S./North American Mine Ventilation Symposium.
  - Stachulak JS, Hensel V [2010]. Successful evaluation of DPF system at Creighton Mine. 16th Annual MDEC Conference.
- The SMF systems installed on the forklift 5109 and loco 368 operated were evaluated in June 2011 with less than 600 hours in operation with DT8i additive :
  - Bugarski AD, Cauda EG, Stachulak JS [2011]. Field Evaluation of Sintered Metal Filter Systems at Nickel Mine. 17th Annual MDEC Conference.

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The second in a series of emissions tests took place at the surface shop of Creighton Mine in May 2012 when the SMF systems on the forklift 5109 and loco 368 accumulated approximately 1500 and 2100 hours, respectively

- The primary objective of the tests was assessment of the effects of these systems on gaseous and aerosol emissions.
- The results of this series of tests were qualitatively compared with the results of the first series of tests conducted in June 2011 to establish the effects of aging of the SMF systems on aerosol emissions.
- The emissions of tested vehicles/engines were assessed for three engine operating conditions:
  - hydraulic stall (HS),
  - high idle (HI), and
  - low idle (LI).

Engine Speed [rpm]	Forklift 5109/ Kubota V2203-M-ES	Loco 368 / Deutz F6L912W
HS	2160	2800
HI	2240	3100
LI	760	1000

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The effects of SMF systems were assessed using the results of sequential measurements performed on the exhaust drawn from the ports located upstream and downstream of the SMF systems installed on forklift 5109 and loco 368.

The measurements at each location were performed sequentially for three series of four-minute HI and LI test, and two-minute HS test (LI 1, HI 1, HS 1, LI 2, HI 2, HS 2, LI 3, HI 3, HS 3).

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The effects of the systems on concentrations of criteria (CO, CO_2, NO, and NO_2) and other gases, predominantly hydrocarbons were determined using results of measurements made in undiluted exhaust using FTIR analyzer (Gasmet, Model 4000).

- Hydrocarbons :
  - Methane (CH_4)
  - Ethane (C_2H_6)
  - Propane (C_3H_8)
  - Butane (C_4H_{10})
  - Pentane (C_5H_{12})
  - Hexane (C_6H_{14})
  - Octane (C_8H_{18})
  - Ethylene (C_2H_4)
  - Acetylene (C_2H_2)
  - Propene (C_3H_6)
  - 1,3-Butadiene (C_4H_6)
  - Formaldehyde (HCOH)
  - Acetaldehyde (CH_3CHO)
  - Benzene (C_6H_6)
  - Toluene (C_7H_8)

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Aerosol measurements were performed on the exhaust diluted using partial dilution system (Dekati, Model FPS4000).

Dekati FPS4000 is designed to dilute exhaust in two stages.

- Primary dilution occurs in perforated disk diluter;
- Secondary dilution provided by ejector diluter;
- The residence chamber was inserted between those two stages.

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Concentrations and size distributions of aerosols in the exhaust diluted by partial dilution system were measured using Fast Mobility Particle Sizer spectrometer (TSI, Model 3091 FMPS).

Surface area of aerosols deposited in alveolar region of human lungs was measured in exhaust diluted by partial dilution system using Nanoparticle Surface Area Monitor (TSI, Model 3550 NSAM).

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Results:
Concentrations of CO□, CO, NO, NO□, and selected hydrocarbons (HC)

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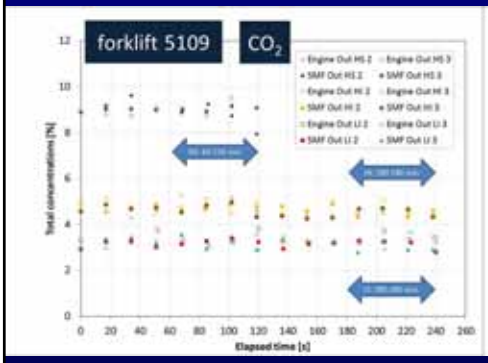
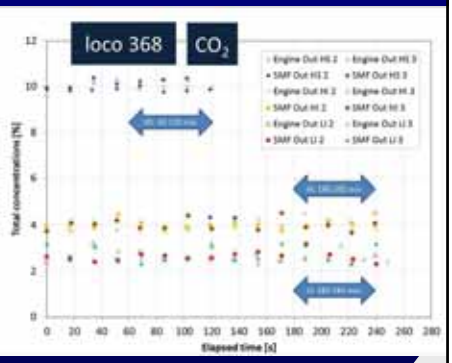
FTIR measurements

- The FTIR was used to measure concentrations of CO, CO□, NO, NO□, and HC upstream and downstream of SMF systems installed on the forklift 5109 and loco 368.
- The results of FTIR measurements performed during the last minute of the second and third test were used to calculate average CO, CO□, NO, NO□, and HC concentrations.





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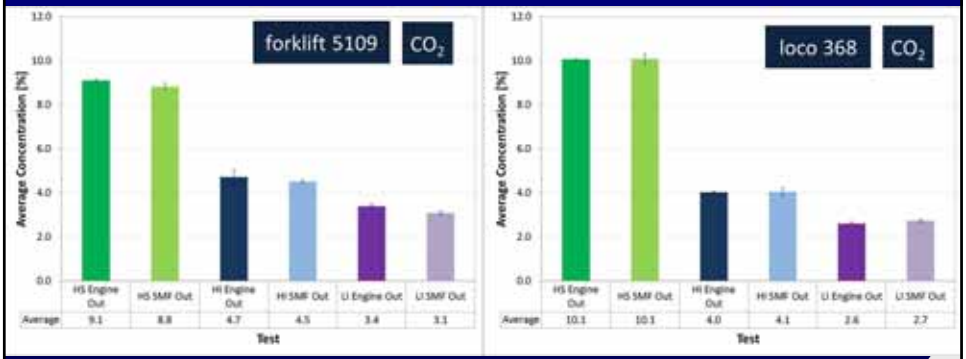
The analysis of CO□ results showed the following:

- Hydraulic stalls (HS) performed on the forklift 5109 and loco 368 produced fairly high loads for the engines in those vehicles;
- The repeatability of engine operating conditions indicated by CO□ results allowed for direct comparison of the results of emission measurements.



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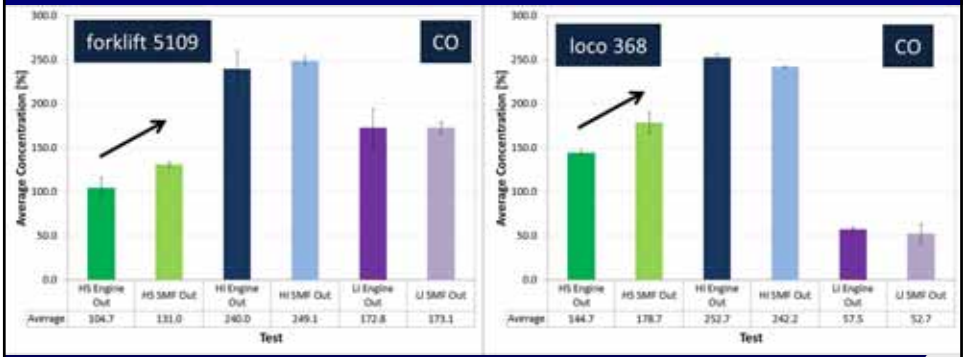
The analysis of CO results showed the following:

- The effects of SMF systems on CO emissions were relatively minor, in a number of the cases those are within accuracy limits of the method;
- Higher “SMF out” CO emissions measured for HS conditions potentially indicate spontaneous regeneration of the SMF elements. At HS conditions the exhaust temperatures for forklift 5109 and loco 368 were 400°C and 450°C, respectively.



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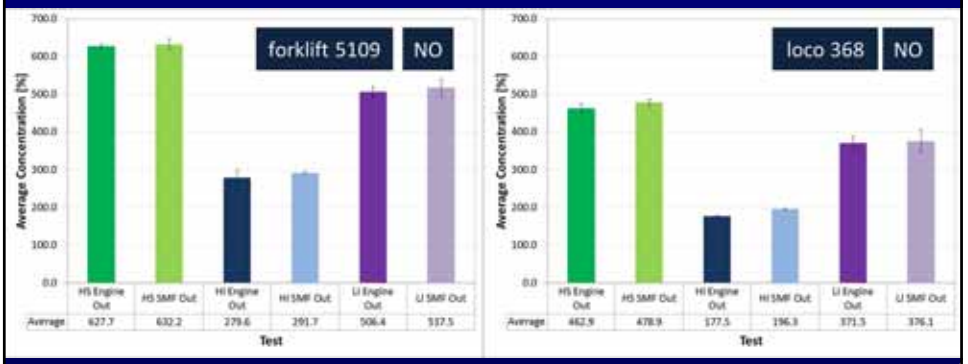
The analysis of NO results indicates the following:

- The effects of SMF systems on NO emissions were relatively minor, in the majority of the cases within accuracy limits of the method.



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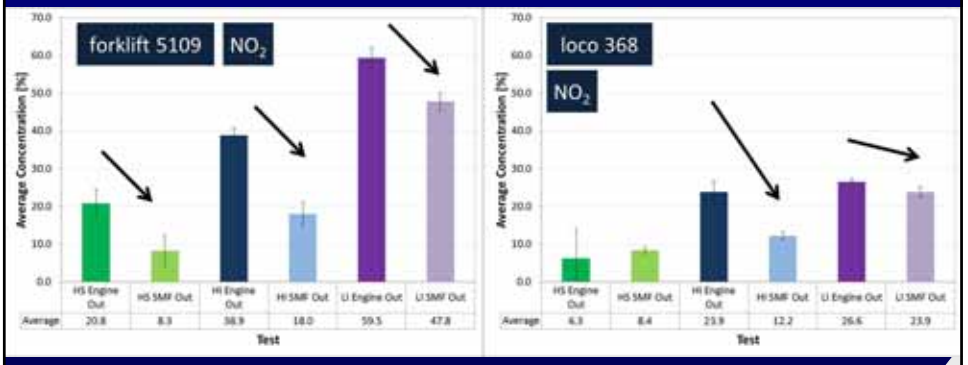
The analysis of NO_2 results indicates the following:

- It appears that the substantial fraction of NO□ was consumed in reaction with soot stored in SMF element;
- That fraction was probably a function of amount of soot trapped in the element.



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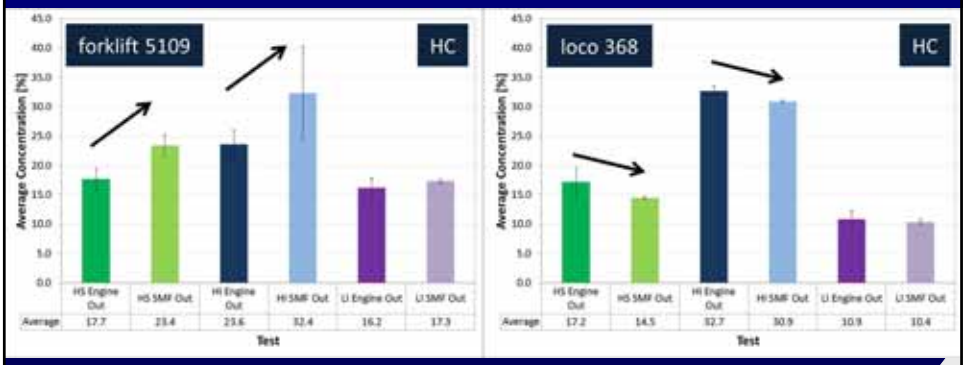
The analysis of HC results indicates the following:

- In the case of forklift 5109, the concentrations of HC were higher out of the SMF than out of the engine;
- In the case of loco 368, the concentrations of HC were lower out of the SMF than out of the engine;



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Results:
Number Concentrations and Size Distributions (FMPS)

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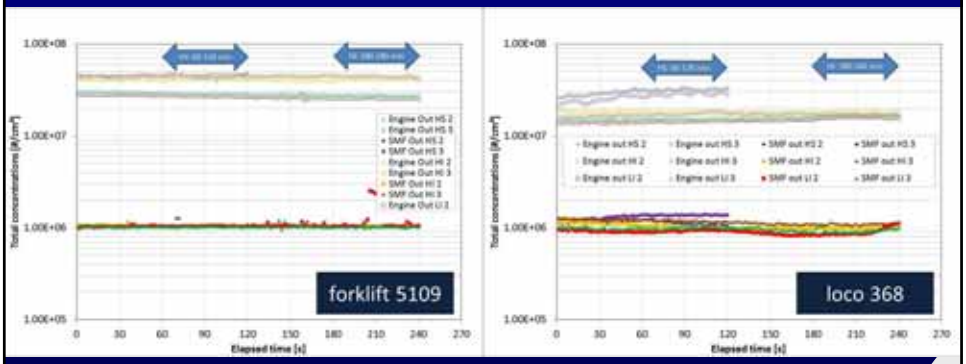
Simultaneously with FTIR measurement, the concentrations and size distributions of aerosols were measured using FMPS.

- In order to calculate the “Engine Out” and “SMF Out” concentrations, the measured concentrations were multiplied by test specific average dilution ratios.
- In the case of both vehicles and for all test conditions the “SMF-Out” number concentrations were found to be very similar, around 1.00e6 #/cm³.



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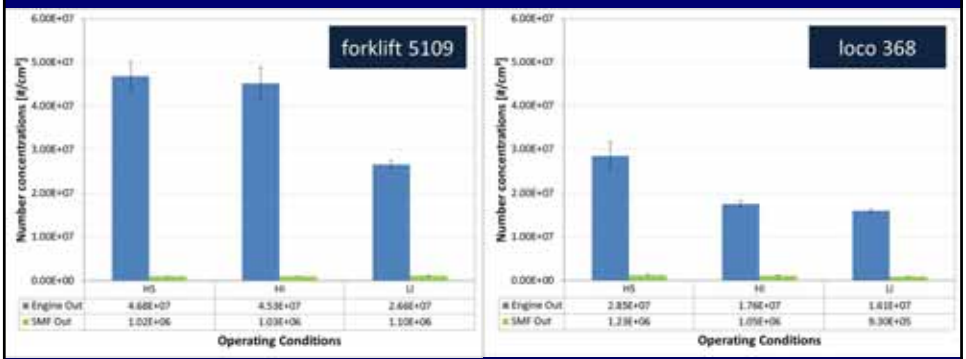
The dilution-corrected FMPS results for measurements performed during the last minute of the second and third test were used to calculate average concentrations and corresponding efficiencies of SMF systems.

- The average concentrations downstream of the SMF system installed on the forklift 5109 and loco 368 were found to be more than 90 % lower than corresponding average concentrations upstream of the SMF system.



Operating Condition	Average Efficiency [%]
HS	97.8
HI	97.7
LI	95.9

Opearting Condition	Average Efficency [%]
HS	95.7
HI	94.0
LI	94.2

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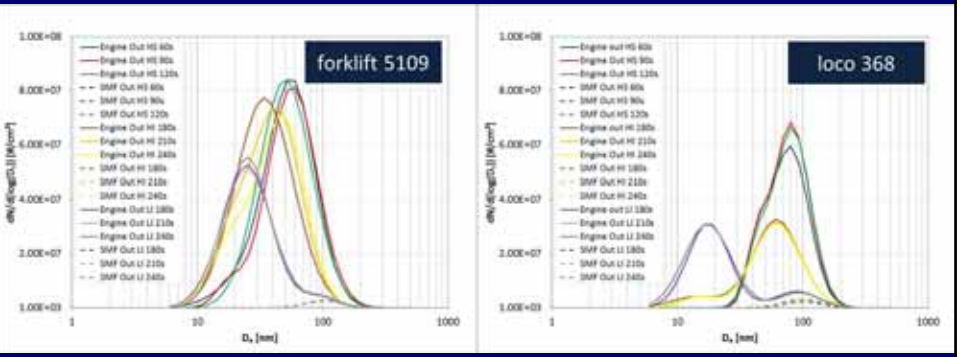
The FMPS size distribution measurements showed that the SMF systems installed on both vehicles not only dramatically reduced concentrations, but also changed size distributions of aerosols.

- If shown on the same linear scale as the engine-out size distributions, the size distributions of aerosols emitted from SMF systems are almost unnoticeable.



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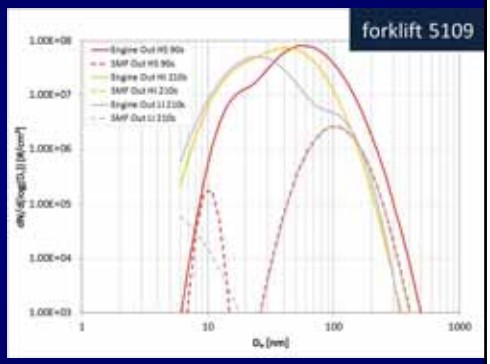
- The size distributions of aerosols emitted by the engine in forklift 5109 were generally bimodal.
- For HS and HI conditions the majority of the aerosols were distributed in accumulation mode with average median diameter of 57 nm for HS and 48 nm for HI conditions.
- In LI case, the majority of the aerosols were found in nucleation mode with average median diameter of app. 25 nm.
- The SMF-out size distributions were single modal or bimodal depending on engine operating conditions.
- The majority of the aerosols were distributed in accumulation mode with average median diameter of 102 nm.



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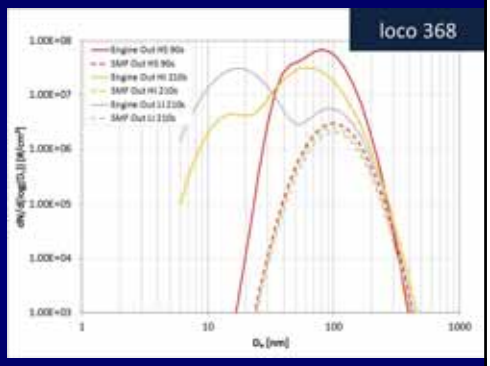
- In general, the size distributions of aerosols emitted by the engine in loco 368 were bimodal.
- For HS and HI conditions the majority of the aerosols were distributed in accumulation mode with average median diameter of 80 nm for HS and 62 nm for HI conditions.
- For LI conditions the majority of the aerosols were distributed in nucleation mode with average median diameter of 18 nm.
- The SMF-out size distributions were single modal.
- The majority of the aerosols were distributed in accumulation mode with average median diameter ranging from 98 to 51 nm.



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Results:
Surface Area of Aerosols Deposited in Alveolar Region (NSAM)

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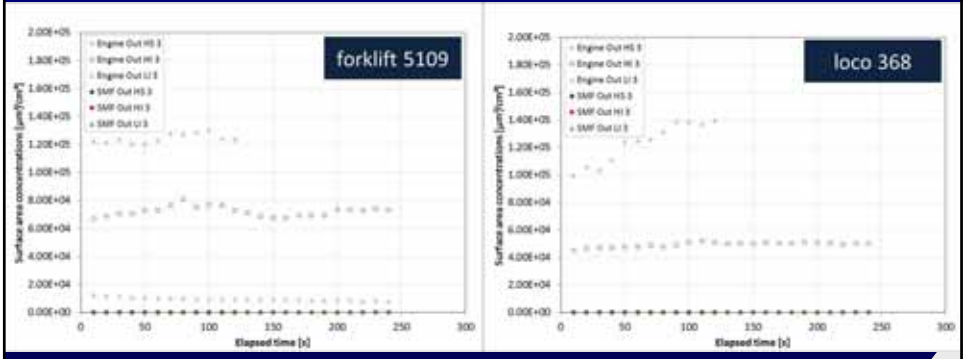
The surface area of aerosols deposited in alveolar region of lungs were measured upstream and downstream of the SMF systems on the forklift 5109 and loco 368 using NSAM for three series of sequential two-minute (HS) and four-minute (HI&LI) tests.

- In the case of both vehicles and for all test conditions the "SMF Out" surface area concentrations were found to be below the detection limit of the NSAM.
- This corroborates the results of the FMPS measurements that showed very low concentrations of sub-100 nm aerosols.



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Results:
Effects of Aging on SMF Effectiveness (FMPS)

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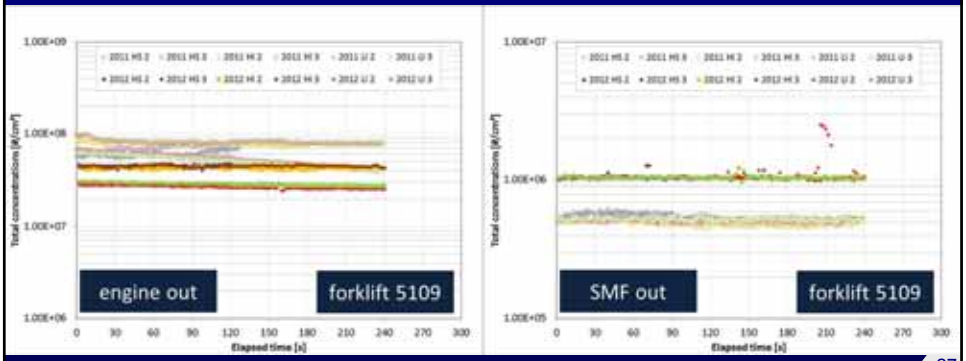
The efficiency of filtration system is a function of "engine out" and "SMF out" concentrations.

- The engine in forklift 5109 emitted lower number of aerosols in May 2012 than in June 2011.
- However, the "SMF Out" aerosol concentrations of the system installed on forklift 5109 were higher in May 2012 than in June 2011.
- Consequently, the efficiency of aged SMF system on forklift 5109 (96-98 %) were calculated to be somewhat lower than those of the same system when relatively new (98-99 %).



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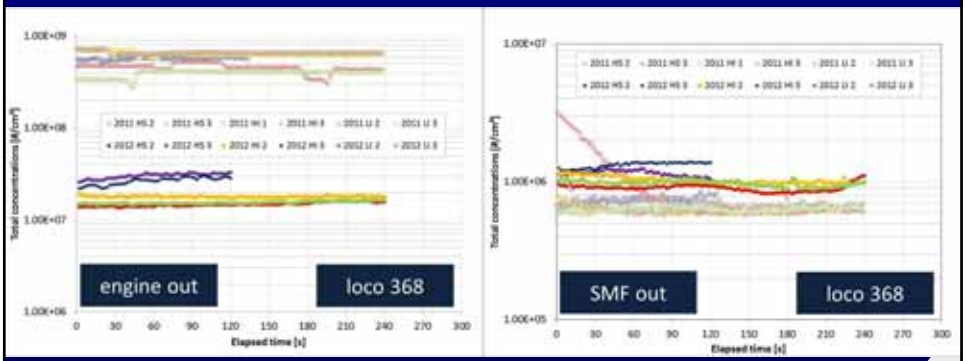
- The engine in loco 368 emitted a lower number of aerosols in May 2012 than in June 2011.
- However, the "SMF Out" emissions of the system installed on loco 368 were found to be higher in May 2012 than in June 2011.
- Consequently, the efficiencies of the aged SMF system (94 – 96 %) on loco 368 were somewhat lower than those of the same system when relatively new (>99 %).



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Conclusion and Future Activities

- This testing showed that the aged SMF systems with substantial number of hours in operation were still very effective in reducing number and surface area concentrations of aerosols emitted by tested diesel engines.
- The aging did not change how the SMF systems affected gaseous emissions. The effects on CO and NO emissions were still relatively minor. It appears that a measurable fraction of NO□ was consumed by soot oxidation process.
- NIOSH and Vale are currently conducting a study at the NIOSH Diesel Laboratory at Office of Mining Safety and Health Research (OMSHR) with objective of assessing the effects of fuel additives on emissions of aerosolized metals and hydrocarbons.

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Thank you for your attention!!!

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