Evaluation of an Electrically Regenerated Sintered Metal Diesel Particulate Filter System in Underground Mine Laboratory

By

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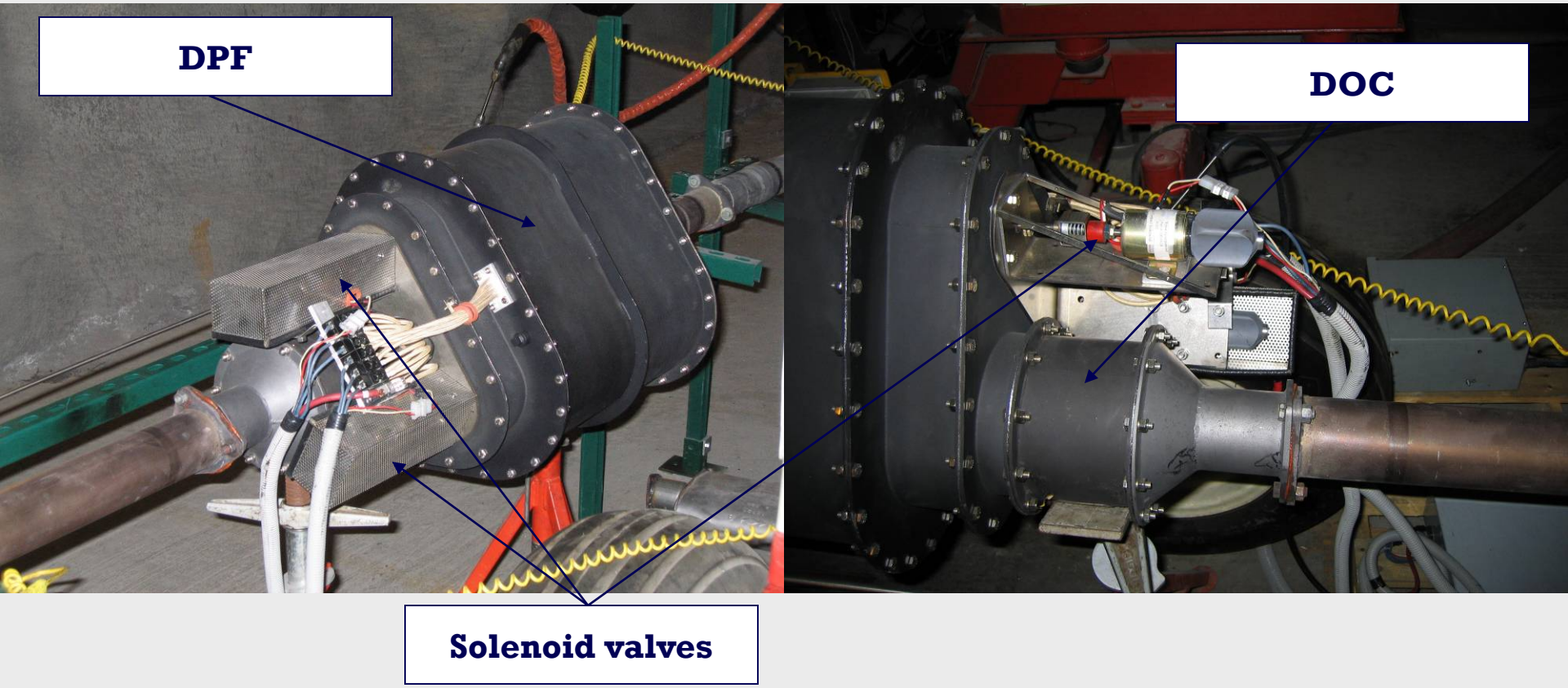
Objective

- Evaluate effects of an electrically regenerated sintered metal diesel particulate filter (DPF) system on concentrations of aerosols and NO and NO_2 in mine air.
- Evaluate effects of regeneration strategy on concentrations of aerosols and NO and NO_2 in mine air.
- Characterize physical and chemical properties of aerosols emitted from engine equipped with sintered metal DPF system.

Electrically Regenerated DPF System Supplied by Rypos Inc., Holliston, MA



Rypos DPF system

- Three stacks of active sintered metal filter elements;
- Two stacks actively (electrical current) and one passively regenerated;
- Two solenoid actuated valves;
- DOC at the outlet of the system;
- Controls for regeneration;
- The 12 VDC system was powered during this study via transformer from 220VAC power supply.

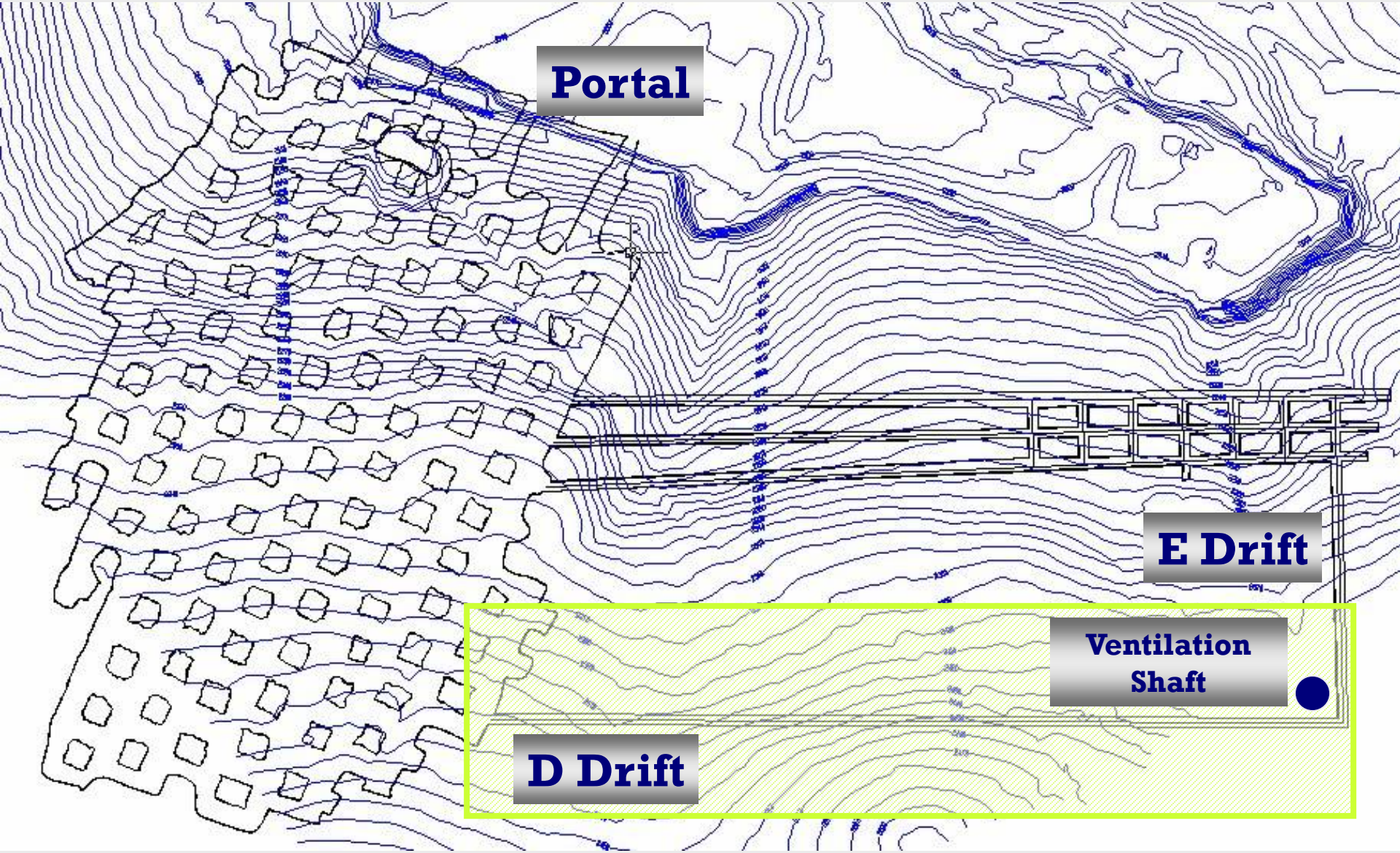
More Information on Rypos DPF system available from:

- http://www.rypos.com
- DePetrillo, F., Saeid, A., Nardi, Z. An actively regenerated diesel particulate filter. 12th Annual MDEC Conference, Richmond Hill, Ontario, October 10-13, 2006;
- DePetrillo, F.S., Ibrahim O.M., Wenghoefer H.M. An actively regenerated diesel particulate filter that demonstrated significant NO_2 reduction. 13th Annual MDEC Conference, Richmond Hill, Ontario, October 3-5, 2007.

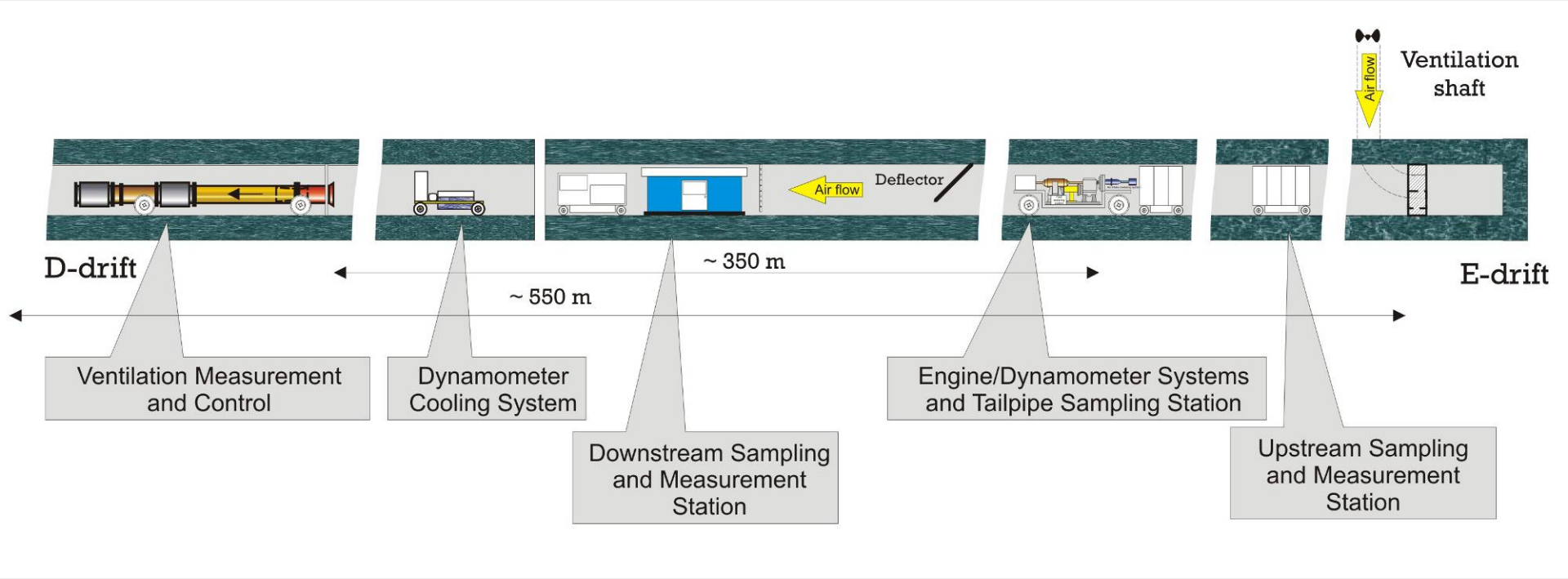
Methodology

- Characterization of DPM in occupational setting:
  - NIOSH Mobile Engine Emissions Laboratory (MEEL) at Lake Lynn Laboratory (LLL)
  - Avoid laboratory uncertainties introduced with various simulations of processes
  - Bridge gap between inherently inaccurate field and unrealistic laboratory experiments
- Physical characterization
  - Size distribution
- Chemical characterization
  - Carbon analysis

NIOSH Lake Lynn Laboratory (LLL)



NIOSH Diesel Laboratory at LLL



Engine/Dynamometer Systems:
150 kW Dynamometer Coupled to Isuzu C240 Engine

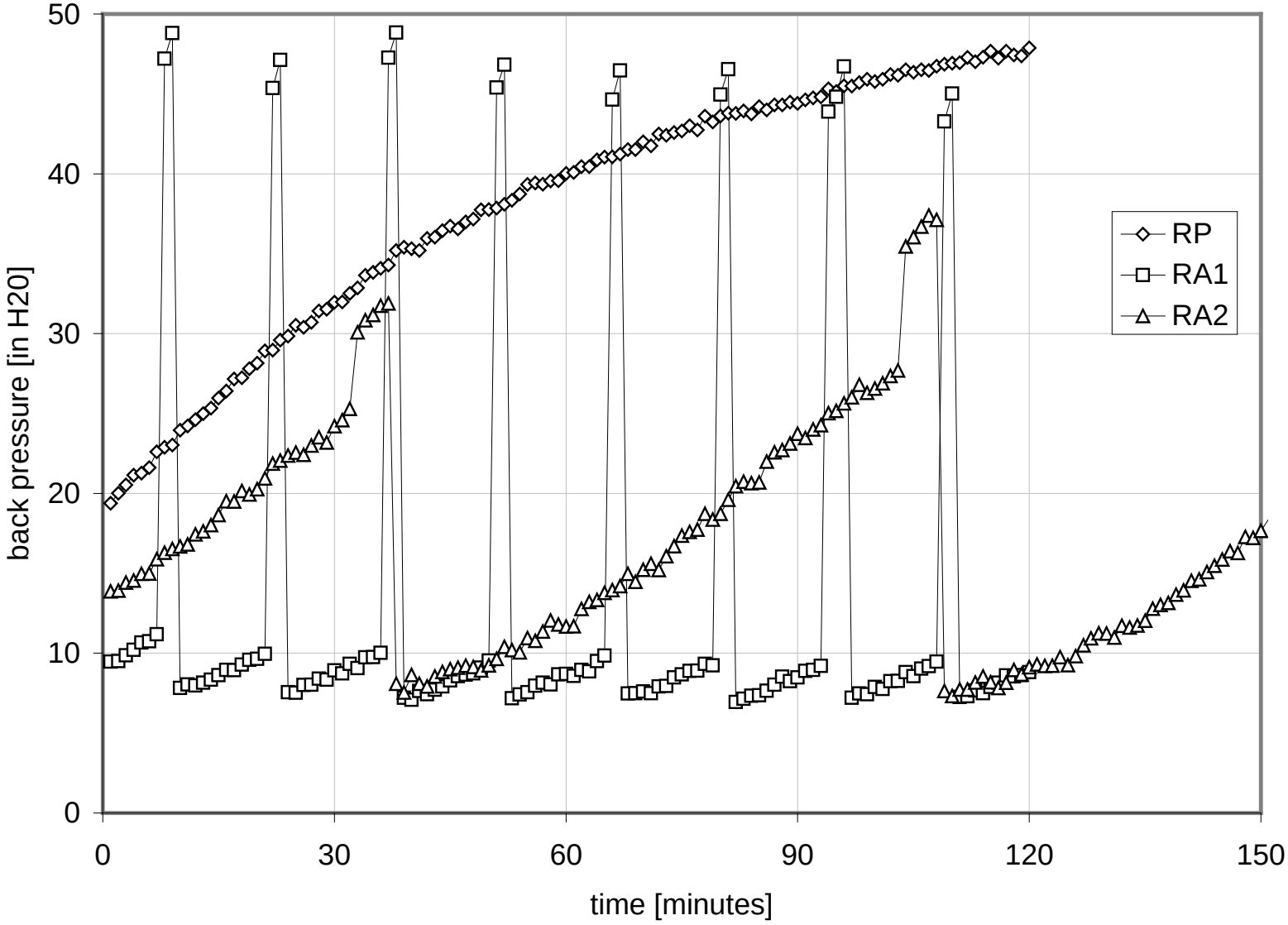
Test Modes

Mode	Description	Engine Speed	Torque	Power
		rpm	Nm	kW
M1	Rated speed ~50% load	2950	55.6	17.2
M2	Rated speed ~100% load	2950	111.2	34.3
M3	Intermediate speed ~50% load	2100	69.1	14.9
M4	Intermediate speed ~100% load	2100	136.9	30.6

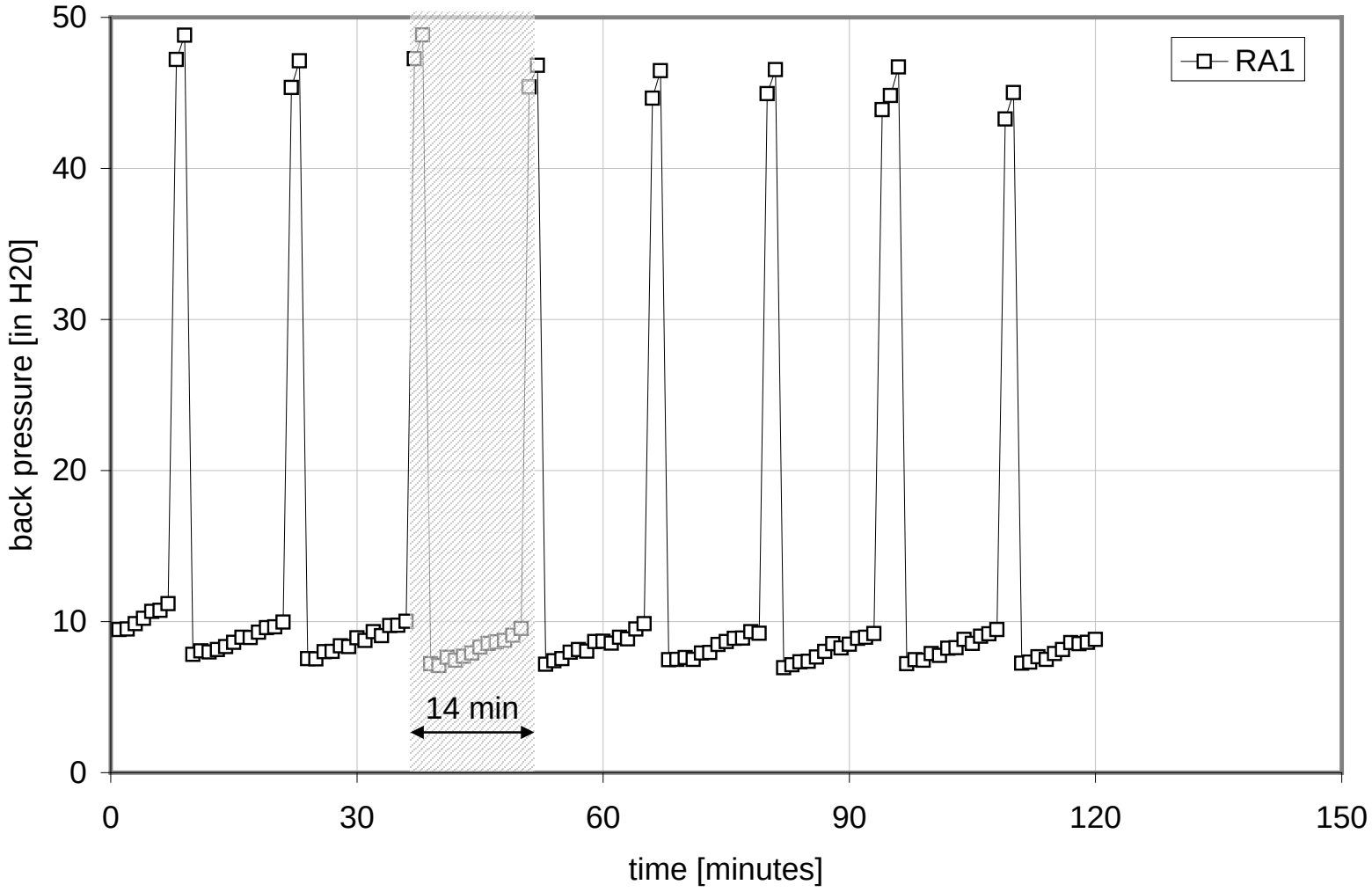
Test Matrix

- Rypos Passive (RP), 4 modes;
- Rypos Active 1 (RA1), time driven regeneration (14 min), 4 modes;
- Rypos Active 2 (RA2), engine back pressure driven (30 in H_2O), 4 modes
- Muffler, 4 modes

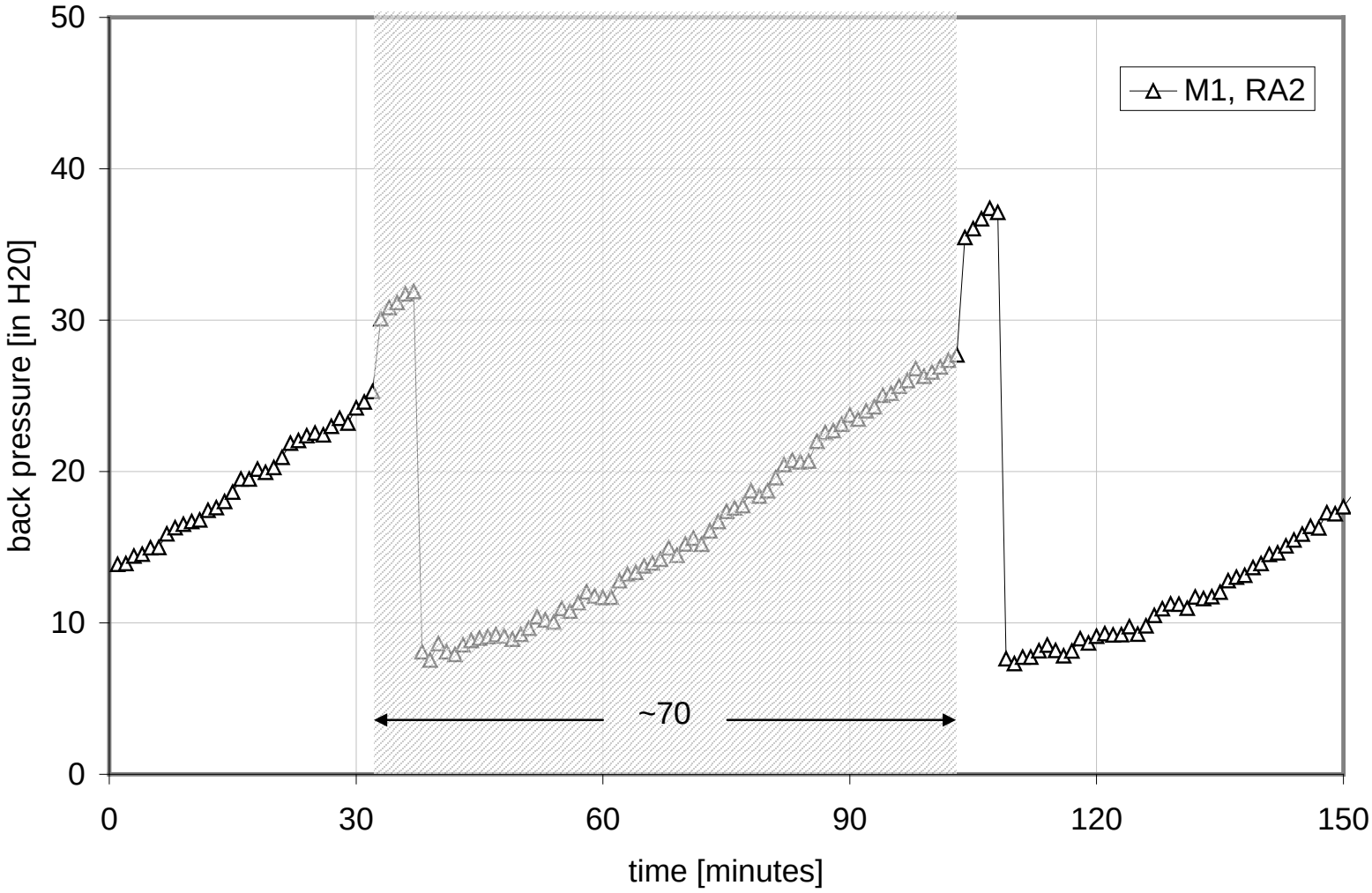
Regeneration Strategies - Engine Back Pressure Traces Mode 1



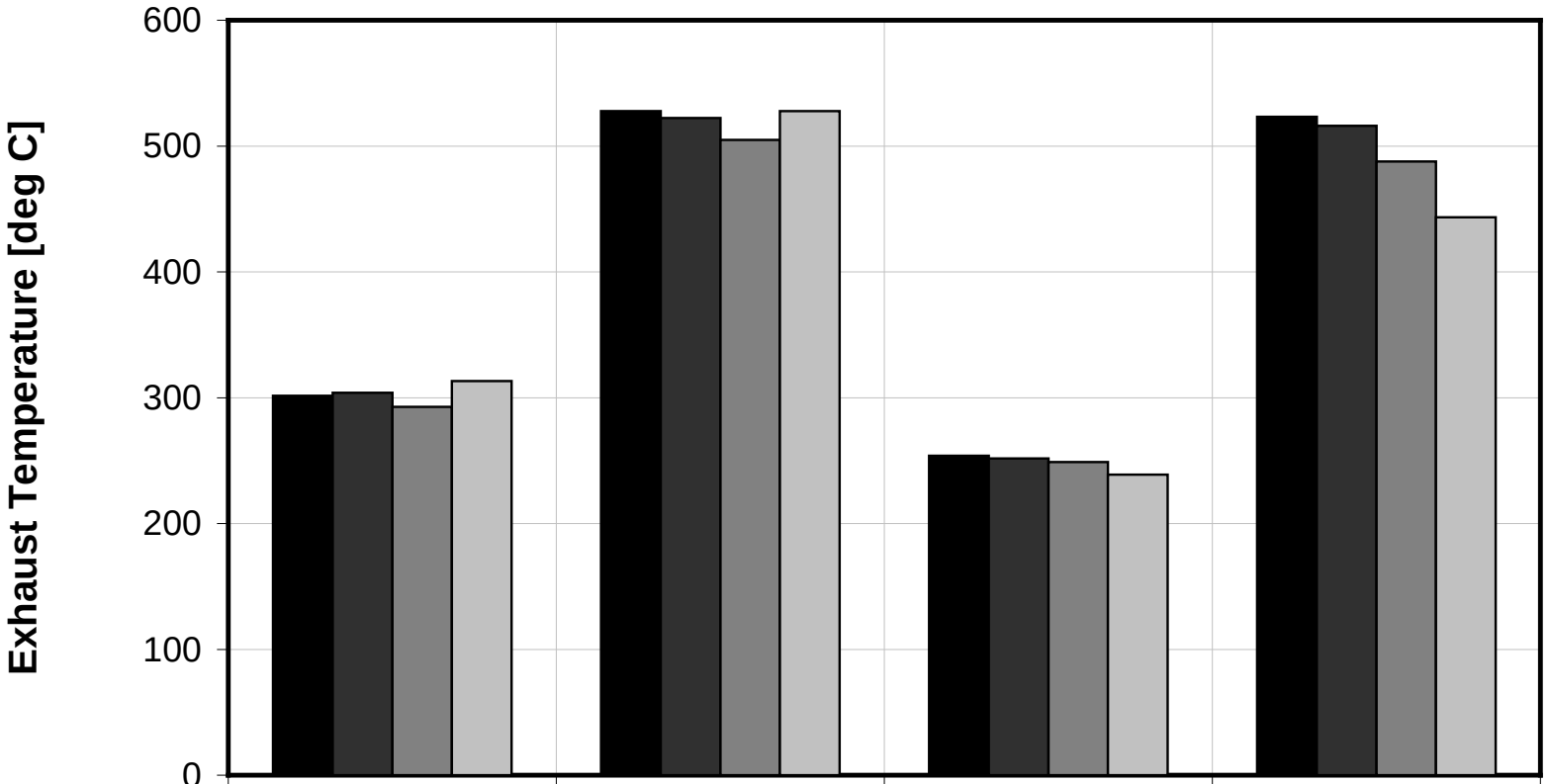
Engine Back Pressure Regeneration Strategy Mode 1, Rypos Active 1 (RA1)



Engine Back Pressure
Regeneration Strategy
Mode 1, Rypos Active 2 (RA2)



Engine Operating Modes – Average Exhaust Temperatures at the Inlet to the System M1, M2, M3, & M4



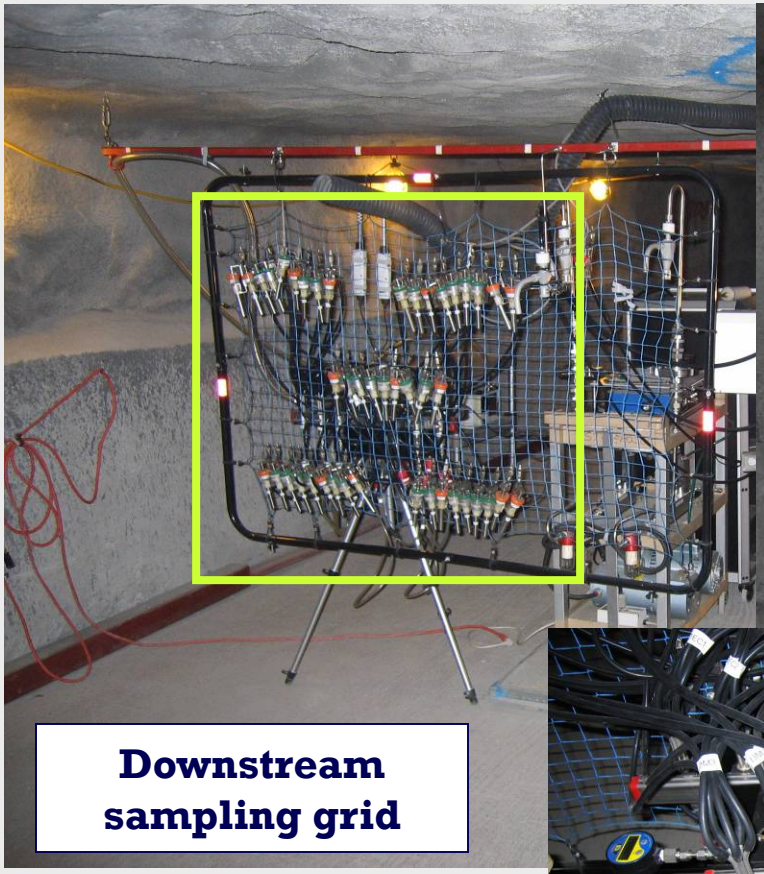
	M1	M2	M3	M4
Muffler	301.7	527.8	253.9	523.3
RP	303.9	522.2	251.7	516.1
RA1	292.8	505.0	248.9	487.8
RA2	313.3	527.8	238.9	443.3

Instrumentation
Downstream Sampling and Measurement Station

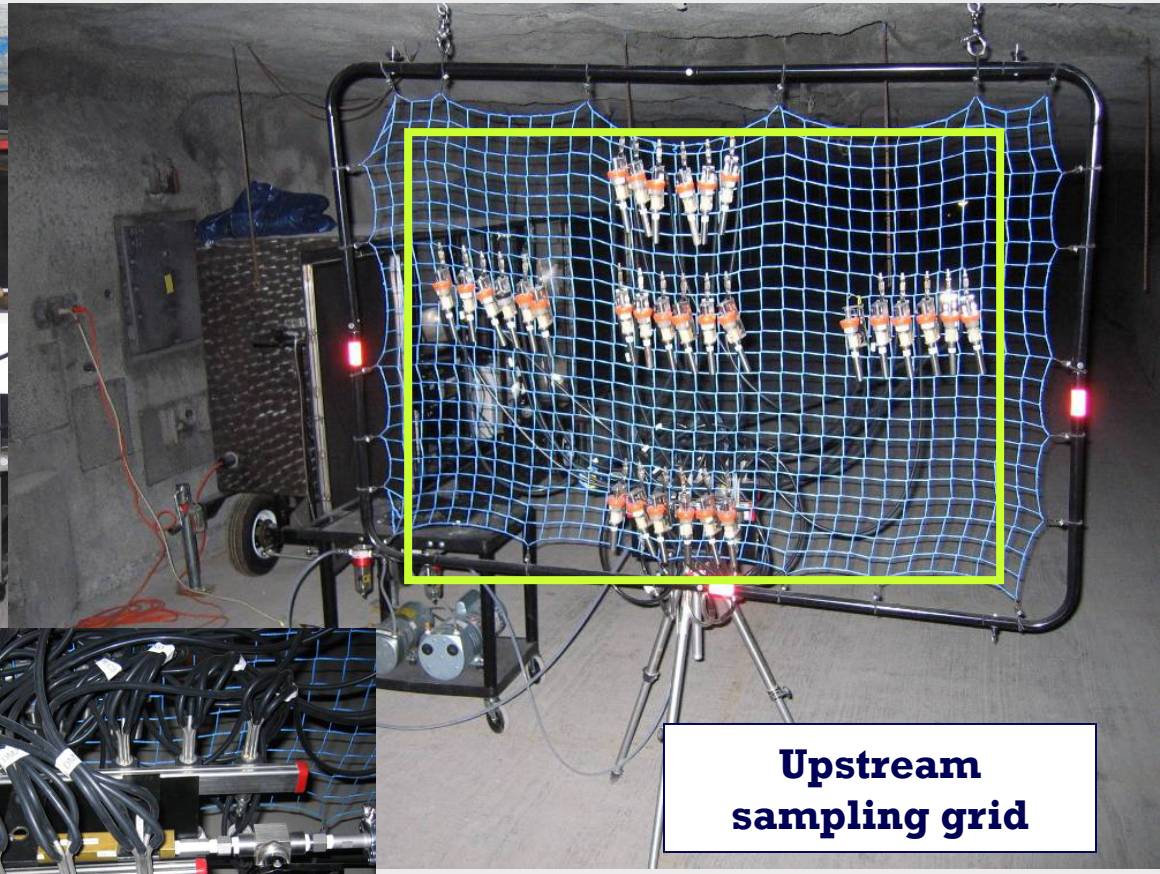
Fast Mobility Particle Sizer (FMPS, TSI 3091) & Nanoparticle Surface Area Monitor (NSAM, TSI 3550)

Tapered Element Oscillating Microbalance (TEOM, Thermo 1400a)

Filter Sampling for Carbon Analysis (NIOSH 5040)

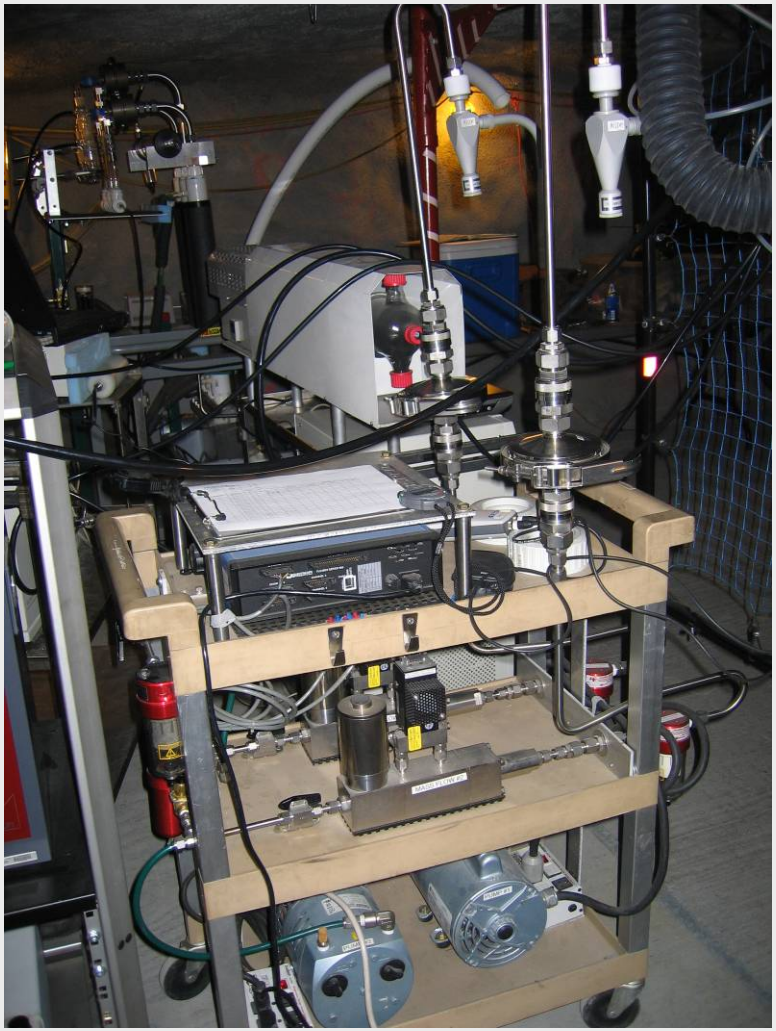


Downstream sampling grid



Upstream sampling grid

High-volume Sampling for Gravimetric and Carbon Analysis

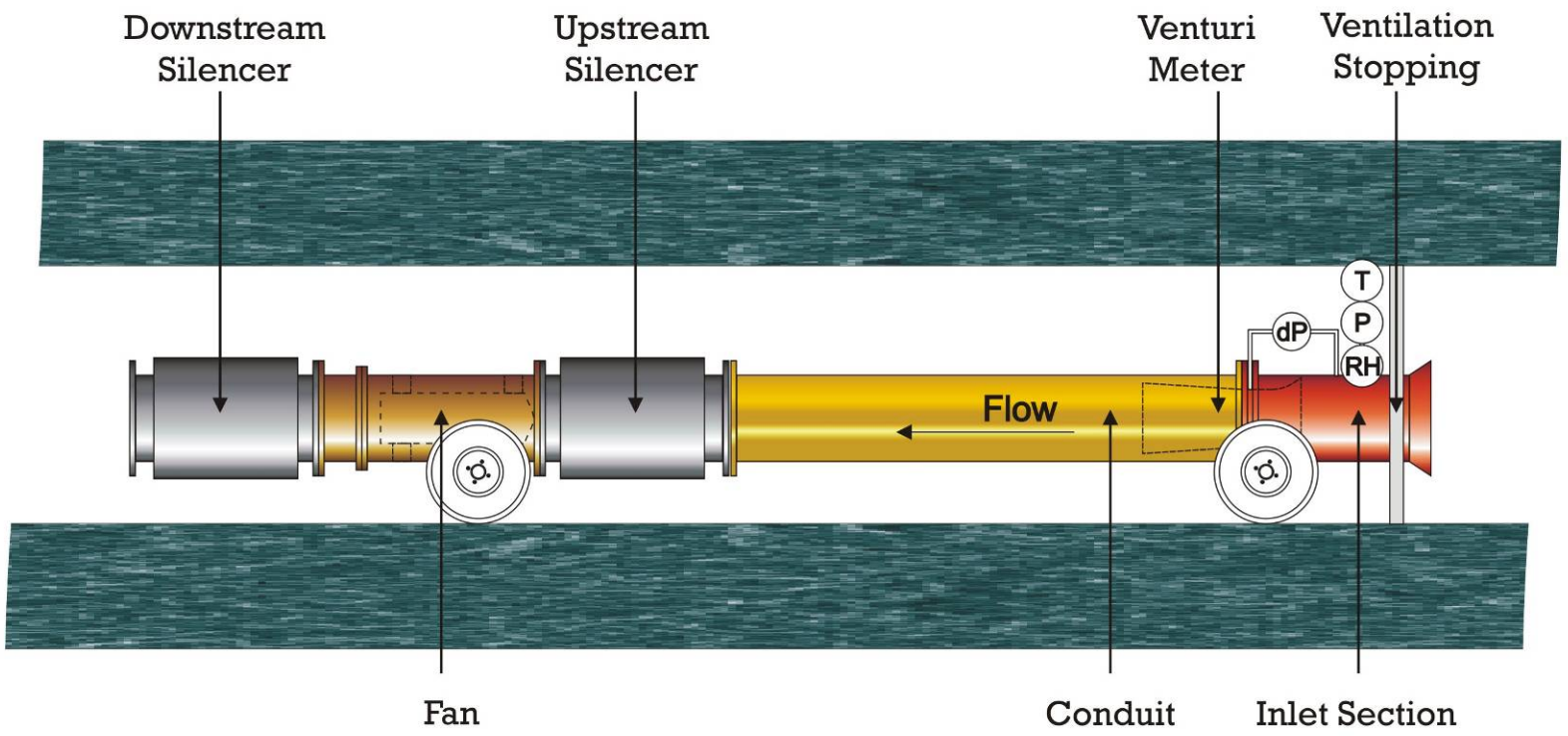


Instrumentation
Downstream and Tailpipe Sampling and Measurement Stations

Chemiluminescence Detector
Eco Physics, CLD 700 MED

Non-dispersive IR &
Heated FID (California Analytical Instruments, Models 300 –NDIR, and 300-HFID)

Ventilation Measurement and Control



$Q_{AVG} = 5.75 \pm 0.04\ m^3/s\ (12188 \pm 78\ ft^3/min)$

Fuel Used in the Study

ULSD: Guttman Oil (Belle Vernon, PA)

Analysis done by Core Laboratories, Houston, TX

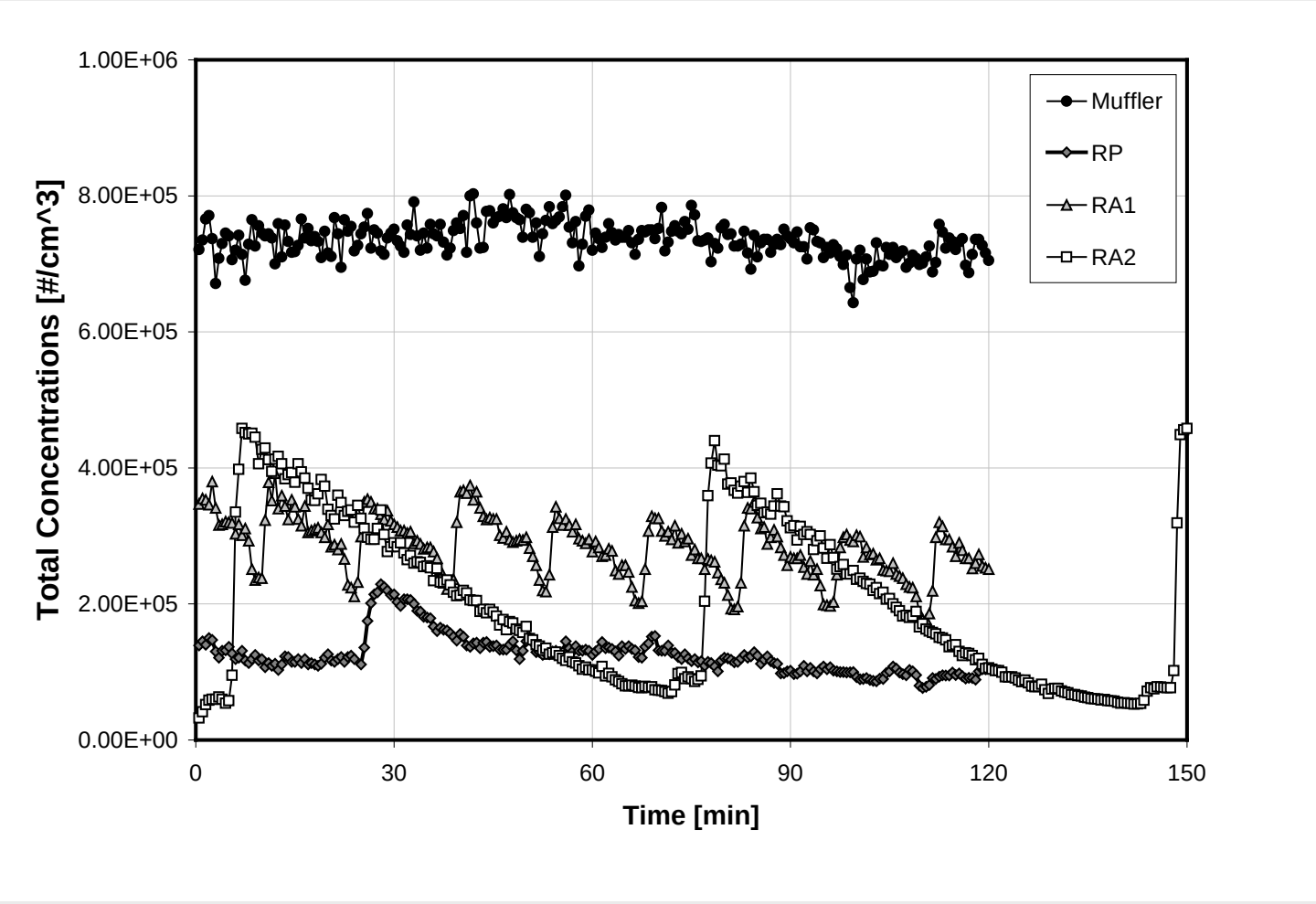
Test	Method	Unit	ULSF
Energy, Net	ASTM D-240	kJ/kg (BTU/lb)	46486 (19999)
Cetane Number	ASTM D-613	-	58.1
Density	ASTM D-4052	g/ml	0.8050
Oxygen Content	ASTM D-5291M	Wt. %	0.51
Flash Point, PMCC	ASTM D-93A	°C (F)	61 (142)
Sulfur Content	ASTM D-5453	mg/kg	10.0

Results

- Effects of the system on concentrations and size distribution of diesel aerosols in mine air (FMPS).
- Effects of the system on total aerosol number concentrations (FMPS).
- Effects of the system on total aerosol mass concentrations (TEOM).
- Effects of the system on total elemental carbon concentrations (NIOSH 5040).
- Effects of the system on total alveolar region deposited aerosol surface area (NSAM).
- Effects of the system (DOC) on tailpipe CO and HC emissions.

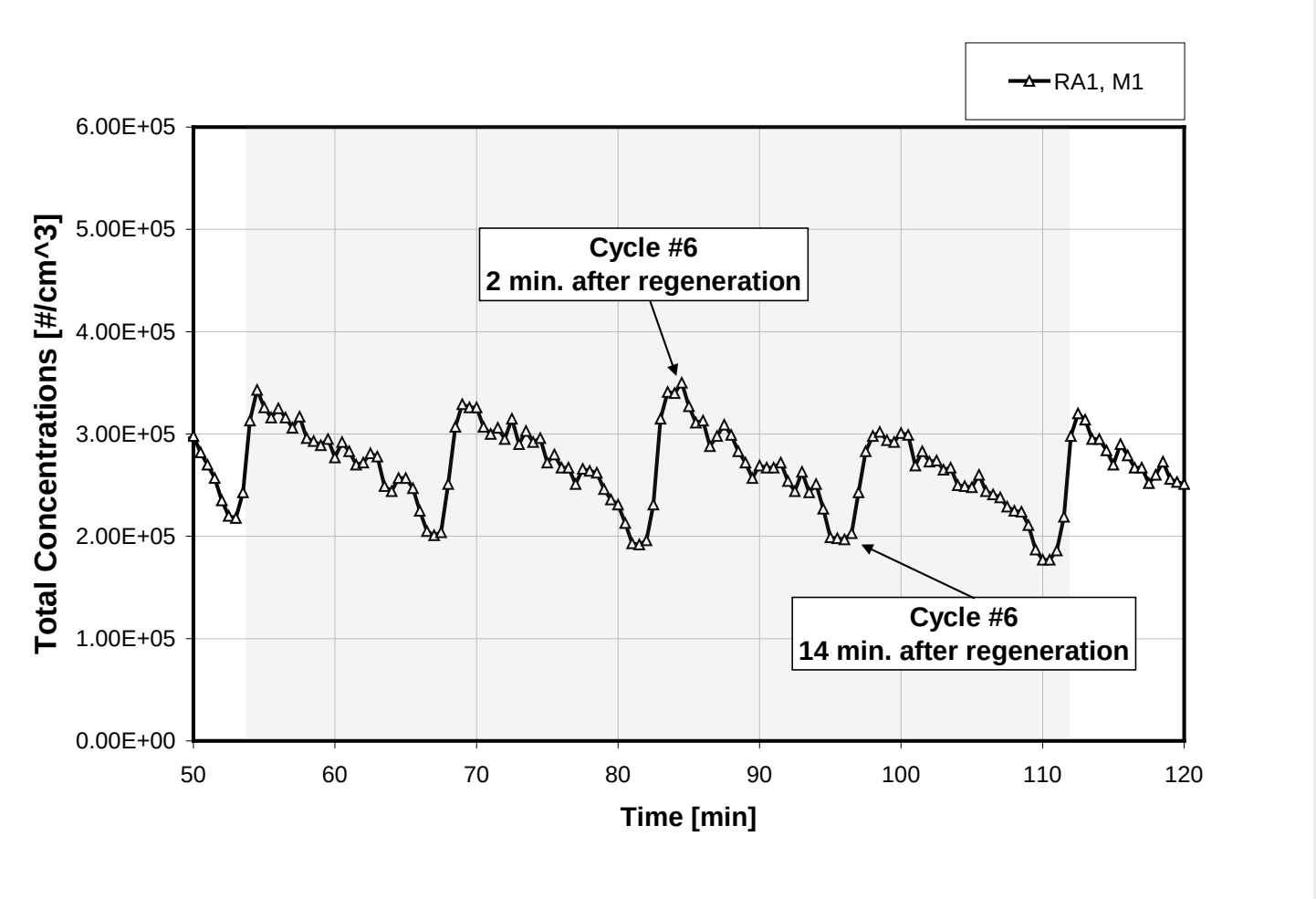
Effects of the System on Total Number Concentrations and Size Distributions
Fast Mobility Particle Sizer (FMPS)

Effects of the System on Number Concentrations (FMPS) Mode 1



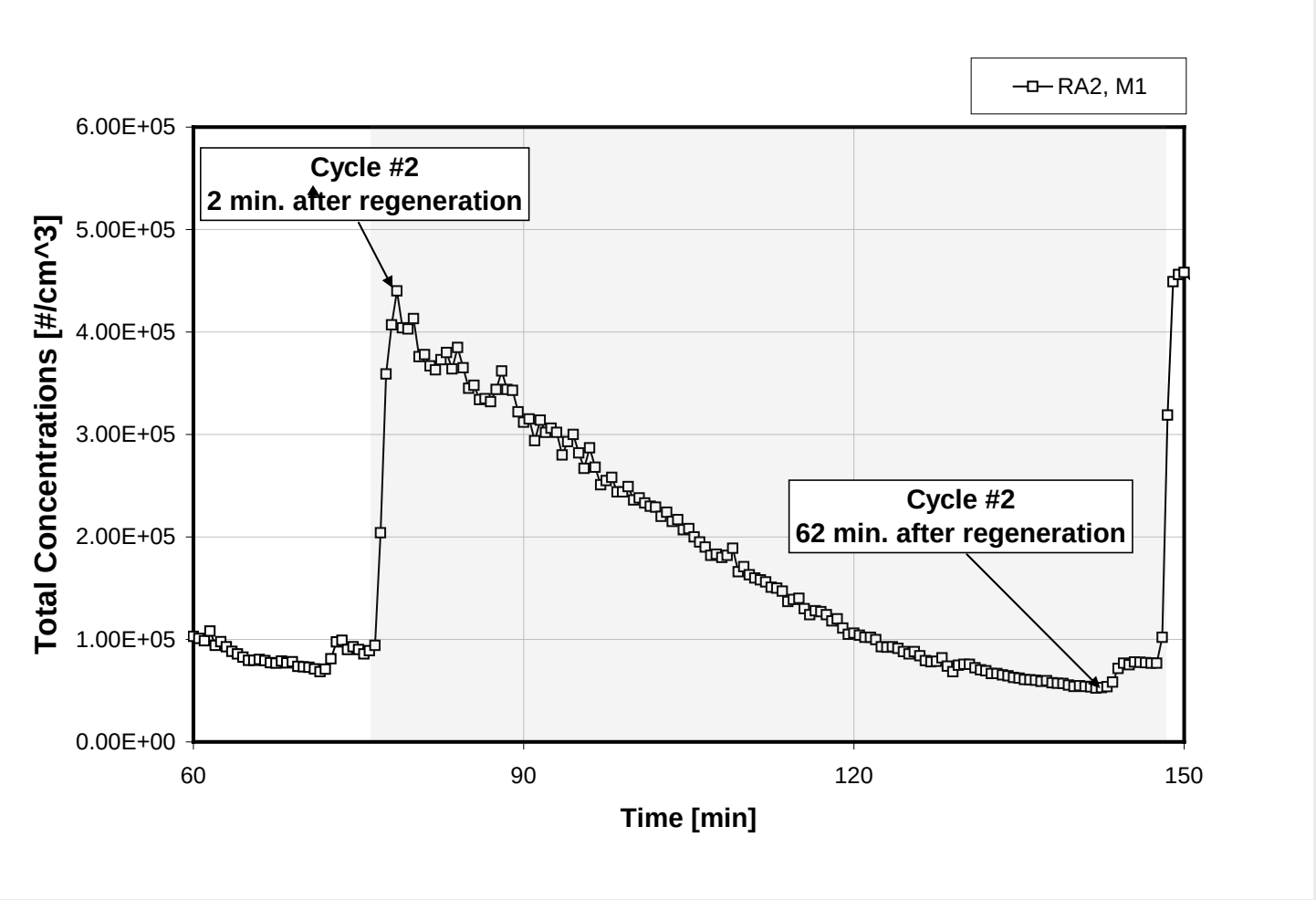
- Number concentrations of aerosols at the downstream station were strongly affected by the system and regeneration scheme.
- The concentration were found to be relatively constant during muffler and RP runs. The concentrations were highest for muffler case.

Effects of the System on Number Concentrations (FMPS) Mode 1, Rypos DPF Active 1 (RA1)



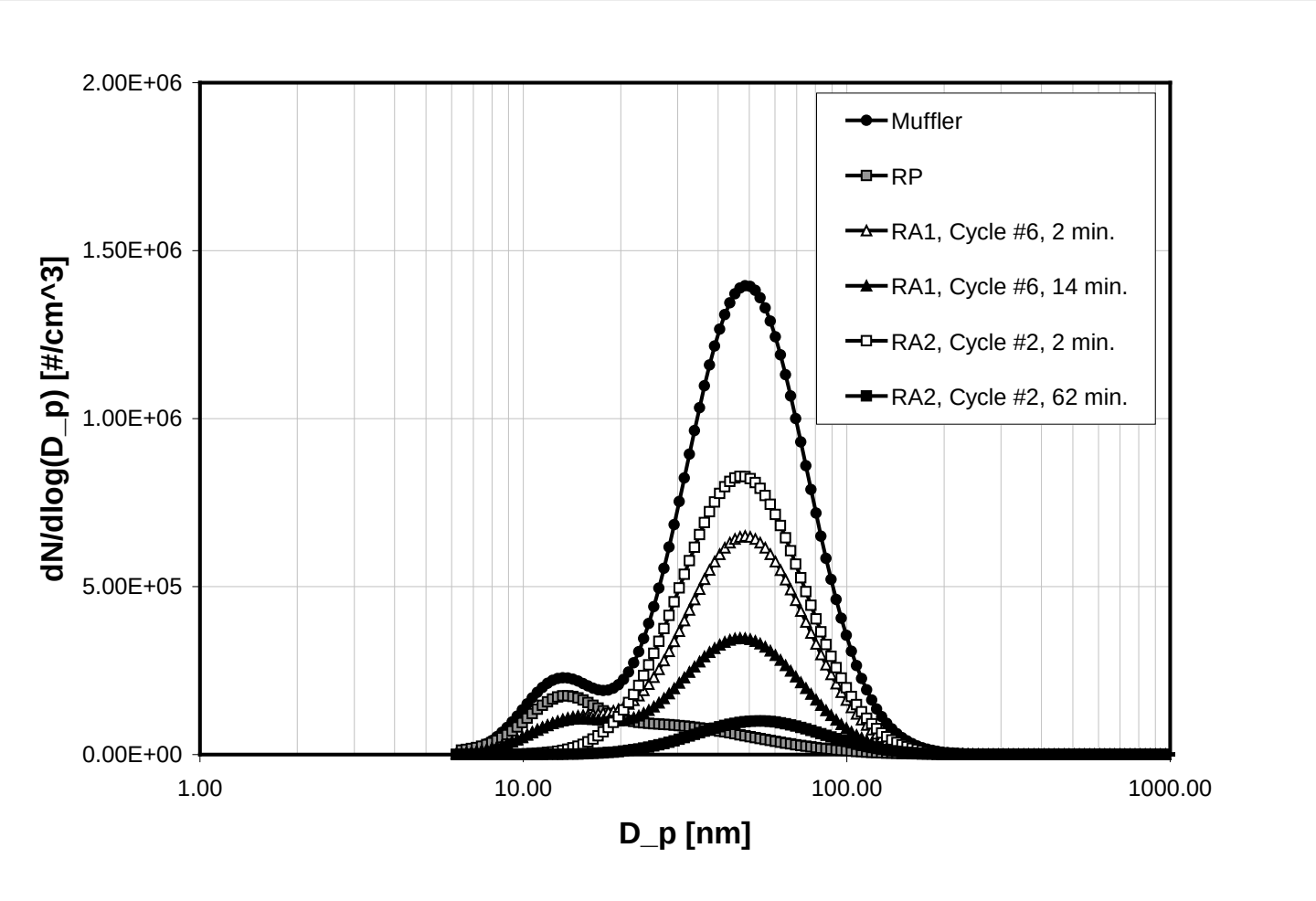
- When the system was operated with activated regeneration system (RA1 & RA2) the concentrations were found to have cyclic transient nature.
- The cycles were directly related to regeneration events.

Effects of the System on Number Concentrations (FMPS) Mode 1, Rypos DPF Active 2 (RA2)



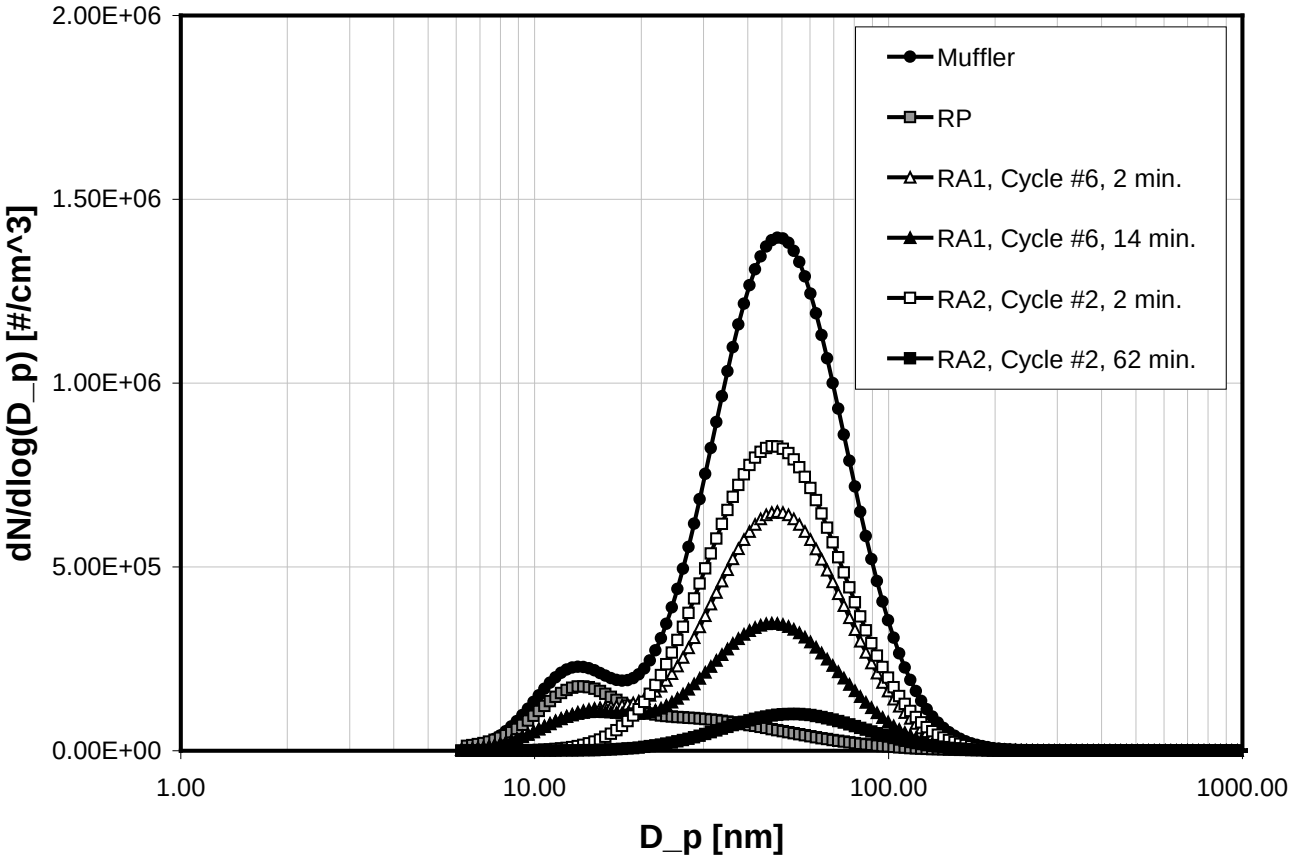
- The transient nature of the processes made data processing complicated.
- E.g., averaging involved recognizing and time lining regeneration cycle patterns.
- The representative size distributions were selected for specific events.

Effects of the System on Size Distributions (FMPS) Mode 1, Summary



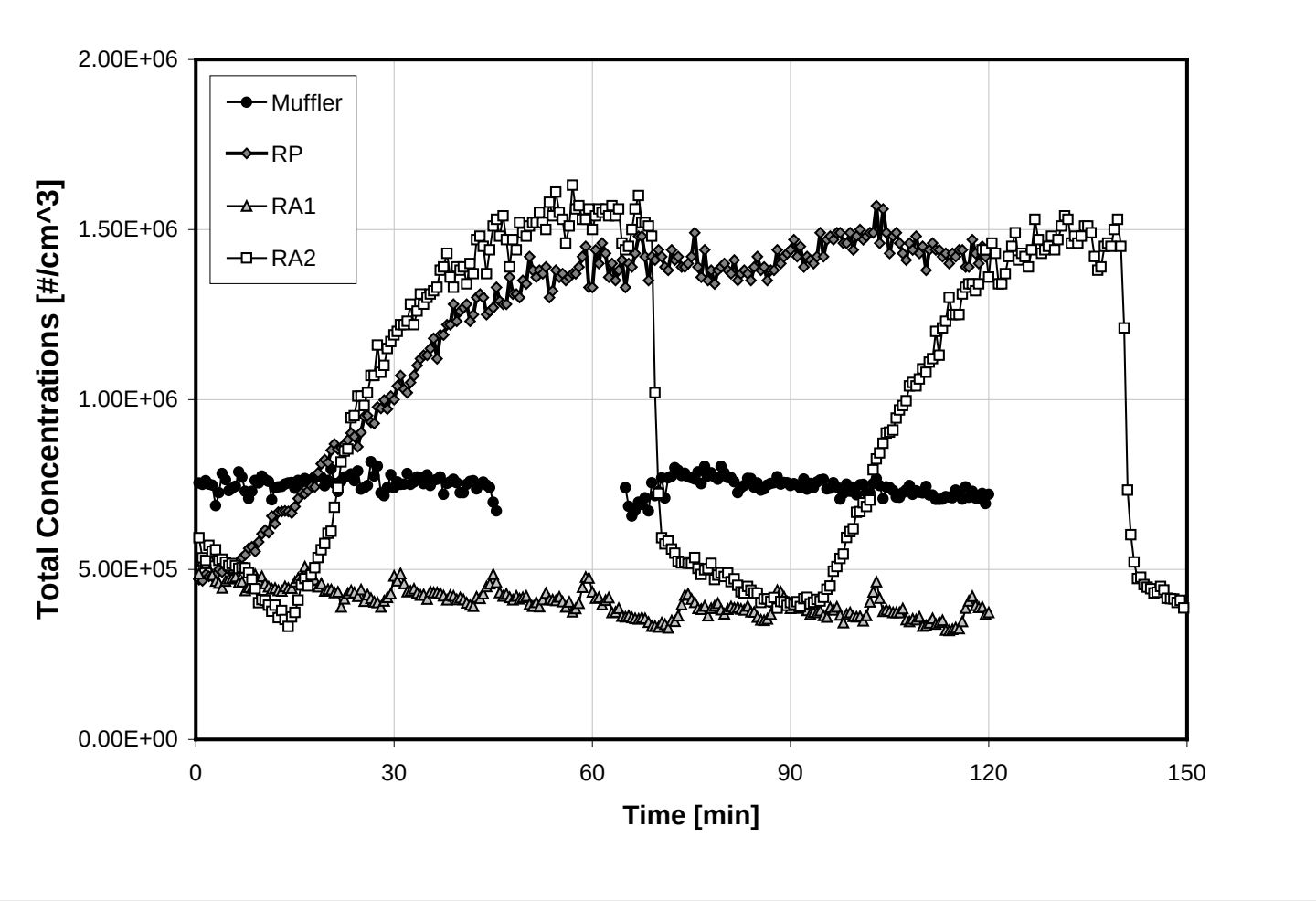
- For M1 (Muffler, RA1, and RA2) size distributions were found to be bimodal with pronounced accumulation and slight hint of nucleation mode.
- The system in passive mode reduced very effectively concentrations of aerosols in accumulation mode.

Effects of the System on Size Distributions (FMPS) Mode 1, Summary - continued



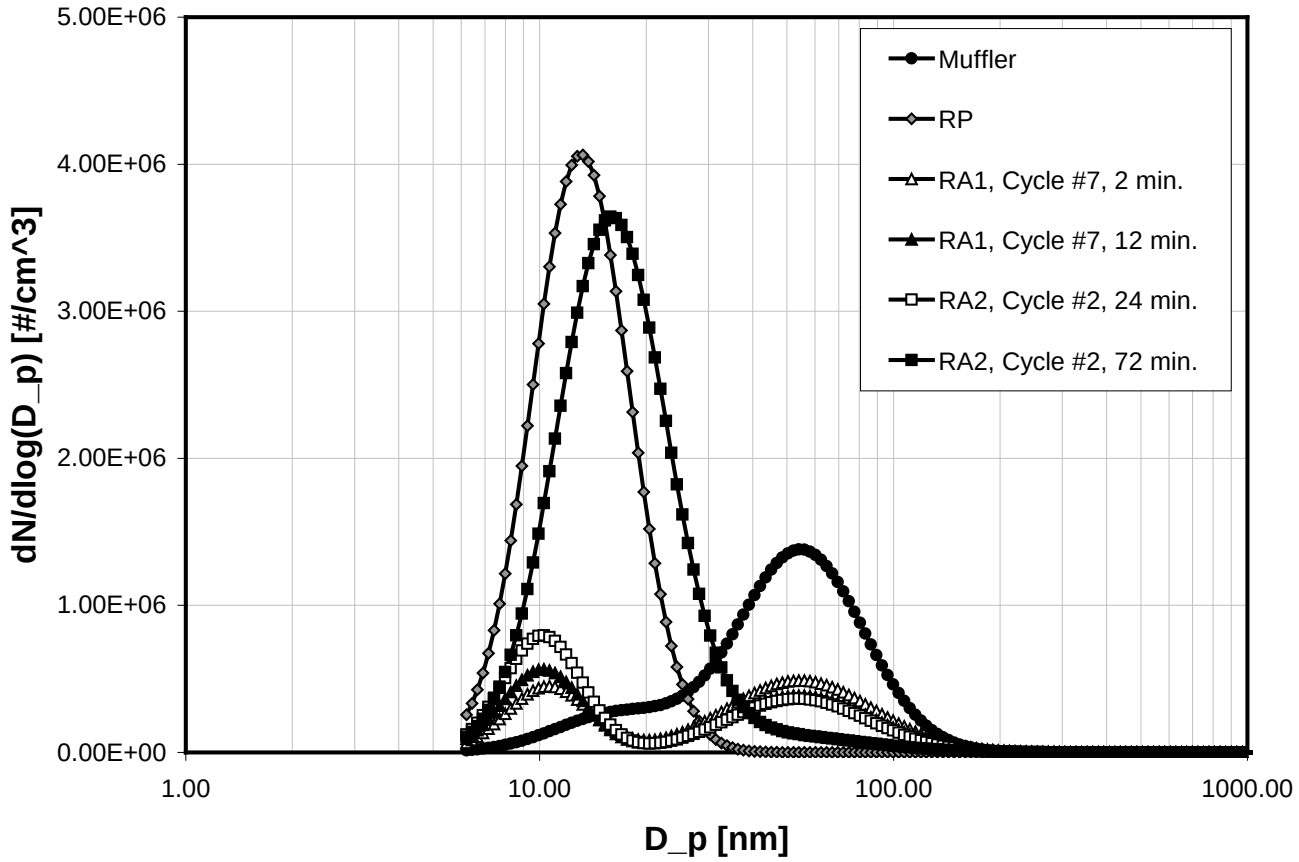
- For RA1 and RA2, the concentrations of aerosols in accumulation mode were significantly higher at the beginning then at the end of the regeneration cycles.

Effects of the System on Number Concentrations (FMPS) Mode 2



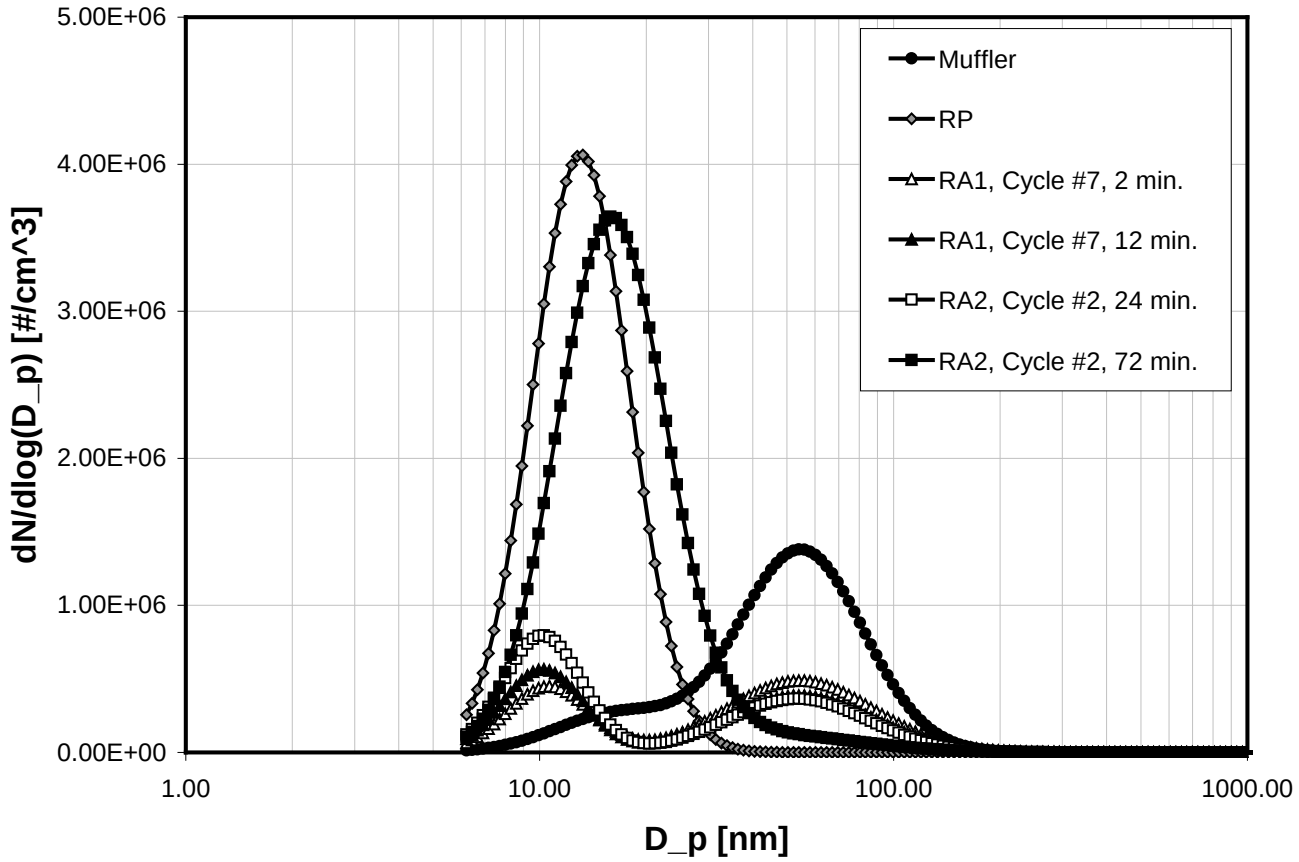
- For M2, number concentrations of aerosols at the downstream station were also found to be strongly affected by the system and regeneration scheme.
- The concentrations were highest for RP and RA2 cases.

Effects of the System on Size Distributions (FMPS) Mode 2, Summary



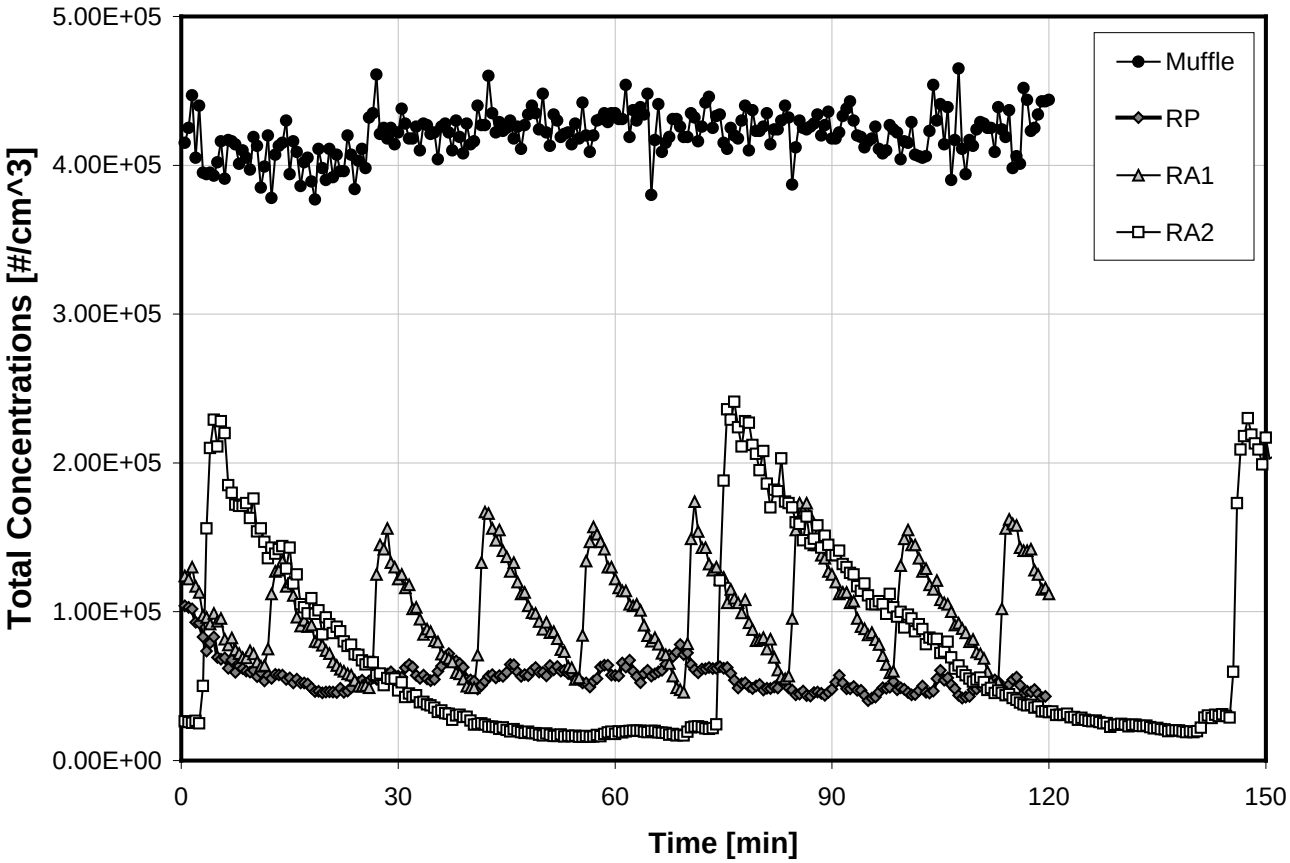
- For M2, all size distributions were found to be bimodal.
- In the case of the muffler the majority of aerosols were in accumulation mode.
- For the passive system (RP), majority of aerosols were found in nucleation mode.

Effects of the System on Size Distributions (FMPS) Mode 2, Summary



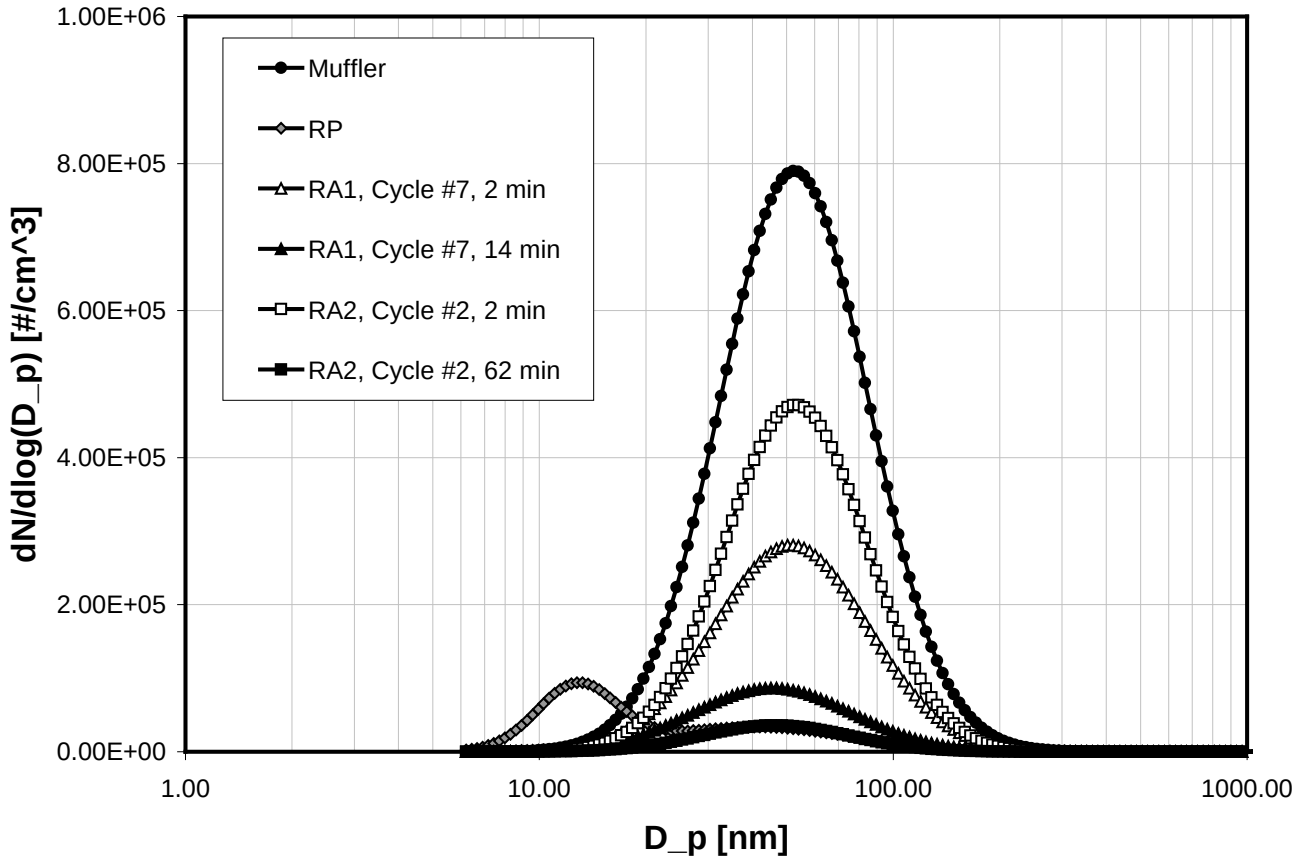
- In the case of actively regenerated system, the length of regeneration cycle was found to have tremendous affect on size distributions.
- The concentrations of aerosols in nucleation mode were found to grow significantly with time between regenerations.

Effects of the System on Number Concentrations (FMPS) Mode 3



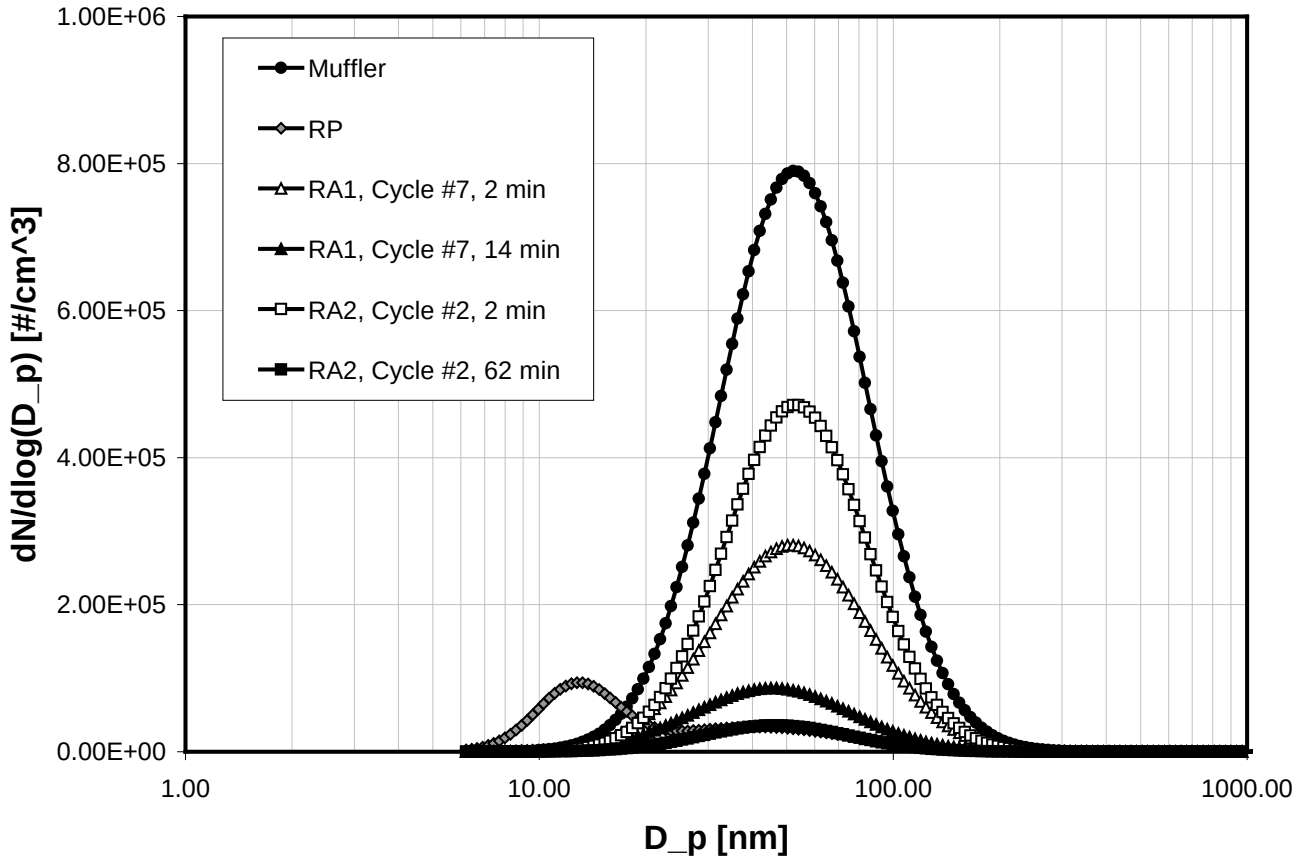
- For M3, number concentrations of aerosols at the downstream station were also found to be strongly affected by the system and regeneration scheme.
- The concentrations were highest for muffler case.

Effects of the System on Size Distributions (FMPS) Mode 3, Summary



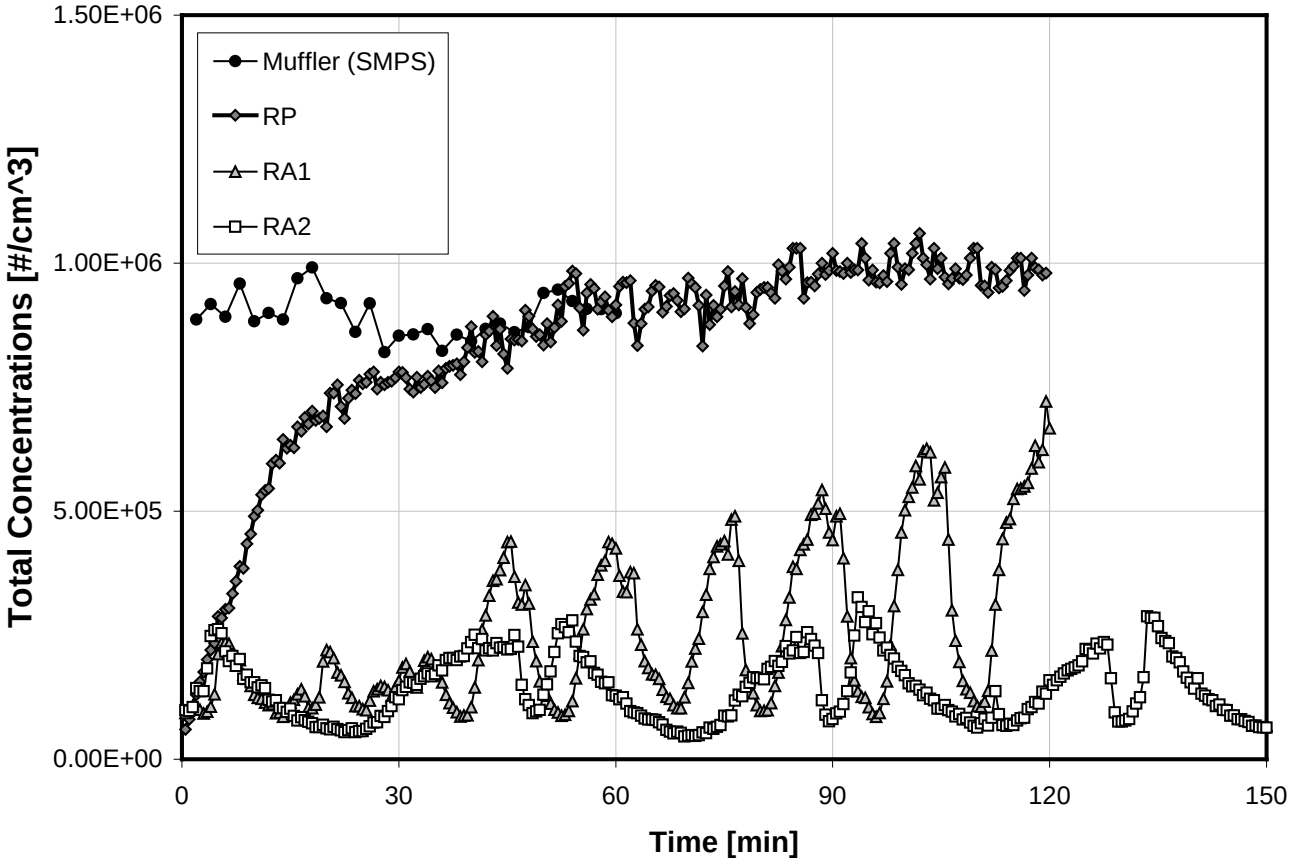
- For M3, all size distributions, except one for the passively operated system were found to be single modal with the majority of aerosols in accumulation mode.
- For the passive system (RP), the aerosols were found to be equally distributed between nucleation and accumulation modes.

Effects of the System on Size Distributions (FMPS) Mode 3, Summary



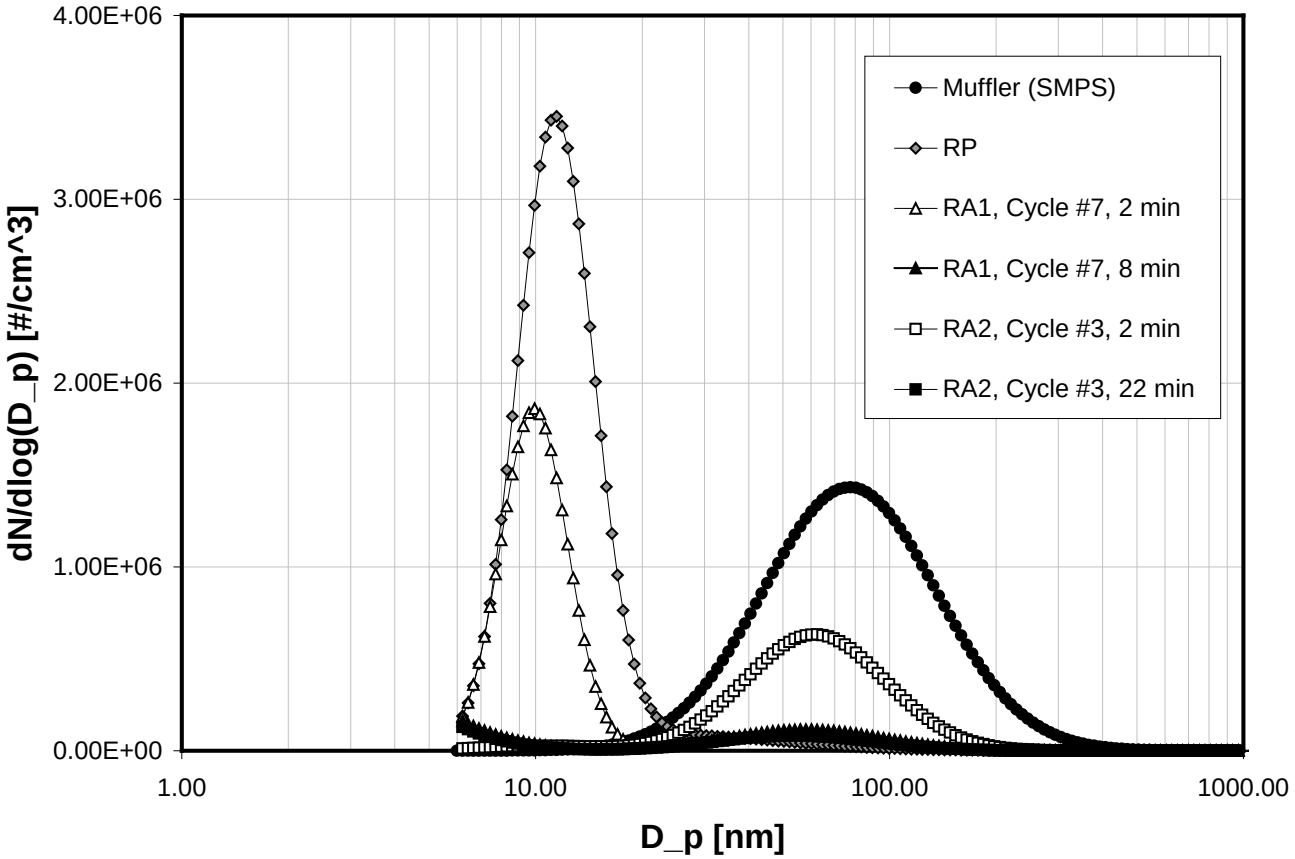
- In the case of actively regenerated system, the length of regeneration cycle was directly related to increase in effectiveness of the system in removing accumulation mode aerosols.
- For M3 (RA1 and RA2), no aerosols were found in nucleation mode.

Effects of the System on Number Concentrations (FMPS) Mode 4



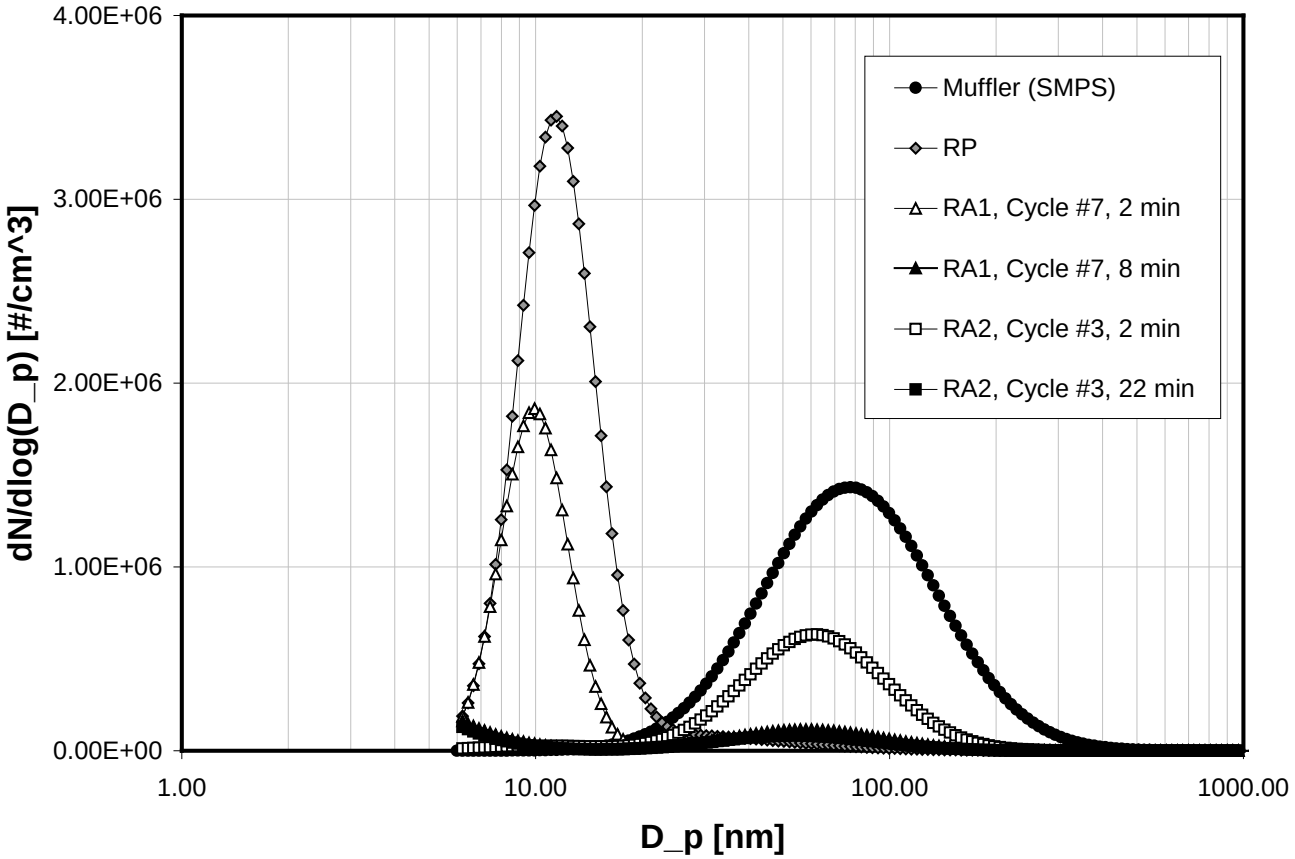
- For M4, number concentrations of aerosols at the downstream station were also found to be strongly affected by the system and regeneration scheme.
- The concentrations were equally high for muffler and RP cases.

Effects of the System on Size Distributions (FMPS) Mode 4, Summary



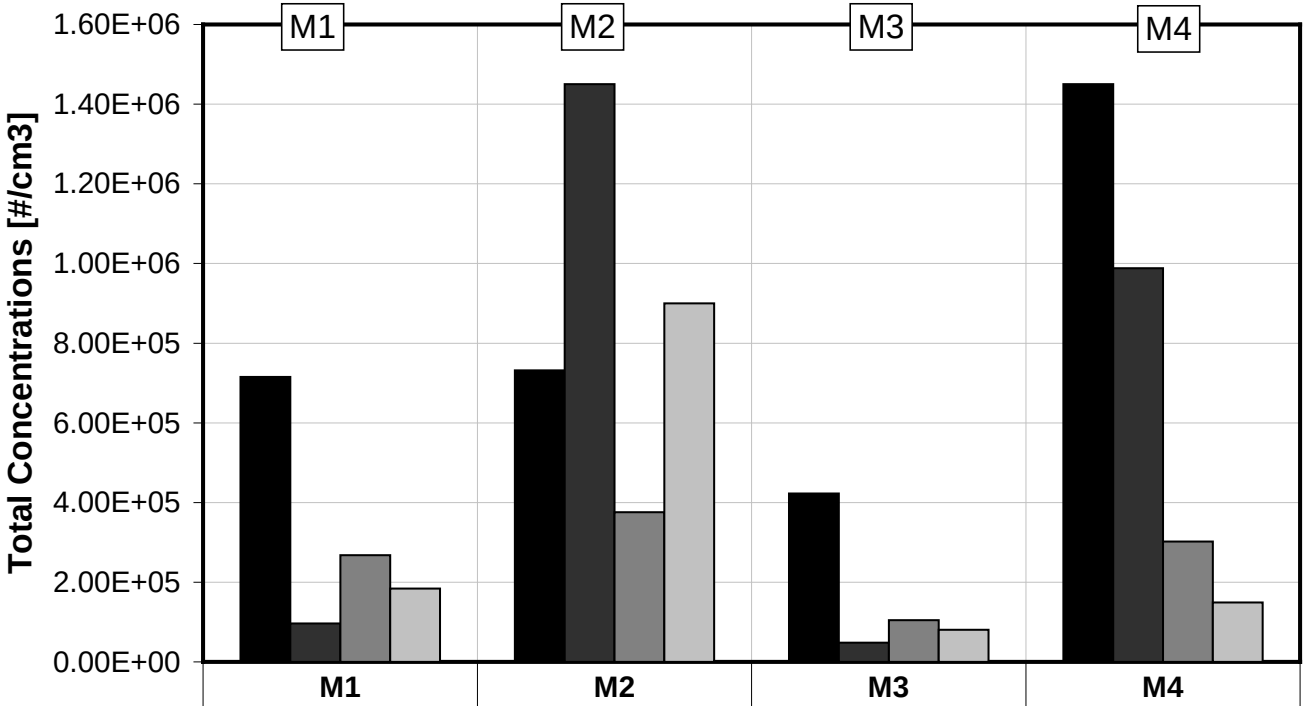
- For M4, the size distributions were found to be single modal (Muffler & RA2) or bimodal (RP & RA1).
- For the passively operated system (RP), the majority of aerosols were found to be in nucleation mode.

Effects of the System on Size Distributions (FMPS)
Mode 4, Summary



- In the case of actively regenerated system (RA1), concentrations of aerosols in nucleation mode were highest shortly after regeneration, and almost completely disappeared several minutes later.
- No aerosols were found in nucleation mode for RA2 case.

Effects of the System on Total Number Concentrations - FMPS M1, M2, M3, and M4

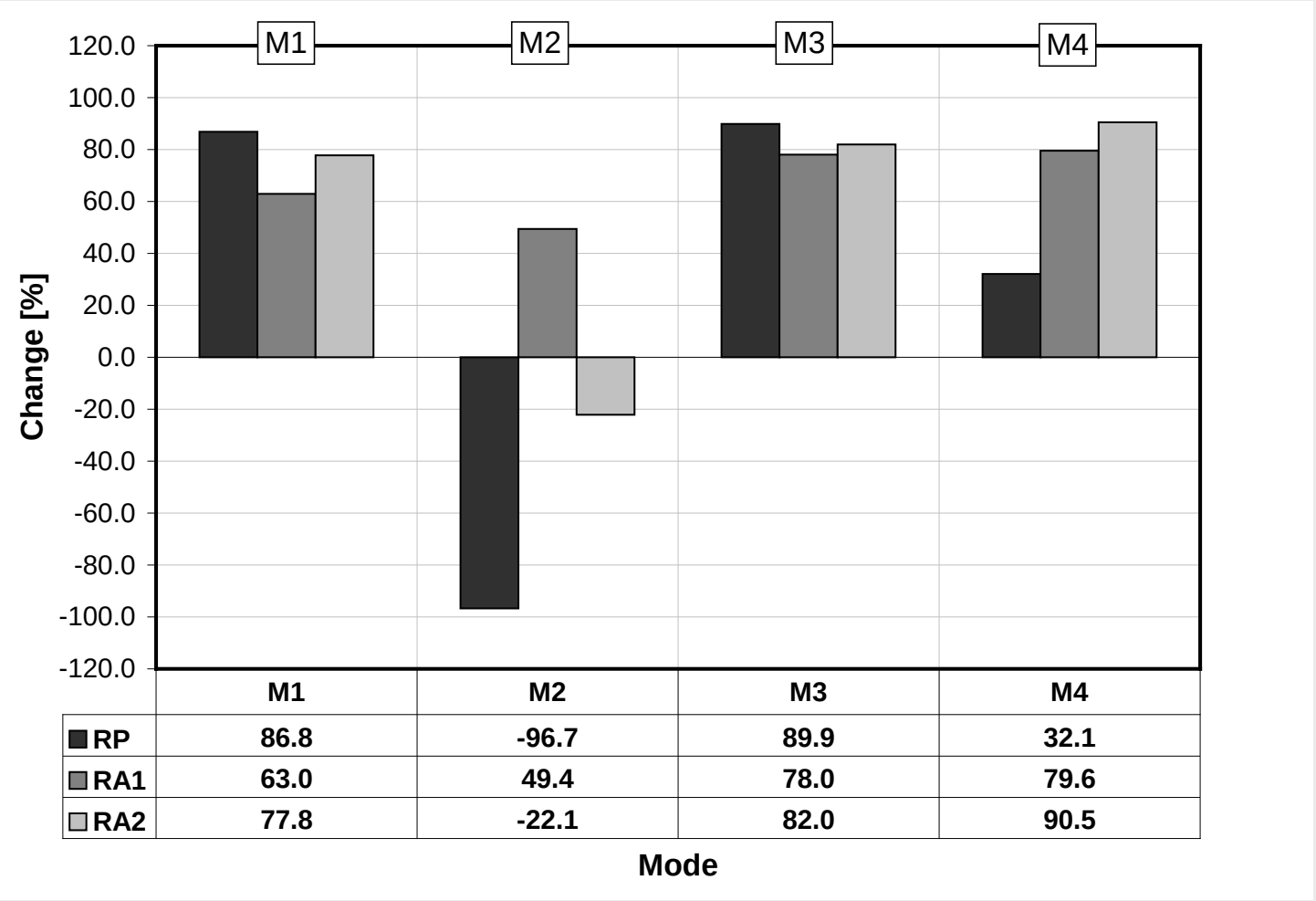


	M1	M2	M3	M4
Muffler	715000	732000	423000	1450000
RP	96300	1450000	48200	988000
RA 1	268000	376000	105000	302000
RA 2	184000	900000	80500	149000

Mode

- Rypos (RP, RA1, RA2) reduced total number concentrations for M1, M3, and M4.
- In the case of M2 (RP and RA2) large number of nucleation mode particles resulted in increase of number concentrations over the baseline.

Effects of the System on Total Number Concentrations - FMPS M1, M2, M3, and M4

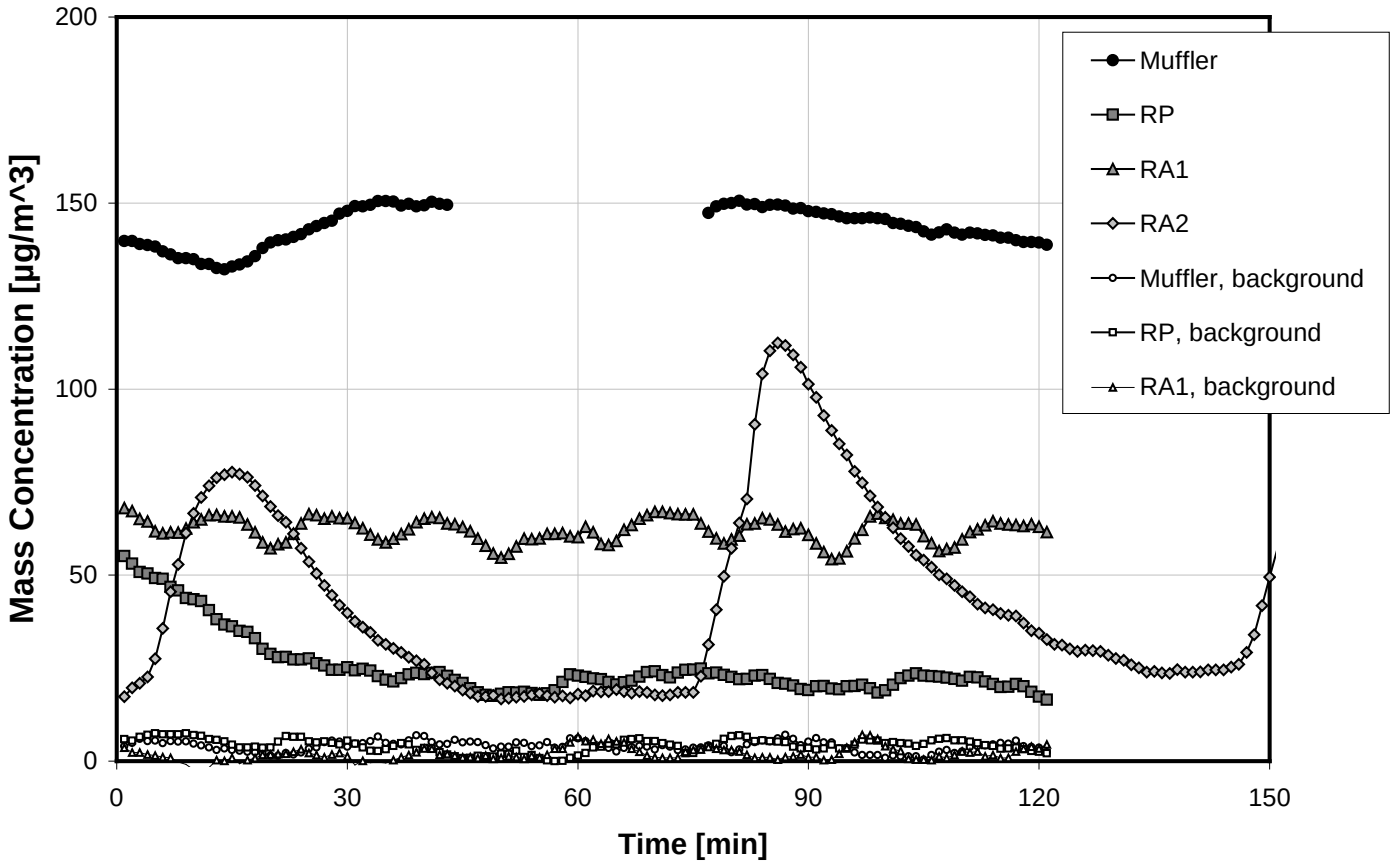


	M1	M2	M3	M4
RP	86.8	-96.7	89.9	32.1
RA1	63.0	49.4	78.0	79.6
RA2	77.8	-22.1	82.0	90.5

- Reductions in total number concentrations for M1 and M3 were highest for passive mode (RP).
- Highest increase in total number concentrations was observed for M2, passive mode (RP).

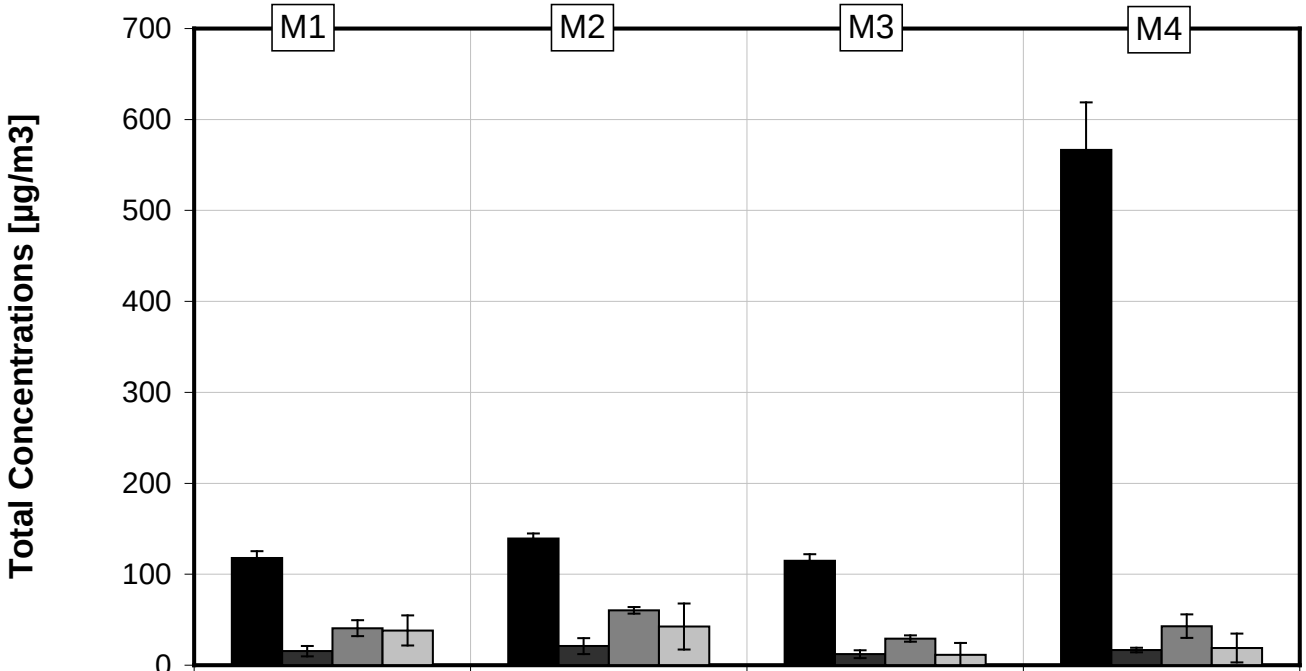
Effects of the System on Mass Concentrations
TEOM

Effects of System on Mass Concentrations, TEOM Mode 2



- Low background concentrations (<10 µg/m³)
- Traces reflect transient nature of the processes for RA1 and RA2.
- The response time of the instruments and averaging process resulted in time shift.

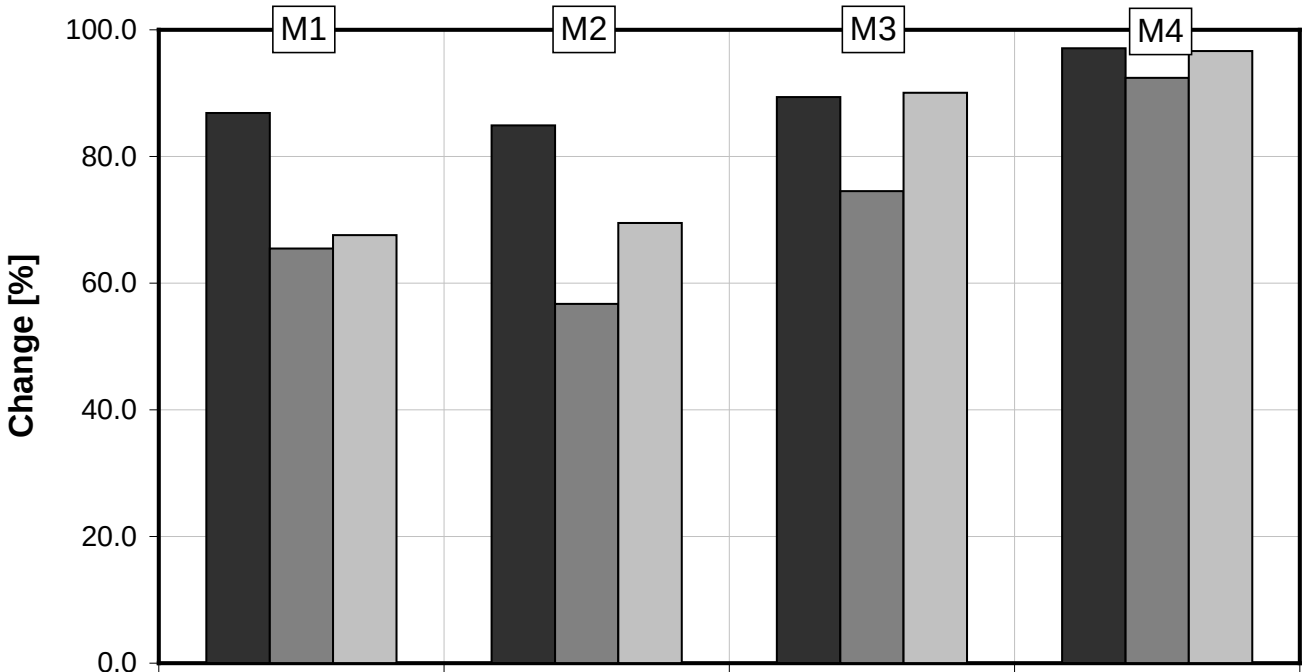
Effects of the System on Average Mass Concentrations TEOM



	M1	M2	M3	M4
Muffler	117.9	139.3	114.8	566.6
RP	15.5	21.0	12.2	16.6
RA1	40.7	60.3	29.3	42.9
RA2	38.2	42.5	11.4	19.0

- Rypos DPF system reduced substantially total mass concentrations measured by TEOM for all modes and regeneration schemes.

Effects of the Rypos DPF System on Average Mass Concentrations TEOM

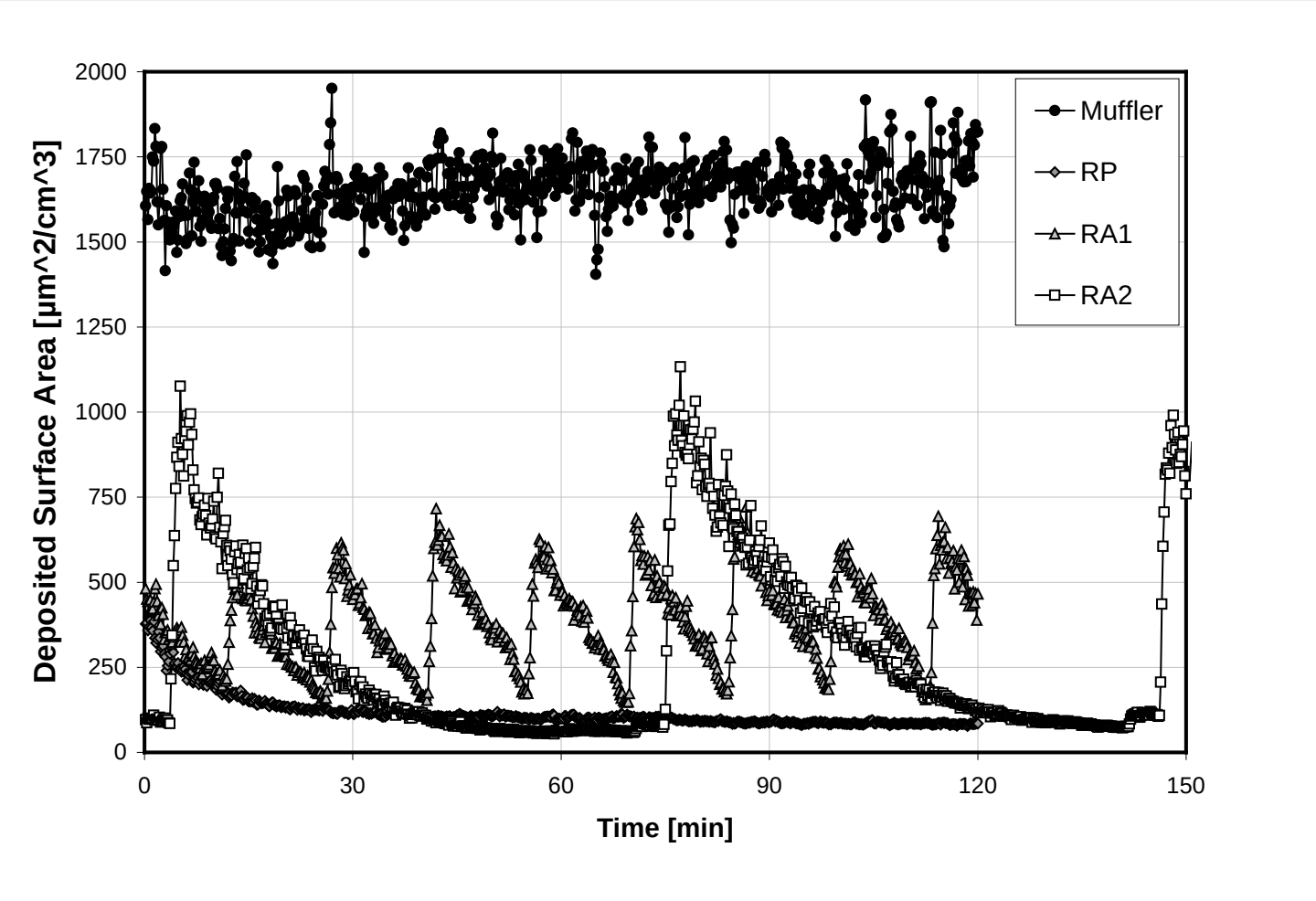


	M1	M2	M3	M4
RP	86.8	84.9	89.4	97.1
RA1	65.5	56.7	74.5	92.4
RA2	67.6	69.5	90.0	96.6

- The highest reductions in mass concentrations were observed for passive system (87-97 %).
- Average reductions were found to be directly and positively related to the length of regeneration cycle.

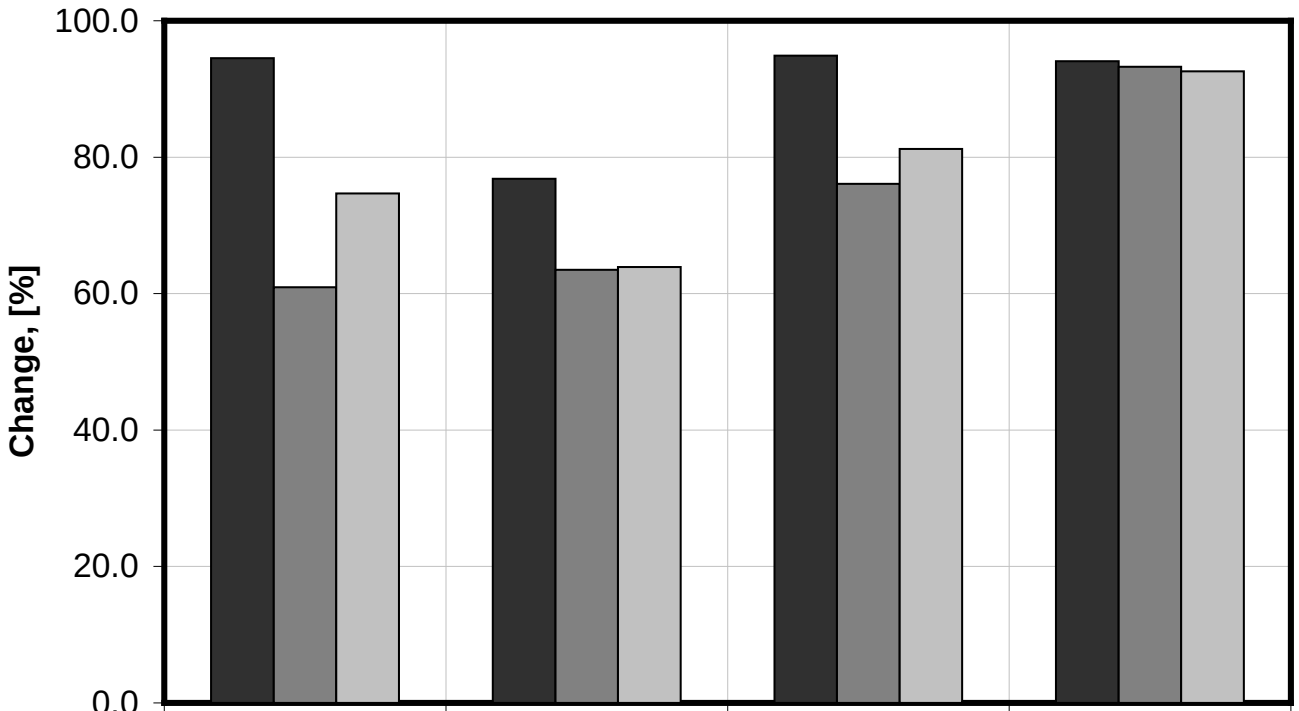
Effects of the System on Total Alveolar Region Deposited Surface Area Nano Surface Area Monitor (NSAM)

Effects of the System on Alveolar Region Deposited Surface Area - NSAM
M3 (Example)



- Traces reflect transient nature of the processes for RA1 and RA2.

Effects of the System on Total Alveolar Region Deposited (TARD) Surface Area M1, M2, M3, and M4

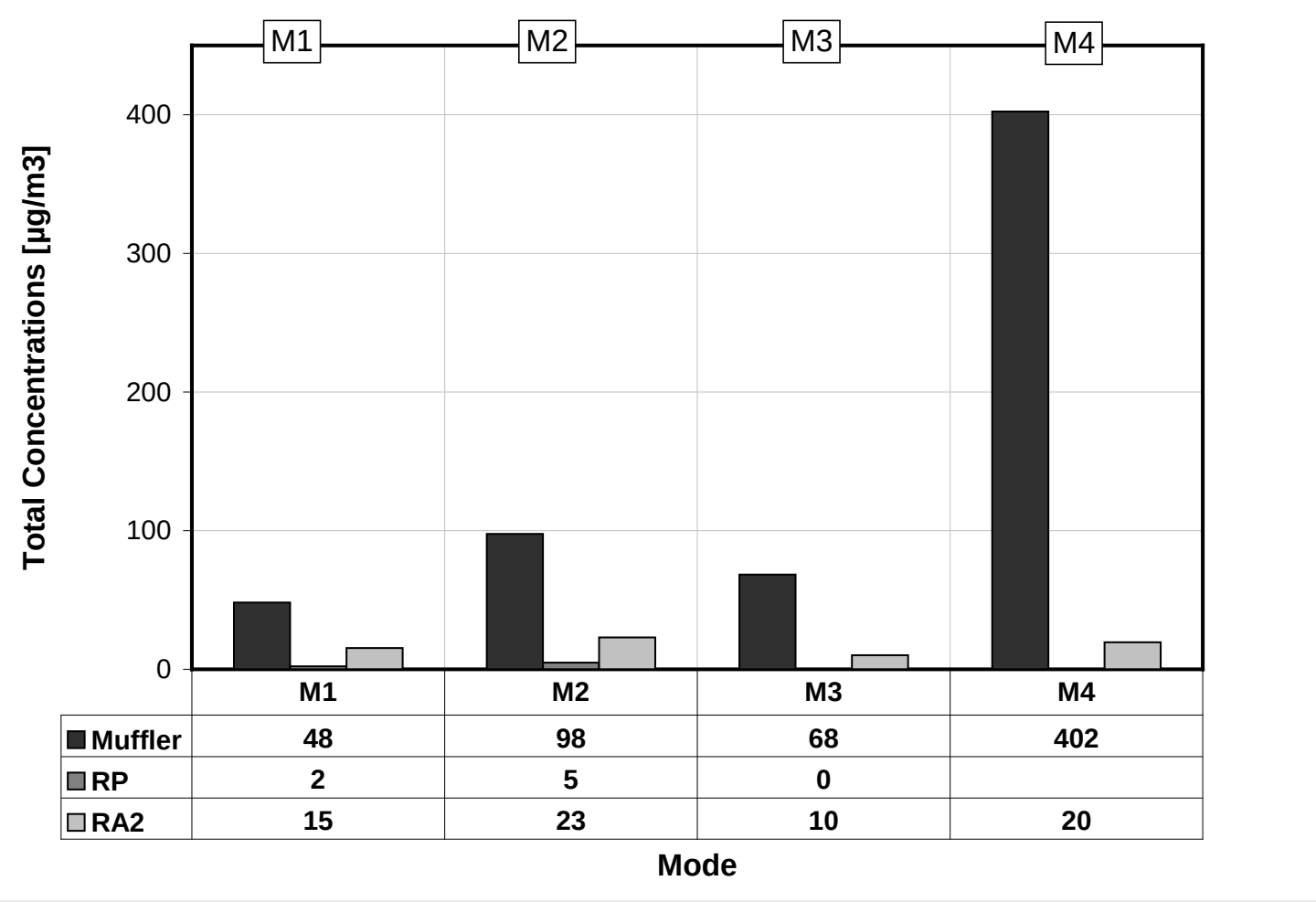


	M1	M2	M3	M4
RP	94.5	76.8	94.9	94.1
RA1	61.0	63.5	76.1	93.3
RA2	74.7	63.9	81.2	92.6

- The highest reductions in total alveolar region deposited surface area were observed for passive system (77 - 95 %).
- The relation between length of regeneration cycle and effectiveness of the system in removing TARD surface area was not clear.

Effects of the System on Integrated Elemental Carbon Concentrations NIOSH 5040, Primary Filter

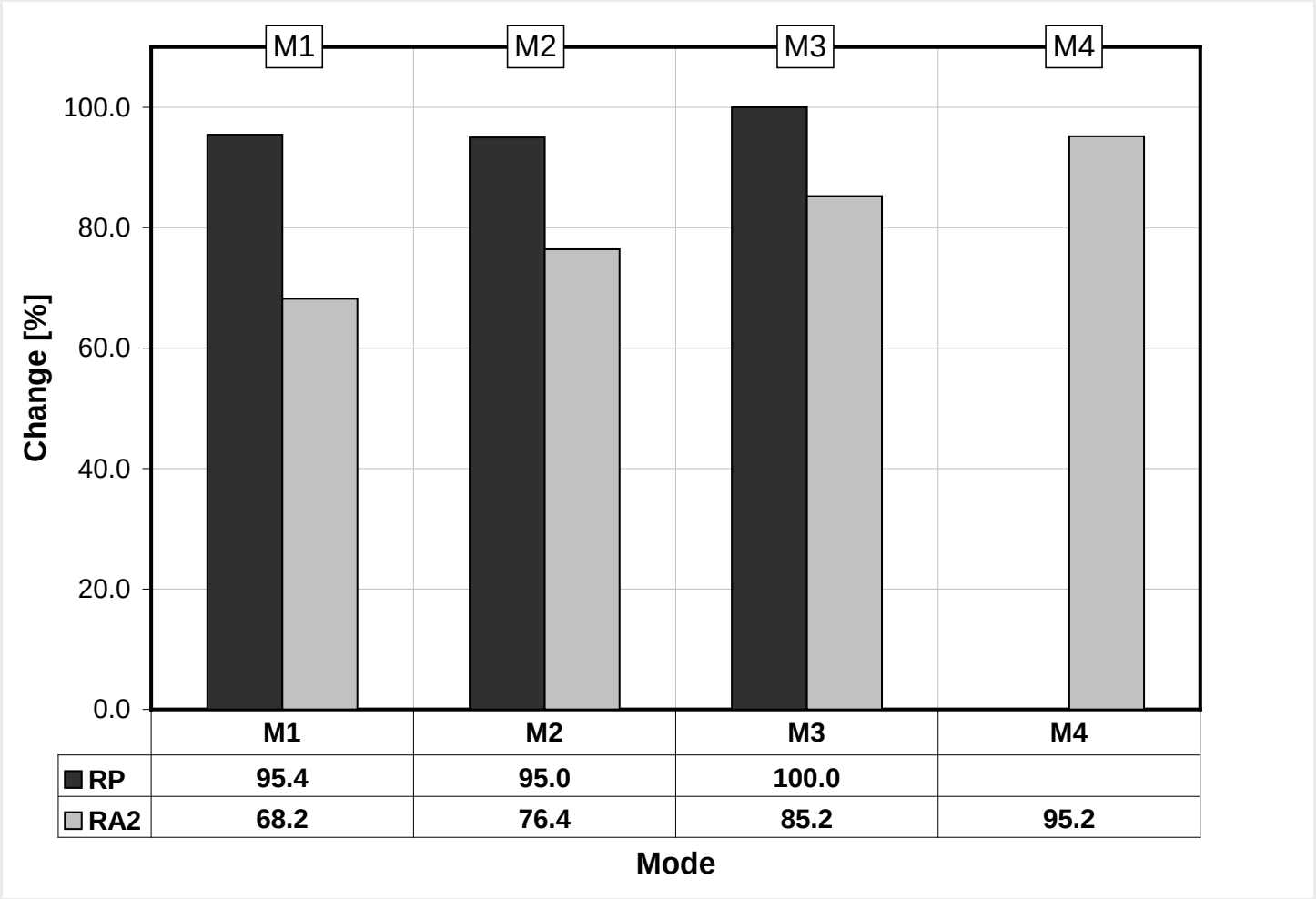
Effects of the System on Average Elemental Carbon (EC) Concentrations [µg/m^3]



	M1	M2	M3	M4
Muffler	48	98	68	402
RP	2	5	0	
RA2	15	23	10	20

- The downstream EC concentrations during RP test were extremely low (reported numbers at LOD level).
- Rypos DPF system reduced substantially EC concentrations for all modes and both regeneration schemes.

Effects of the System on Elemental Carbon (EC) Concentrations [%]

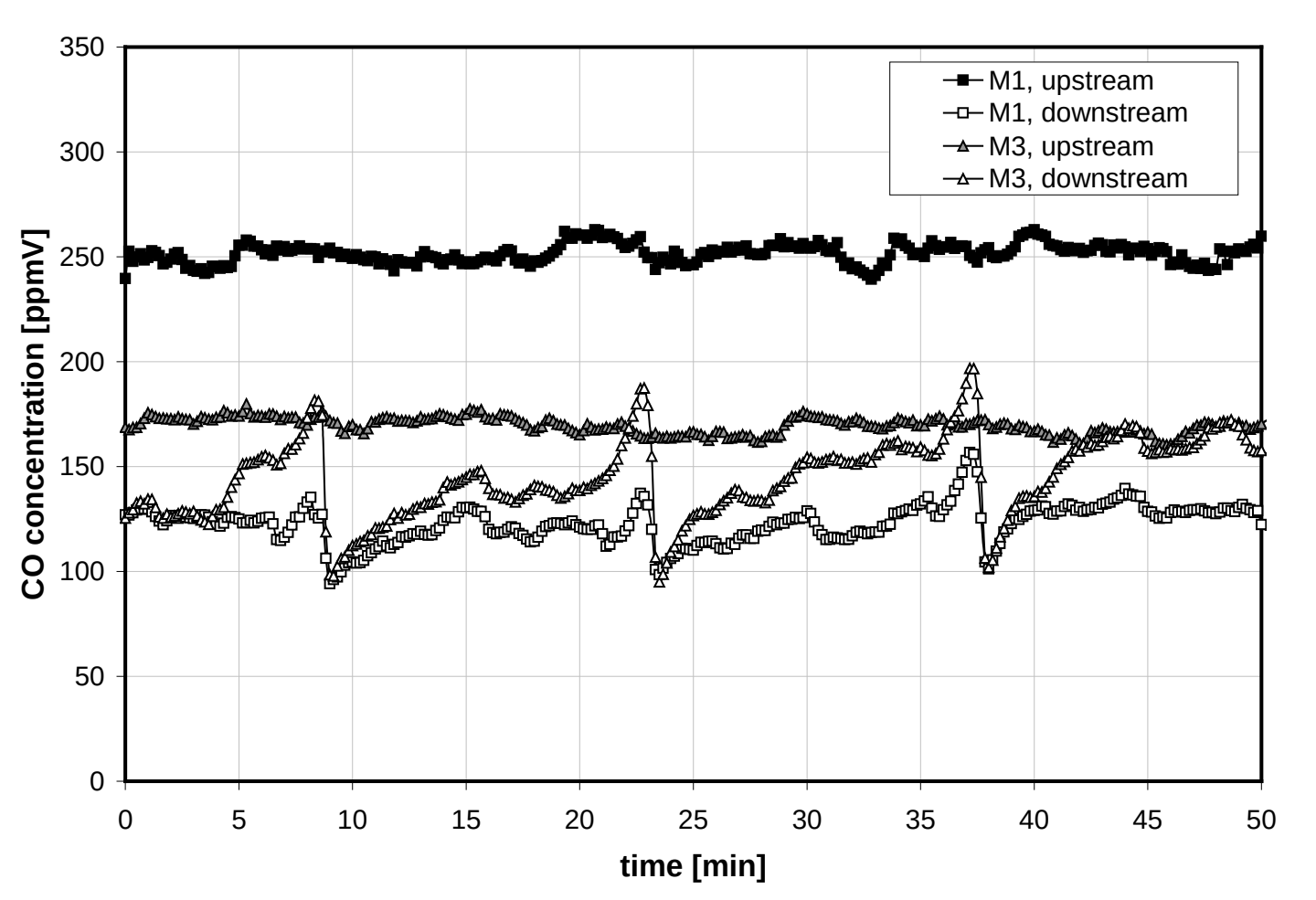


	M1	M2	M3	M4
RP	95.4	95.0	100.0	
RA2	68.2	76.4	85.2	95.2

- The reductions in EC concentrations are higher for passive version (RP) then for active version (RA2) of the system.

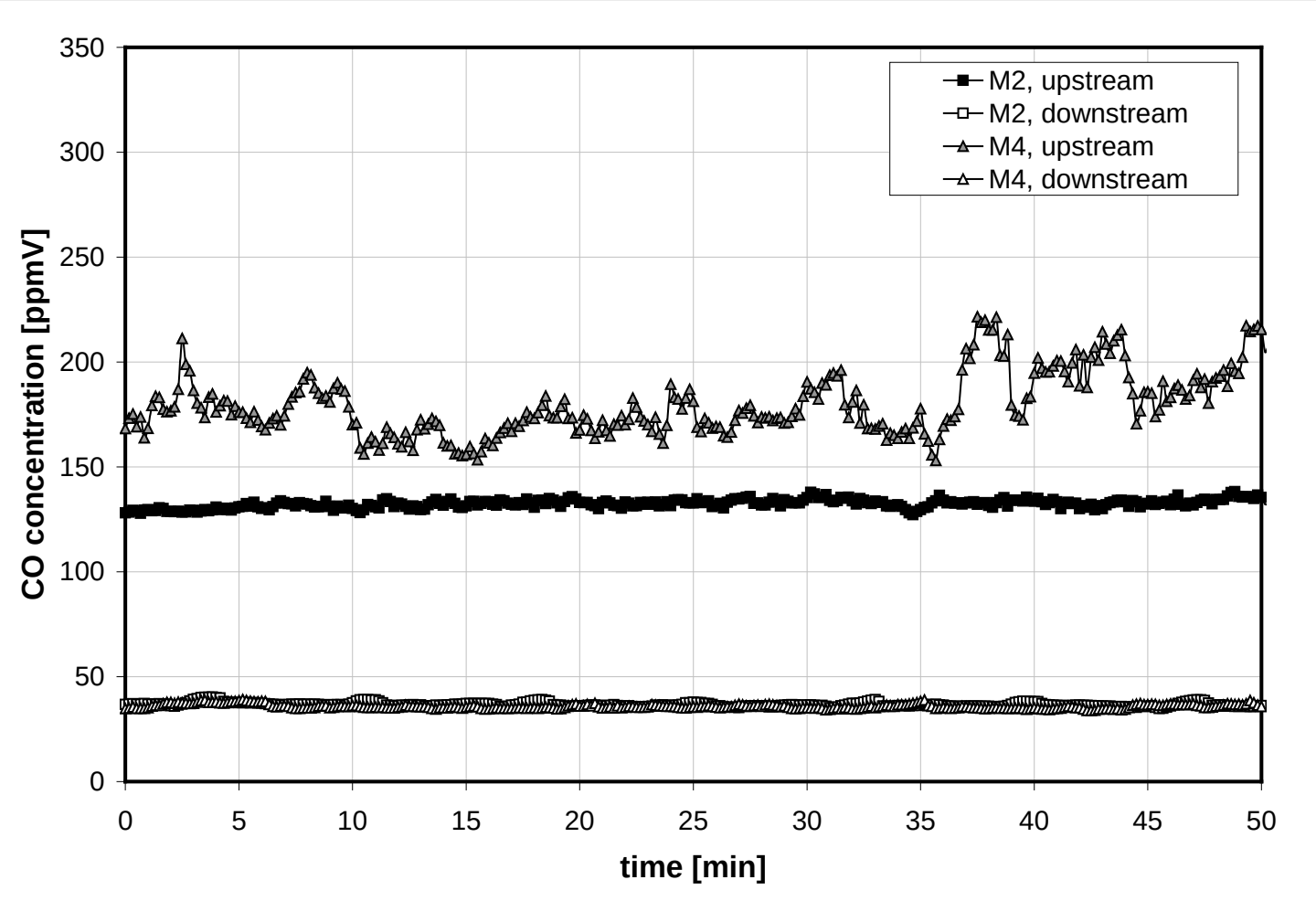
Effects of the System (DOC) on Tailpipe Concentrations of Carbon Monoxide (CO) and Hydrocarbons (HC)

Tailpipe Concentrations of CO Upstream and Downstream of Rypos DPF System, RA1, M1 & M3



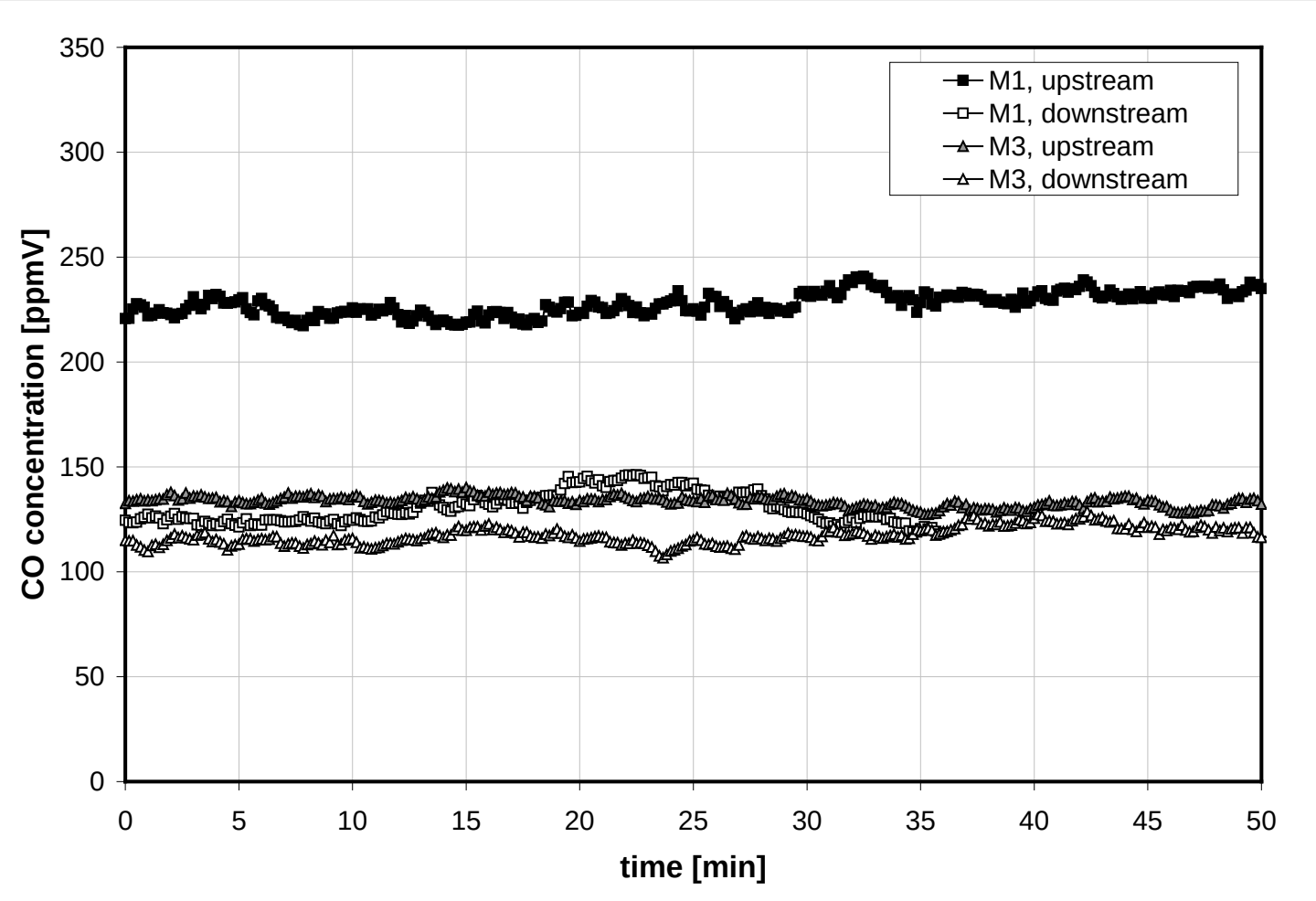
- For M1 and M3, DOC maintained CO concentrations at relatively high levels, but
- the peak concentrations downstream of system were significantly below (M1) or slightly above (M3) corresponding upstream concentrations.

Tailpipe Concentrations of CO Upstream and Downstream of Rypos DPF System, RA1, M2 & M4



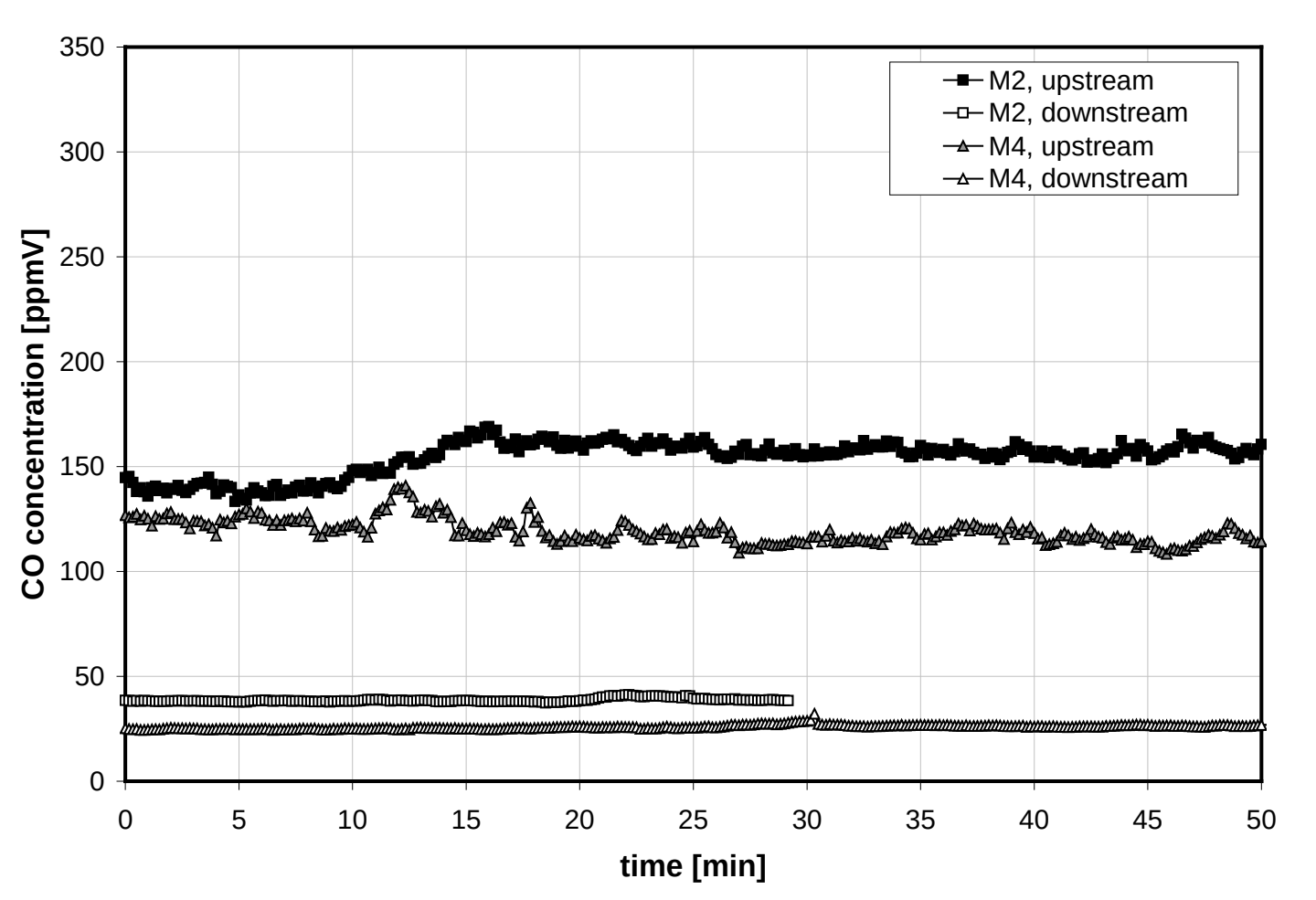
- DOC reduced more efficiently CO concentrations for M2 and M4 then for M1 and M3 but the concentrations were still at relatively high levels.
- In this case, the peak concentrations downstream of system were significantly below corresponding upstream concentrations.

Tailpipe Concentrations of CO Upstream and Downstream of Rypos DPF System, RA2, M1 & M3



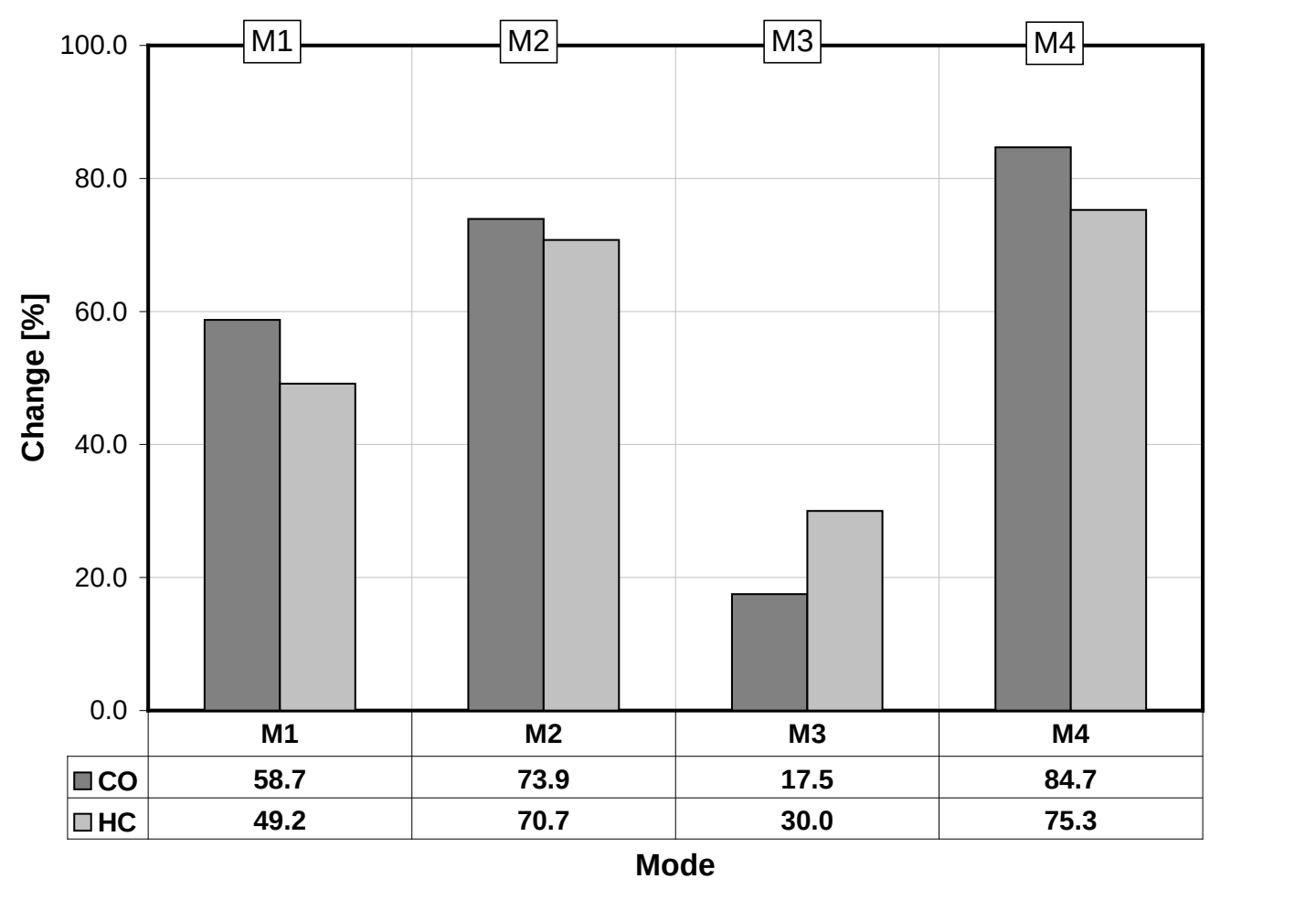
- For M1 and M3, DOC maintained CO concentrations at relatively high levels, but
- the peak concentrations downstream of system were significantly below (M1) or slightly below (M3) corresponding upstream concentrations.

Tailpipe Concentrations of CO Upstream and Downstream of Rypos DPF System, RA2, M2 & M4



- DOC was more effective in conversion of CO for M2 and M4 then for M1 and M3, but the concentrations were still at relatively high levels.
- The peak concentrations downstream of system were significantly below corresponding upstream concentrations for both modes.

Reduction in CO and HC Concentrations [%]



	M1	M2	M3	M4
CO	58.7	73.9	17.5	84.7
HC	49.2	70.7	30.0	75.3

- The CO and HC conversion efficiency of the DOC was found to be relatively modest.

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