Effects of low-NO_2 continuously regenerated trap on aerosol and gaseous emissions from heavy-duty diesel powered underground mining vehicles

Aleksandar D. Bugarski and Steven Mischler
National Institute for Occupational Safety and Health,
Office of Mining Safety and Health Research
&
Jozef S. Stachulak
Vale S.A, Canadian Operations

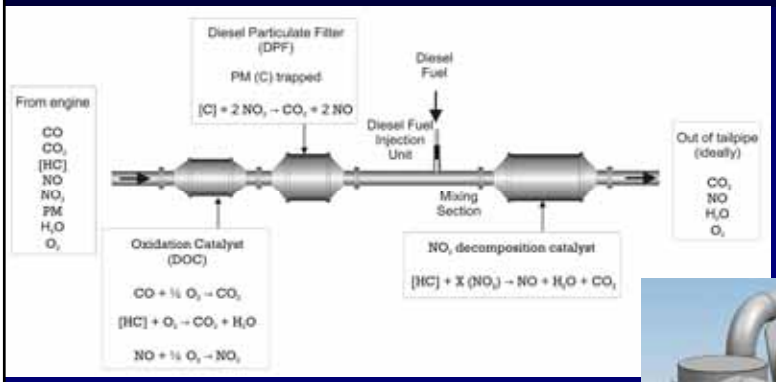
18th MDEC Conference,
North Toronto, October 2-4, 2012

The objective of the study was field evaluation of low-NO_2 Advanced Continuously Regenerate Trap (ACRT) diesel particulate filter (DPF) systems supplied by Johnson Matthey and installed on heavy-duty load-haul-dump (LHD) vehicle #515 from Vale's Totten Mine fleet.

#515	
Vehicle	Caterpillar ScoopTram R1700G
Engine	Caterpillar C11 3176 DITA AAAC, EPA Tier 3
Engine displace.	11.1 L
Number of cylinders	6
Engine type	Turbocharged and aftercooled
Engine Power	263 kW (352 hp)

2

The JM ACRT system is a passive DPF system with hydrocarbon-injection based NO_2 slip control.



3

The series of the emissions tests took place at surface shop of Totten Mine in May 2012.

- The primary objective of the tests was assessment of the effects of the ACRT system with approximately 200 hours in operation on gaseous and aerosol emissions.
- The emissions of tested vehicles/engines were assessed for three engine operating conditions:
  - Torque converter and hydraulic stall (TC&HS),
  - high idle (HI), and
  - low idle (LI).

Caterpillar C11 3176	Engine speed [rpm]
TC&HS	1550
HI	2160
LI	700

4

The effects of ACRT system were assessed using the results of sequential measurements performed on the exhaust drawn from the ports located upstream and downstream of the system.

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

5

The effects of the system 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 Fourier transform infrared (FTIR) analyzer (Gasmet, Mod. 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)

6

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.

8

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).

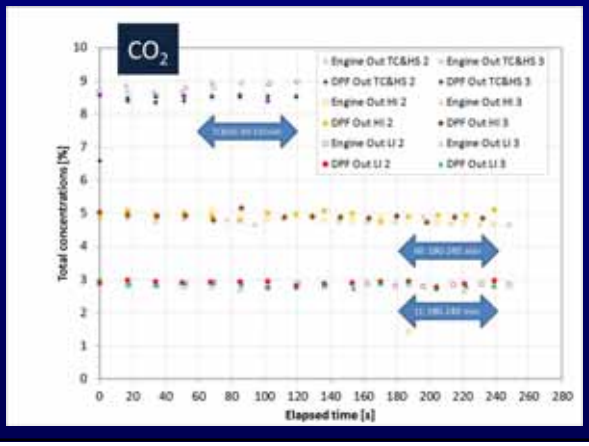
9

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

10

FTIR measurements

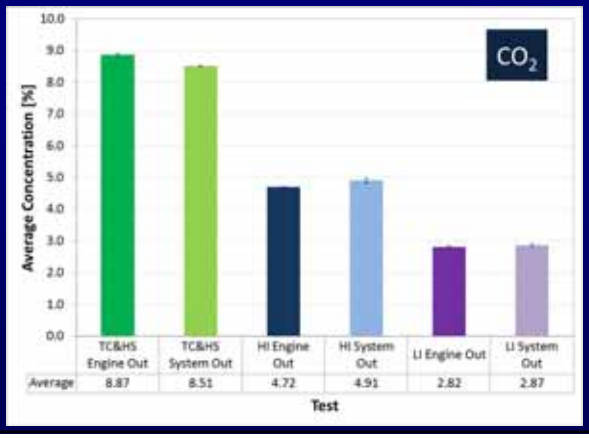
- The FTIR was used to measure concentrations of CO, CO□, NO, NO□, and HCs upstream and downstream of the ACRT system.
- The results of FTIR measurements performed during the last minute of the second and third test were used to calculate average CO, CO□, NO, NO□, and HC concentrations.



11

The analysis of CO□ results showed the following:

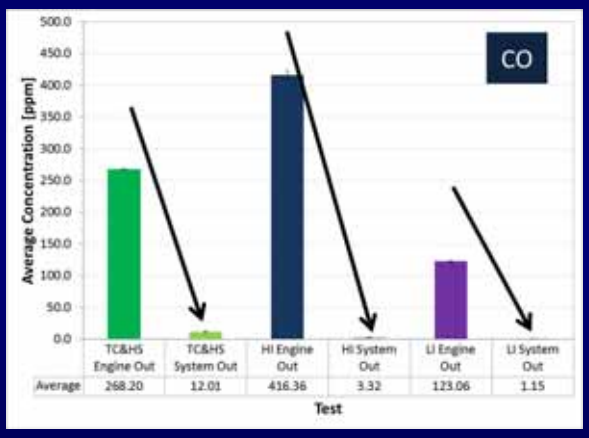
- Torque converter and hydraulic stalls (TC&HS) performed on the LHD 515 produced fairly high loads for the engines in those vehicles;
- The repeatability of engine operating conditions indicated by CO□ results allowed for direct comparison of the results of emission measurements from various tests.



12

The analysis of CO results showed the following:

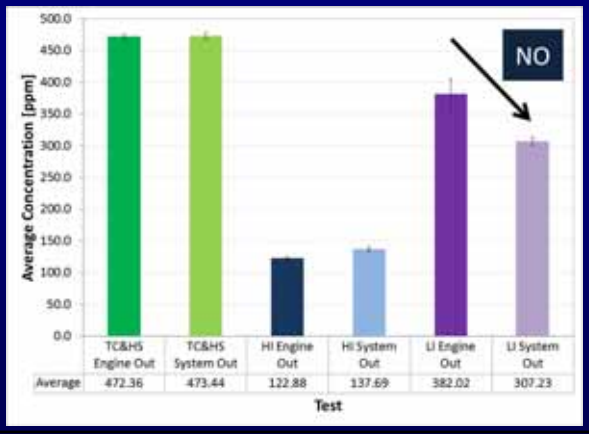
- The ACRT system dramatically (>95%) reduced CO emissions at all test conditions, including LI conditions.



13

The analysis of NO results indicates the following:

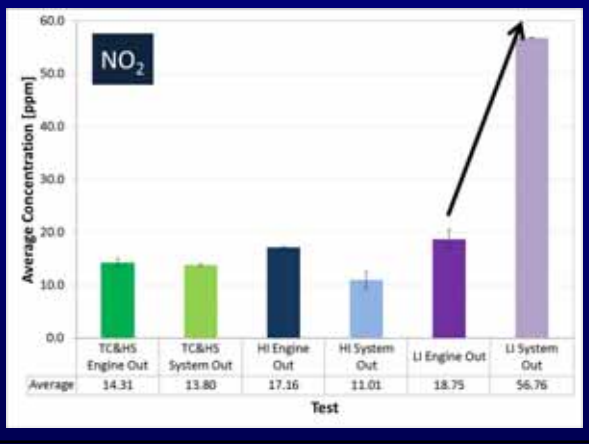
- For TC&HS and HI conditions the effects of ACRT system on NO emissions are relatively minor, in the majority of the cases within accuracy limits of the method.
- At LI conditions, the “System Out” NO concentrations were app. 20% lower than corresponding “ Engine Out” NO concentrations.



14

The analysis of NO_2 results indicates the following:

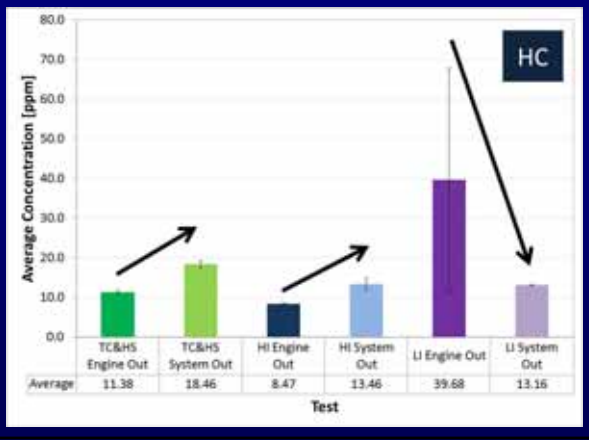
- For TC&HS and HI conditions the effects of ACRT system on NO_2 emissions were relatively minor, in the majority of the cases within accuracy limits of the method.
- At LI conditions, the "System Out" NO_2 concentrations were higher than the corresponding "Engine Out" NO_2 concentrations.



15

The analysis of HC results indicates the following:

- At TC&HS and HI conditions the "System Out" HC concentrations were higher than the corresponding "Engine Out" HC concentrations.
- At LI conditions, the "System Out" HC concentrations were lower than the corresponding "Engine Out" HC concentrations.



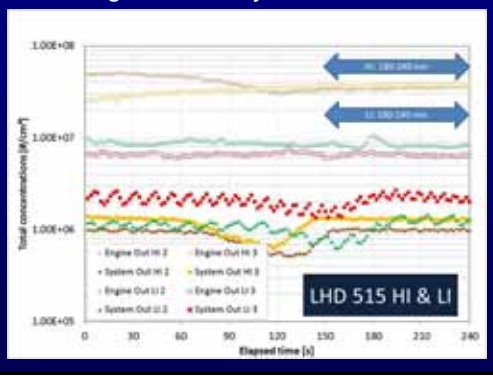
16

Results:
Number Concentrations and Size Distributions (FMPS)

17

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

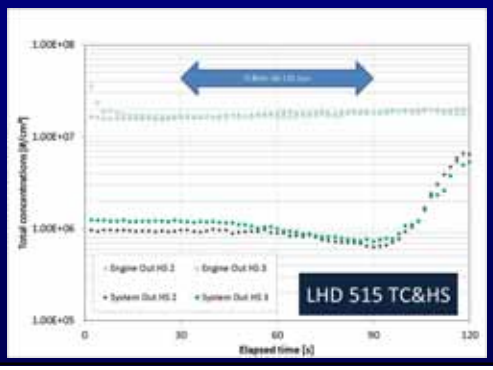
- In order to calculate the "Engine Out" and "SMF Out" concentrations, the measured concentrations were multiplied by test specific average dilution ratios.
- In the case of HI and LI tests, the dilution-corrected FMPS results for measurements performed during the last minute of the second and third test were used to calculate average concentrations and corresponding efficiencies of the ACRT system in removing aerosols by number.



18

The results of FMPS measurements for TC&HS conditions showed the following.:

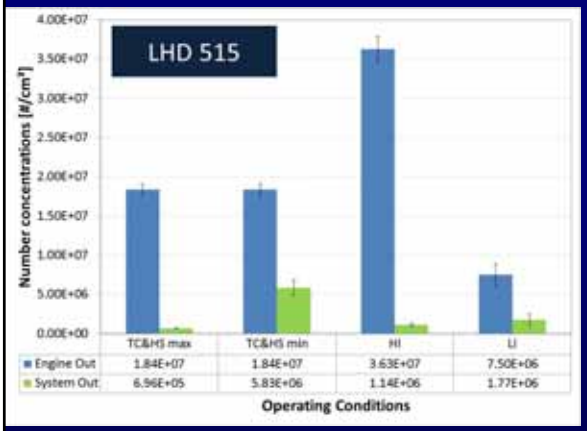
- The aerosol emissions exhibited transient nature with apparent increase in aerosol number concentrations in the last 30 seconds of the 120-second runs.
- Therefore, the efficiency of ACRT systems in removing aerosols by number for TC&HS conditions was expressed as range of values calculated for the second the third test using average engine-out dilution-corrected FMPS concentrations for period between 60th and 120th second and two "System-Out" extreme values.



19

The efficiency of ACRT system in removing aerosols by number was found to vary with operating conditions.

- For TC&HS conditions, the efficiency of the system dropped dramatically toward the end of 120-second tests.
- The efficiency numbers were found to be strongly influenced by test-condition-dependent engine-out emissions.

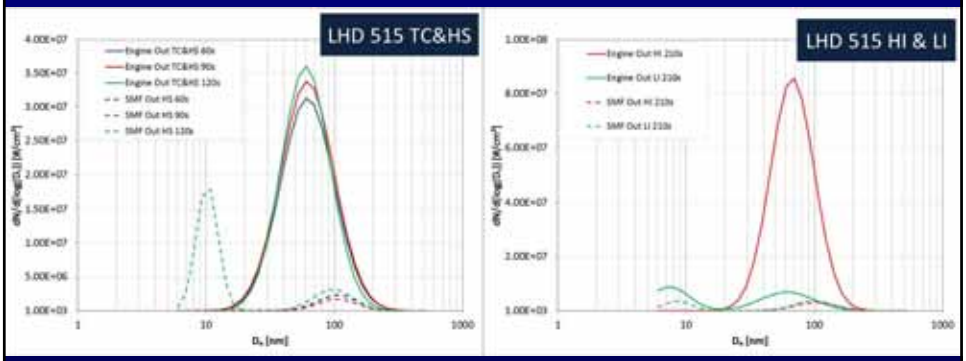


Operating Conditions	Average Efficiency [%]
TC&HS max	96.2
TC&HS min	68.3
HI	96.8
LI	76.4

20

The FMPS size distribution measurements showed that the ACRT system not only dramatically reduced concentrations, but also changed size distributions of aerosols.

- With exception of the case of TC&HS conditions, the concentrations of aerosols emitted from the system were almost negligible compared to those emitted by the engine.



21

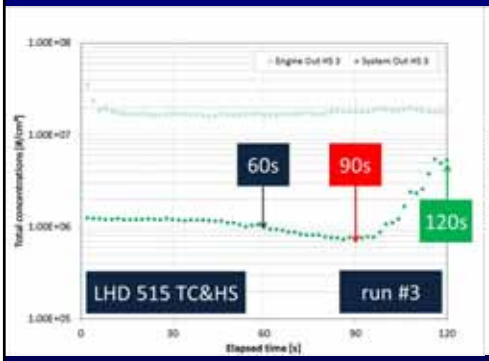
For TC&HS conditions, the aerosol emissions from the engine exhibited steady-state nature in the last minute of the tests.

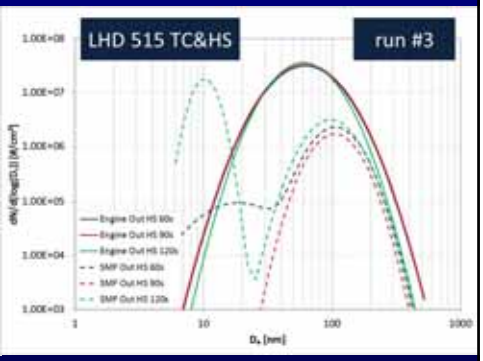
- The majority of aerosols from the engine were concentrated in a single accumulation mode with the media diameters around 60 nm.

22

For TC&HS conditions, the aerosol emissions from ACRT system were found to be transient in nature.

- Those emissions were generally bimodal.
- During the majority of 120-second tests, the majority of the aerosols were concentrated in accumulation mode with the average median diameters between 98 and 106 nm.
- At the final seconds of the tests, the concentrations of nucleation mode aerosols with median diameters of app. 9 nm exceeded corresponding concentrations of aerosols in accumulation mode.

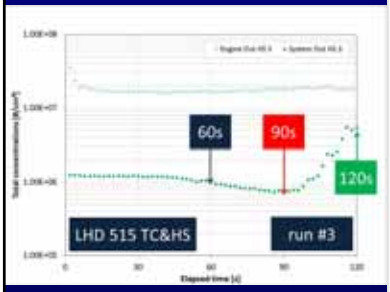


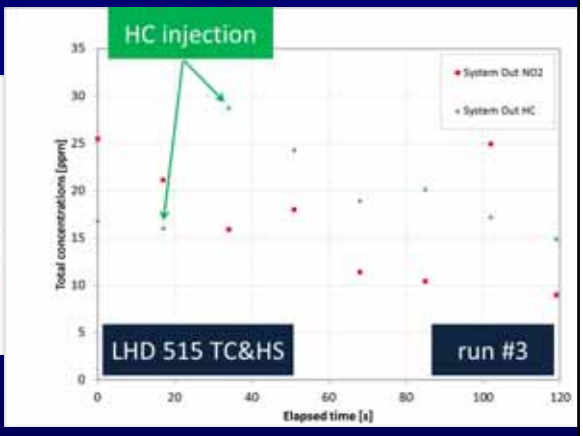


23

The potential source of nucleation mode aerosols was hydrocarbon injection.

- The increase in nucleation mode aerosols coincided with hydrocarbon injection and consequent decrease in NO_2 concentrations.

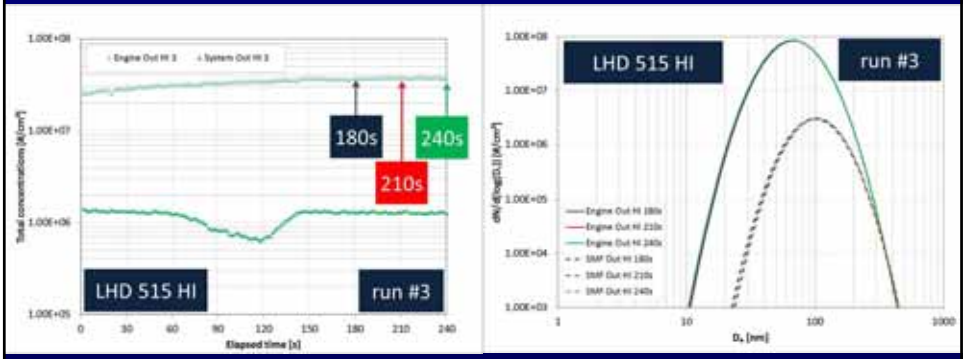




24

For the last minute of each of the HI tests, the aerosol emissions from the engine were found to be steady .

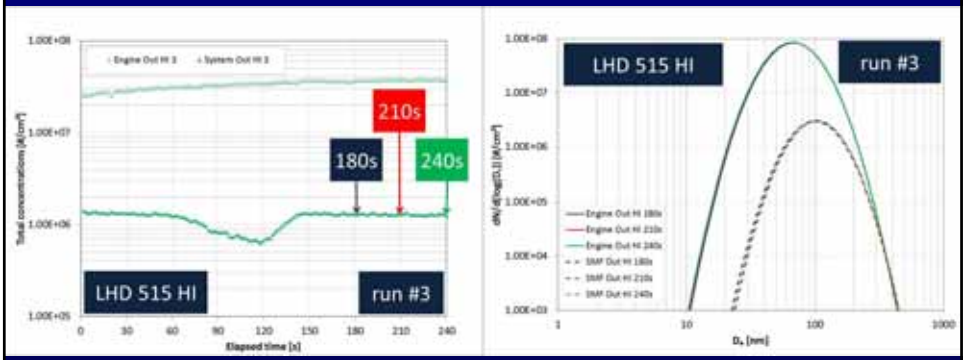
- The majority of aerosols from the engine were concentrated in a single accumulation mode with the media diameters around 68 nm.



25

For the last minute of each of the HI tests, the aerosol emissions from the system were found to be steady .

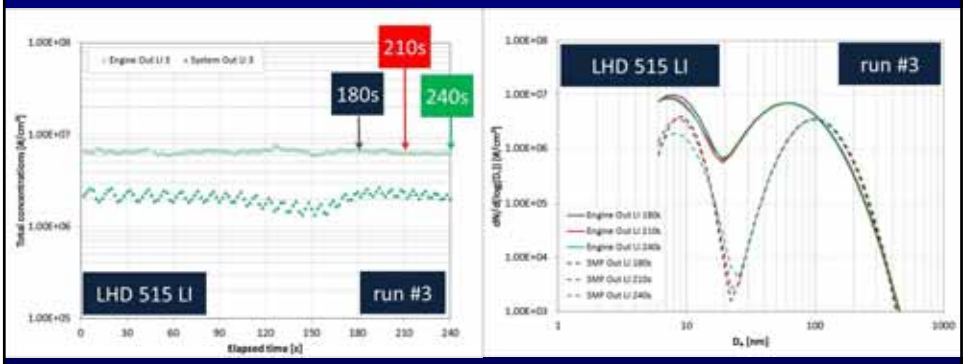
- Those emissions were generally distributed in a single mode.
- The aerosols were distributed in accumulation mode with the average median diameters between 100 and 104 nm.



26

For the last minute of the LI tests, the aerosol emissions from the engine exhibited steady-state nature.

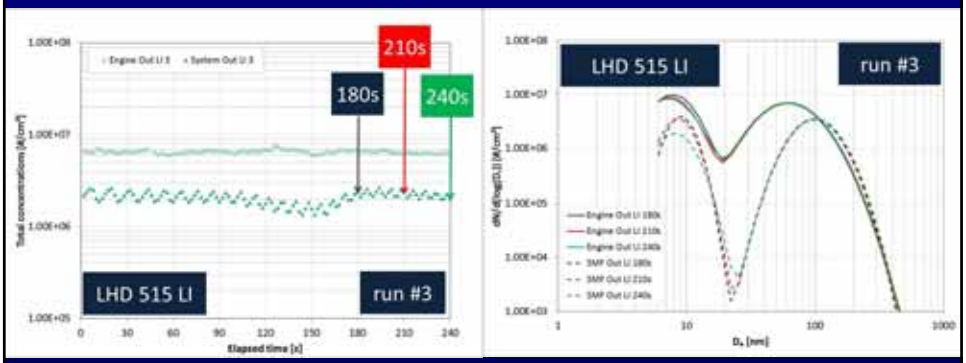
- The distributions for LI conditions were found to be bimodal.
- The aerosols were distributed equally between the accumulation mode with the median diameters around 61 nm and the nucleation mode with the median diameter of 7 nm.



27

For the last minute of the LI tests, the aerosol emissions from the system exhibited quasi steady-state nature.

- The distributions for LI conditions were found to be bimodal.
- The majority of the aerosols were distributed in the accumulation mode with the median diameters around 100 nm.
- The remaining aerosols were distributed in the nucleation mode with the median diameter of 9 nm.



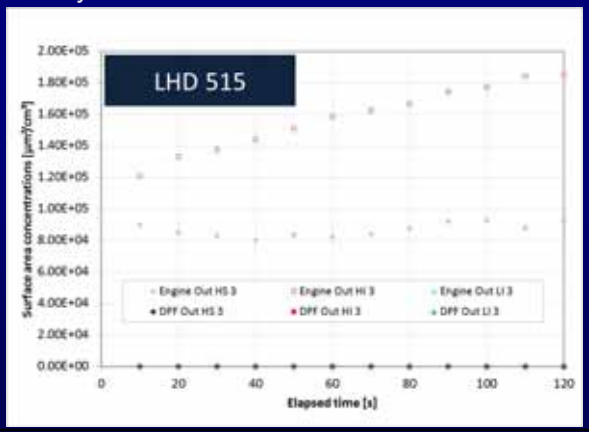
28

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

29

The surface area of aerosols deposited in alveolar region of lungs were measured upstream and downstream of the system using NSAM for three series of sequential two-minute (TC&HS) and four-minute (HI&LI) tests.

- For all test conditions the “System Out” surface area concentrations were found to be below detection limit of the NSAM.
- This corroborated the results of FMPS measurements that showed very low concentrations of sub-100 nm aerosols.



30

Conclusion and Future Activities

- This testing showed that for the majority of test conditions the JM ACRT system was very effective in reducing number and surface area concentrations of aerosols emitted by tested engine. At TC&HS conditions, the hydrocarbon injection resulted in relatively high concentrations of nucleation mode aerosols.
- The system reduced CO emissions at all test conditions.
- For TC&HS and HI conditions, the "System Out" NO emissions were similar to the corresponding "Engine-Out" emissions. However, at LI conditions, the "System Out" NO concentrations were substantially higher than the corresponding "Engine Out" NO concentrations.
- NIOSH and Vale are planning to reevaluate the system after approximately 2000 hours in operation.

31

Thank you for your attention!!!

Acknowledgements go to:

Murray Tann, Vale Totten Mine
Manuel Aguiar, Toromont

32