



Particle Results From The AECC Programme and Their Relationship to PMP

AECC Technical Seminar on Heavy-duty Engine Emissions

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Jon Andersson

Manager, Chemistry Department

Shoreham Technical Centre, Ricardo UK

Objectives

- Measurement Approaches: Equipment
- Measurement Approaches: Particle Number
- PN Results
- Measurement Approaches: Particulate Mass
- PM results
- Overview
- Contributions to PMP

Objectives of AECC Exercise Aligned with PMP ILCE_HD



□ AECC

- Demonstrate the performance of an integrated emissions control system on a modern, low NOx engine.
- **Compare current gravimetric and heavy-duty PMP method for particulate mass (PM)**
- **Assess heavy-duty PMP particle number (PN) methodology**
- **Provide data on European and World-harmonised transient and steady-state test procedures.**
- Provide NTE (not-to-exceed) data for appropriate test points.
- Provide comparison data on US-FTP, Japanese and World-harmonised non-road cycles.
- Provide data on regulated and non-regulated emissions.

□ PMP Inter-laboratory correlation exercises

- **Demonstrate the repeatability and reproducibility of proposed measurement systems for PM and PN developed in earlier phases of PMP**
- **Gain experience in the measurement protocols and use this to revise draft regulatory documentation**
- **Accumulate PN data on engine technologies when testing to the proposed protocols**
- **Test ETC, WHTC and ESC Cycles**

□ Substantial areas of alignment between AECC programme and ILCE_HD

- Objectives

- Measurement Approaches: Equipment**

- Measurement Approaches: Particle Number

- PN Results

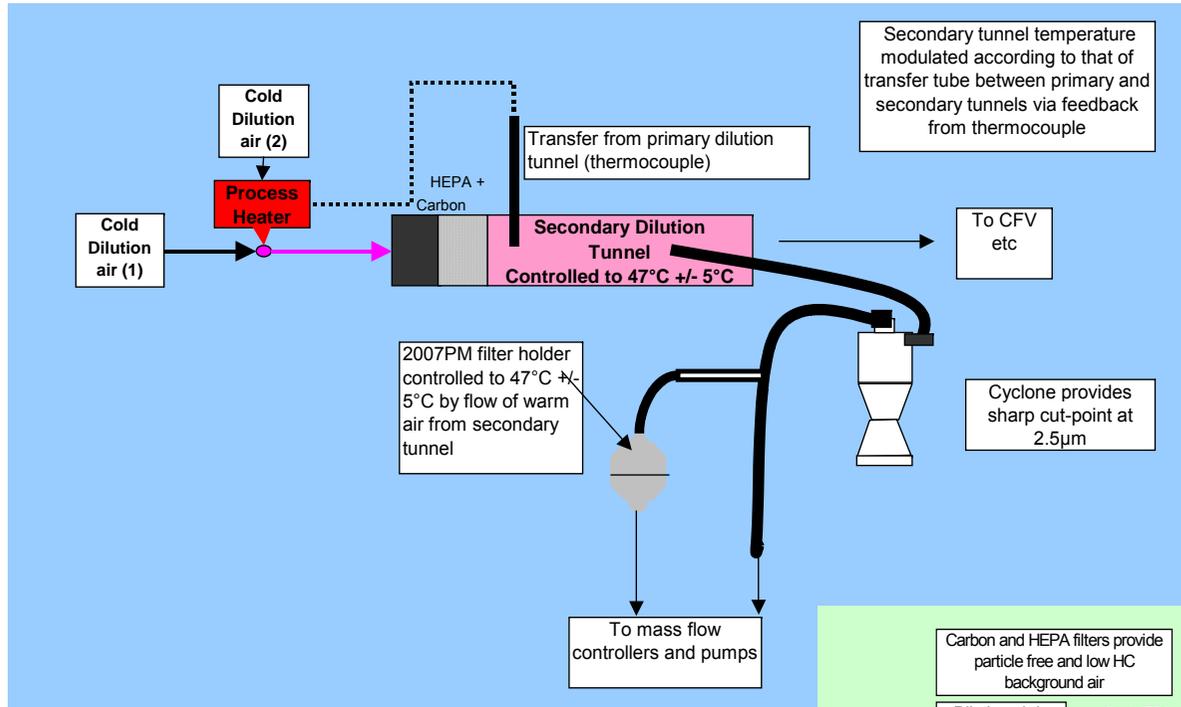
- Measurement Approaches: Particulate Mass

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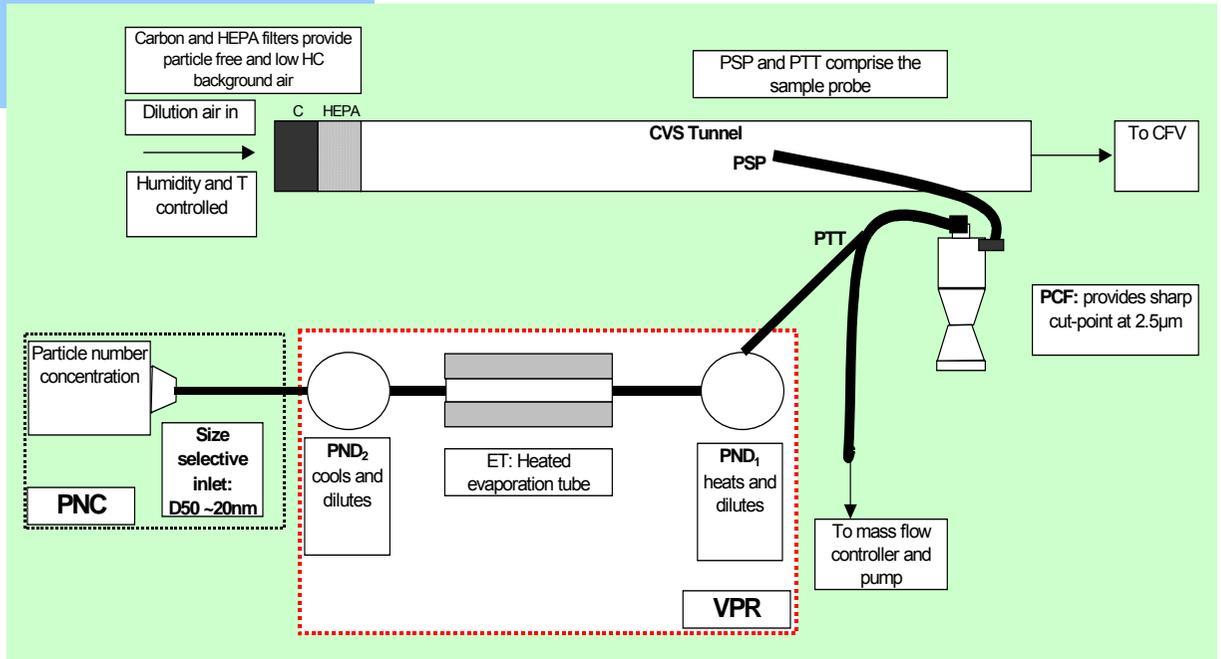
PMP ILCE_HD Measurement Approaches Employed in AECC Study



- ❑ PN: PMP Compliant Method*
 - First method samples from primary CVS and exactly parallels method employed in the ILCE_LD
 - Second method samples engine-out from partial flow system
 - Approach not yet fully defined in PMP
 - Subject to experimentation at JRC before ILCE_HD commences
 - Results engine-out measurements in AECC study to feed into ILCE_HD development process

- ❑ PM: PMP Compliant Method*
 - Broadly based on US2007
 - Dilution air heating maintains filter temp at 47°C
 - Controlled filter face velocity reduces volatile artifact
 - Cyclone to eliminate filter contamination through re-entrainment and wear

- ❑ PM: Current method
 - **not** modified by PMP
- ❑ PM: Current partial flow method
 - **not** modified by PMP



* Most recent published drafts of R83 and R49

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Three Particle Number Measurement Approaches Used



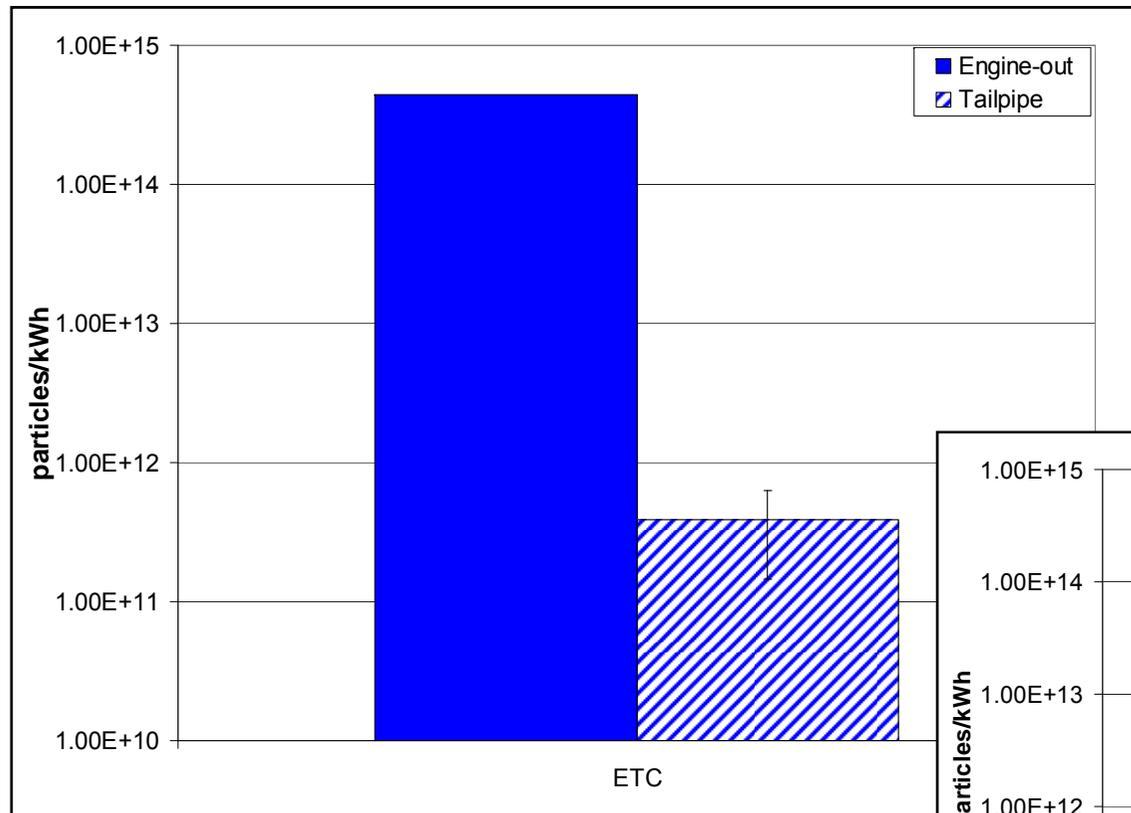
- ❑ Particle number to PMP protocol measured from tailpipe on all tests
 - measurements from CVS Primary dilution system.
 - extra ESC test with Catalysts' bypass gave engine-out PMP levels
- ❑ Particle number measured engine-out on additional tests from partial flow system
 - measurements from Horiba MDLT in parallel with mass measurements
- ❑ Deliverables
 - Per kWh particle number emissions
 - Comparison of engine-out particle measurements from partial flow and full-flow systems
 - Real-time particle emissions traces
 - DPF filtration efficiency for solid particle numbers

Method	Dilution System	Aerosol sampled	Additional Comments
PMP Number	CVS	Tailpipe	All tests
PMP Number	CVS	Engine-out (via catalysts' bypass)	ESC only
Solid Particle Number	Horiba partial flow system (MDLT)	Engine-out	≥1 test, all cycles measurements in parallel with PM

- ❑ PMP does not currently address partial flow for particle number, hence no partial flow tailpipe number measurements.

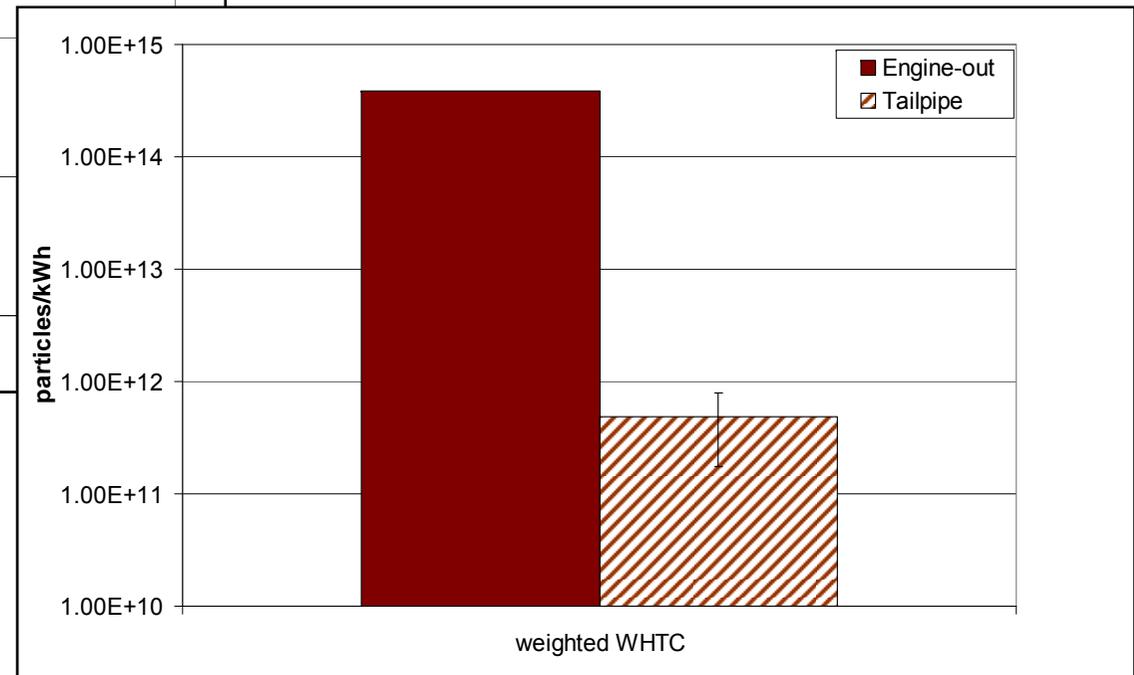
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PMP PN results for ETC and Weighted WHTC show very high filtration efficiencies and emissions of $\sim 5 \times 10^{11}/\text{kWh}$



WHTC

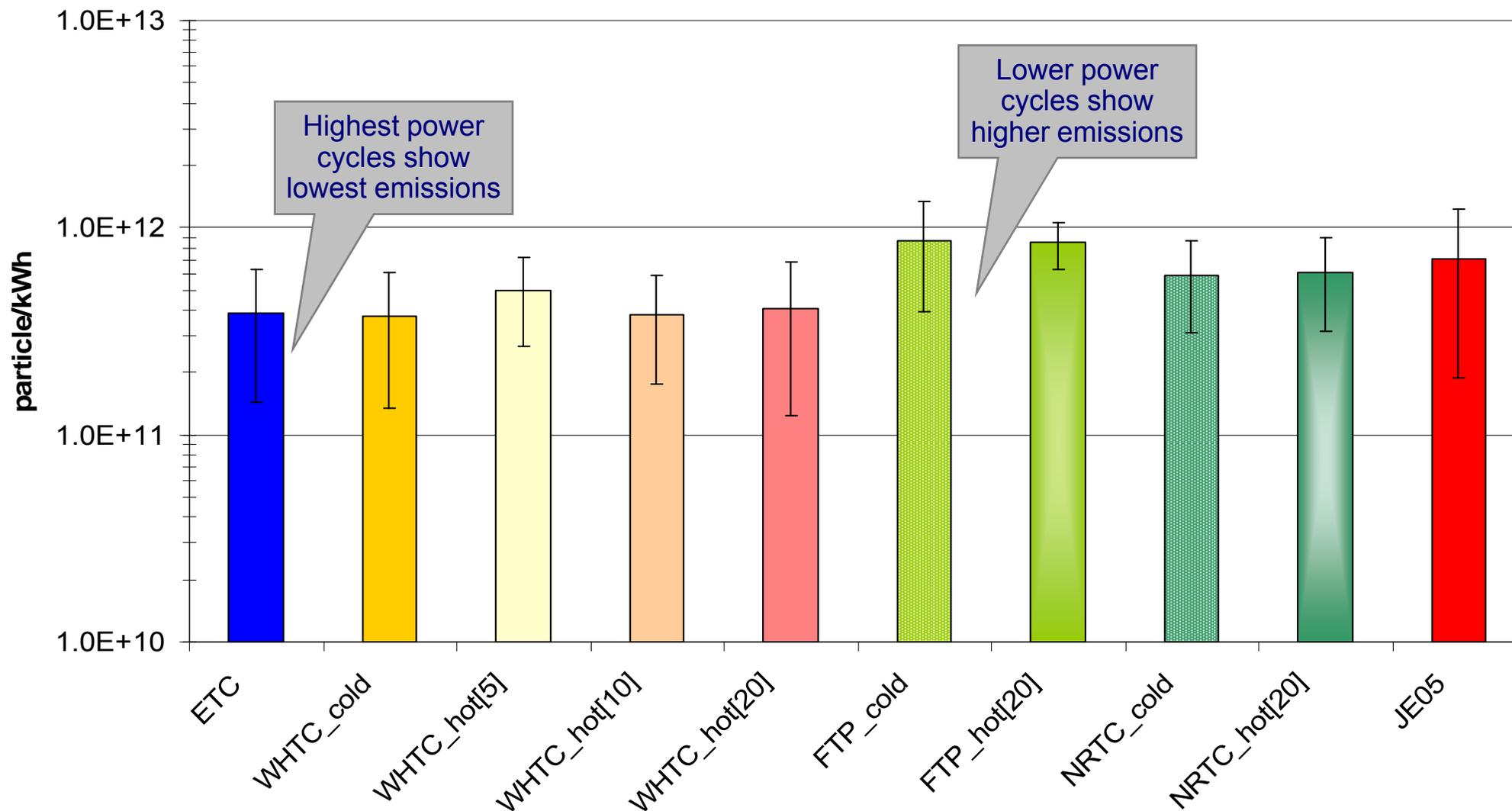
- Tailpipe particle number emissions $< 5 \times 10^{11}/\text{kWh}$
- DPF Efficiency $> 99.8\%$



ETC

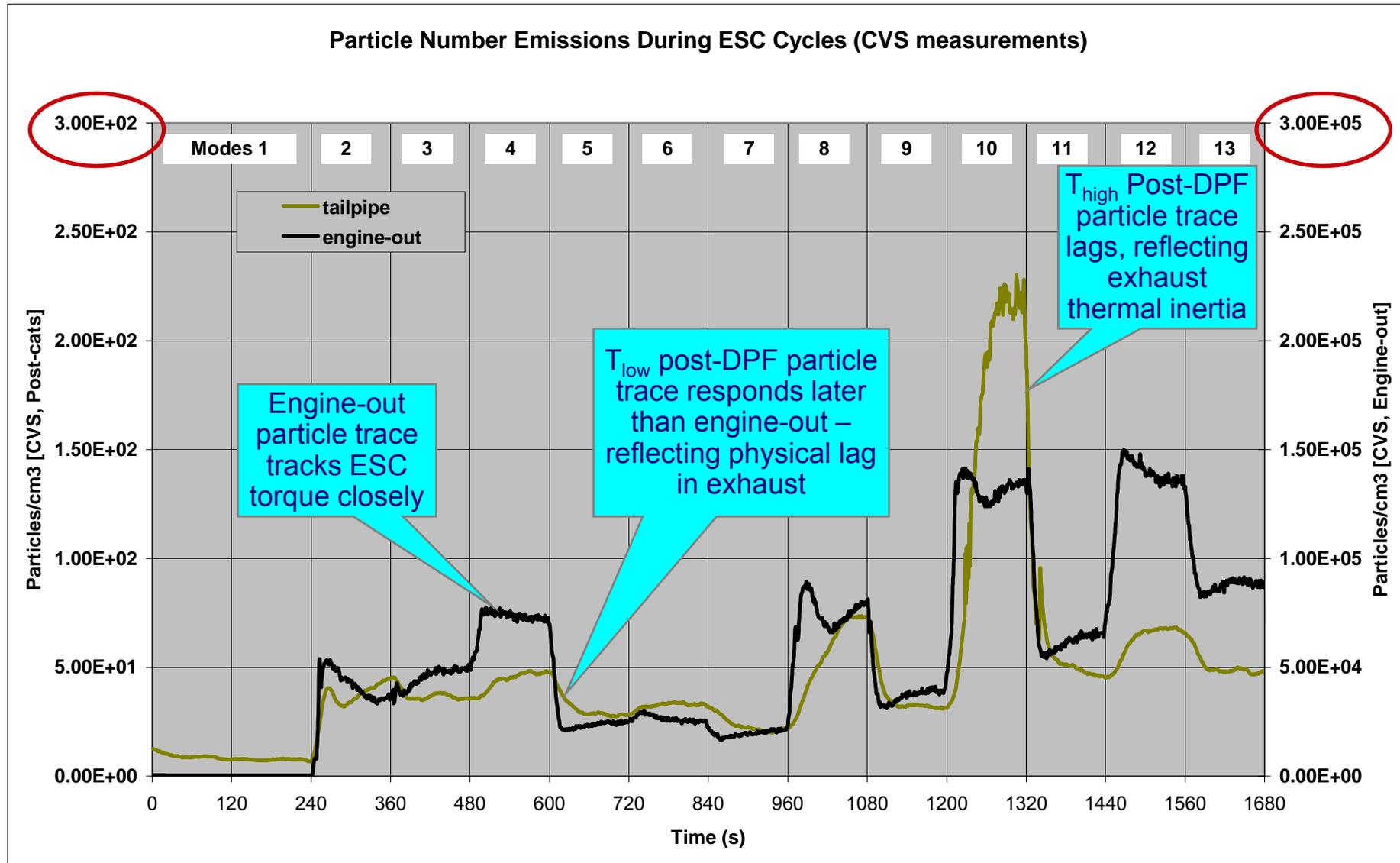
- Tailpipe particle number emissions $\sim 4 \times 10^{11}/\text{kWh}$
- DPF Efficiency $> 99.9\%$

PN Emissions From Several Regulatory Transient Cycles Show Similar Emissions Levels



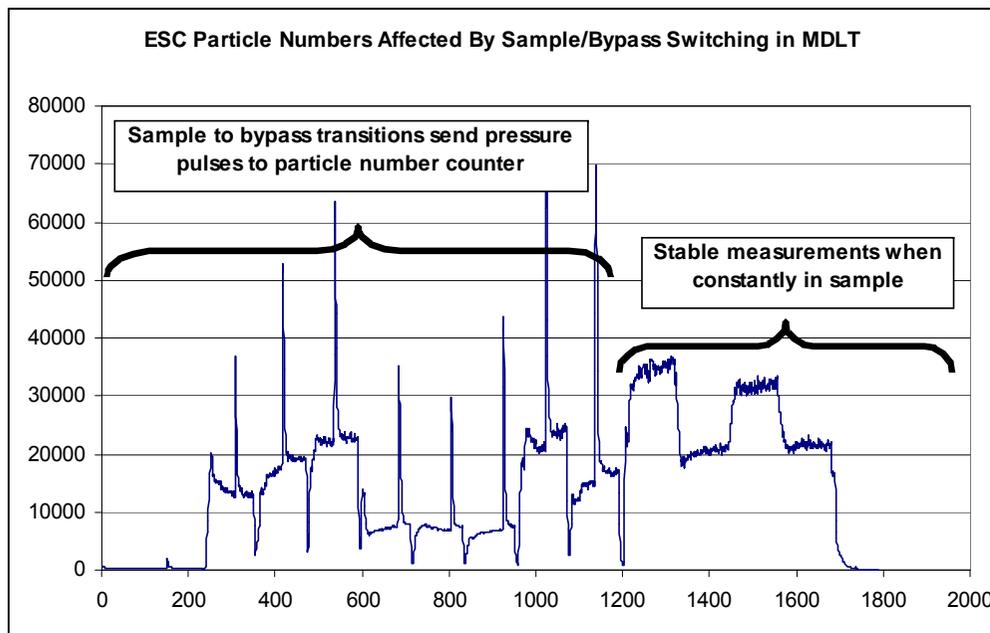
- ❑ Per kWh differences may be due to cycle power or test-to-test variability
- ❑ DPF may normalise emitted concentrations independent of operation

ESC PN Emissions show transient thermal effects at hottest modes – some solid particles are low volatility HCs and not just carbon



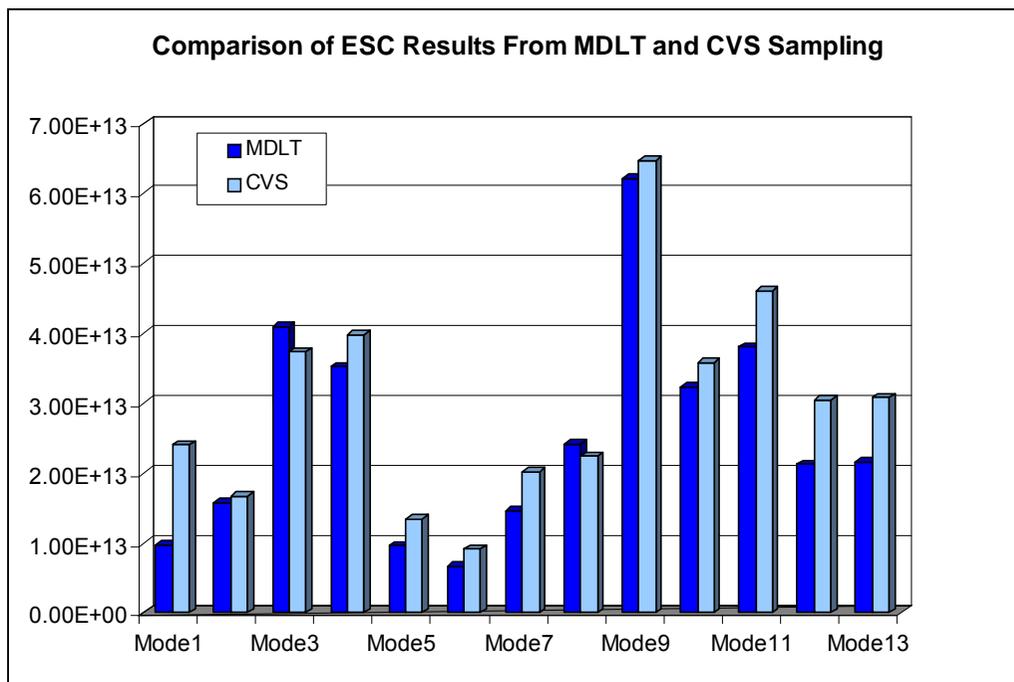
DPF Efficiency is still ~99.9%

MDLT : Issues with Simultaneously Sampling PN + Mass



- ❑ **ESC Cycle causes spikes in PN data as MDLT switches from sample to bypass**
 - Switching required for weighting factor PM sampling
 - Spikes must be edited out of PN data, but these transitions occur at the same time in every test so correction can be automated
 - No issue with CVS sampling since PN from primary tunnel and PM from secondary system
 - No issue with transient cycles
 - Corrected data agrees well with ESC data from CVS

- ❑ **Sampling additional flow from the MDLT during PM analyses demands extra exhaust sample**
 - Flow through filter (total flow through MDLT) is fixed sum of dilution air plus exhaust fraction
 - Dilution air flow is fixed
 - Exhaust fraction increases if more sample is drawn from MDLT but dilution air added is the same
 - Dilution ratio reduced
- ❑ Correction required for additional sample drawn for both mass and number: easy S.State, hard(!) transient



Summary of PM Measurement Results



- ❑ Tailpipe particle number emissions from ETC and WHTC cycles $\sim 5 \times 10^{11}/\text{kWh}$
- ❑ Engine-out particle number emissions from ETC and WHTC cycles $> 10^{14}/\text{kWh}$
- ❑ DPF filtration efficiencies $\sim 99.9\%$
- ❑ Other transient cycles show similar tailpipe emissions and DPF efficiencies
 - Measured particle concentrations post-DPF broadly similar all cycles
 - Emissions may be a function of DPF breakthrough rather than cycle conditions
- ❑ ESC cycle shows
 - Evidence of solid particle emissions release in response to thermal events
 - These particles are not elemental carbon
 - Evidence of particle transport lag through DPF
 - Emissions of particles from exhaust are not mixed with synchronous gases
 - PM in partial flow system post-DPF combines particles with volatiles at incorrect dilution ratios
- ❑ Sampling numbers and mass simultaneously with a partial flow system requires corrections
 - For spiking in particle number profiles
 - For changes in dilution ratio

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- ❑ PN Results
- ❑ **Measurement Approaches: Particulate Mass**
- ❑ PM results
- ❑ Overview
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Four Particulate Mass Measurement Approaches Used

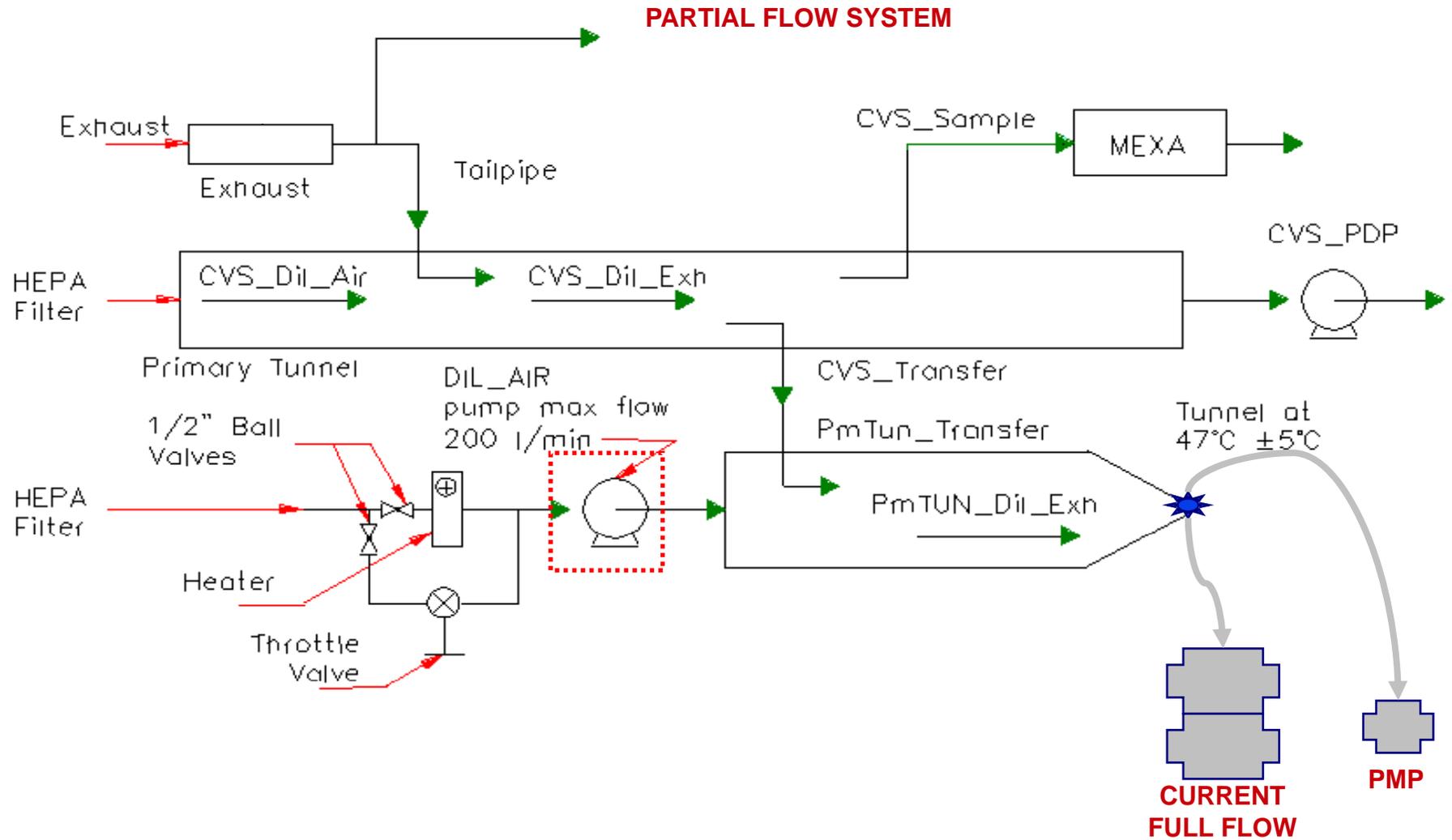


- ❑ Partial flow system using mini dilution tunnel (MDLT)
 - Sample taken directly from exhaust, before CVS system and diluted (variable rate) in the MDLT before collection on sample filter.
 - Current legislation allows this system to be used as alternative to full flow.
- ❑ Current full-flow legislative method
 - Diluted sample taken from the CVS system, further diluted in 2nd tunnel
- ❑ PMP method
 - Sample is taken from the secondary dilution tunnel, as for current method.
 - Same principle as current method, but tighter control on sampling parameters

Method	Dilution System	Aerosol sampled	Additional Comments
Partial Flow PM	MDLT	Tailpipe	All tests
Partial Flow PM	MDLT	Engine-out	≥1 test, all cycles measurements in parallel with PM
PMP Mass Method	CVS and secondary dilution system	Tailpipe	Heated dilution air, 47mm TX40 filters, face velocity constrained
Current Mass Method	CVS and secondary dilution system	Tailpipe	Heated dilution air, 70mm TX40 filters, 120l/min

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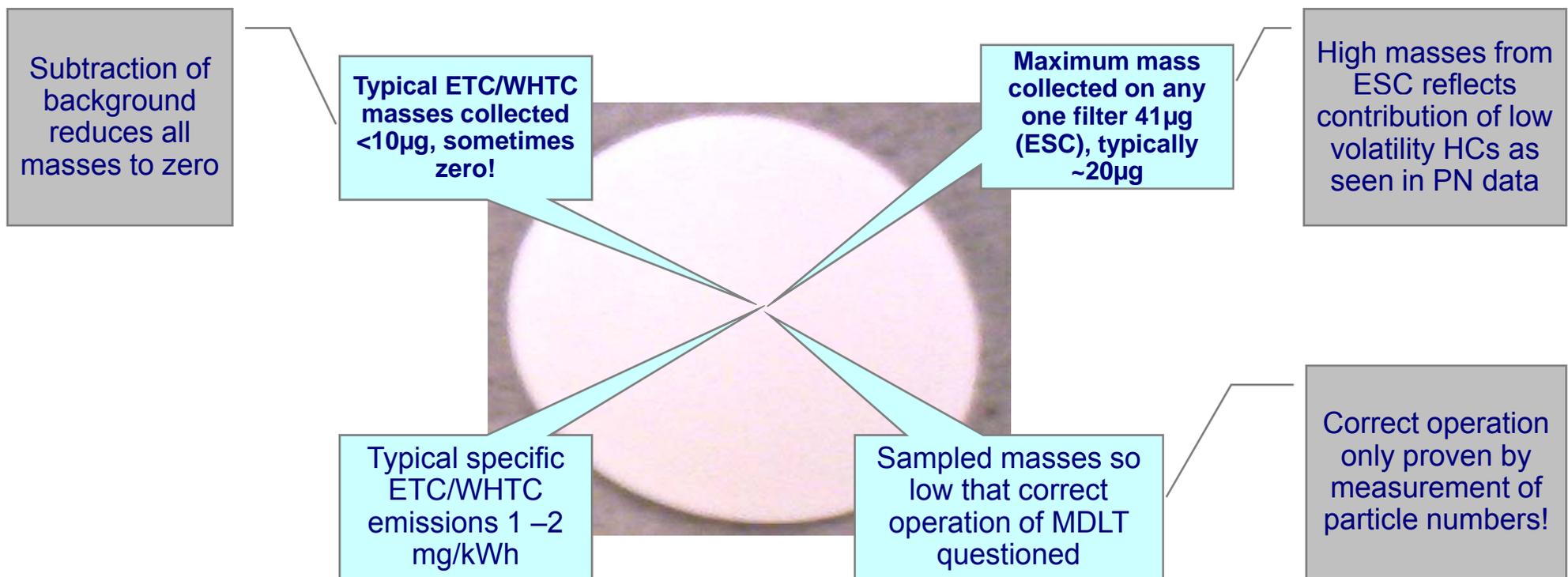
Schematic of PM sampling systems



Partial Flow Particulate Mass Measurements



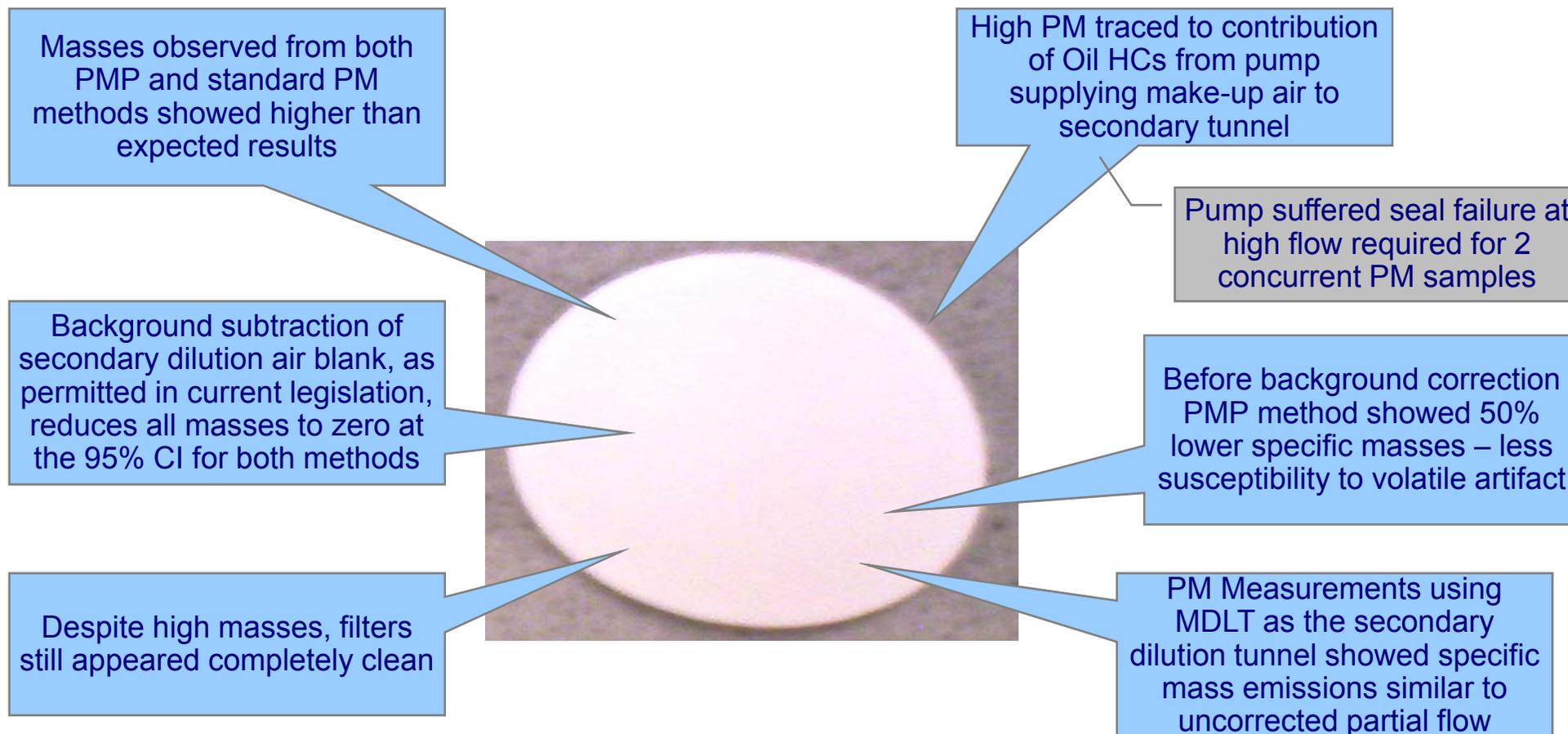
- ❑ Emissions levels very low
- ❑ Tailpipe filters visually identical to unexposed filters



- ❑ **With background correction all tailpipe masses, except an occasional ESC, were zero**

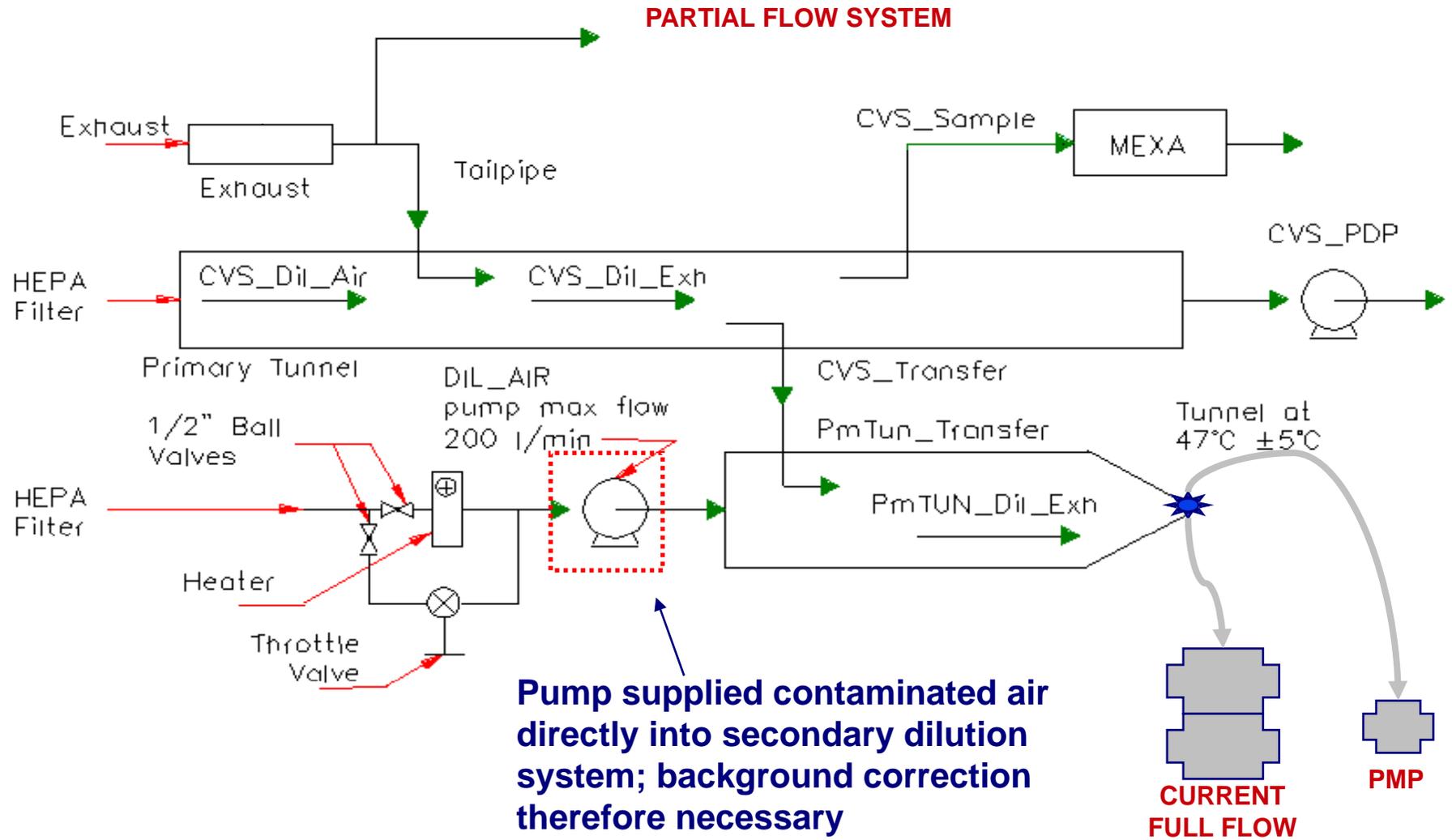
Full Flow Particulate Measurements (Current & PMP)

- ❑ Emissions levels higher than expected
- ❑ Tailpipe filters visually identical to unexposed filters



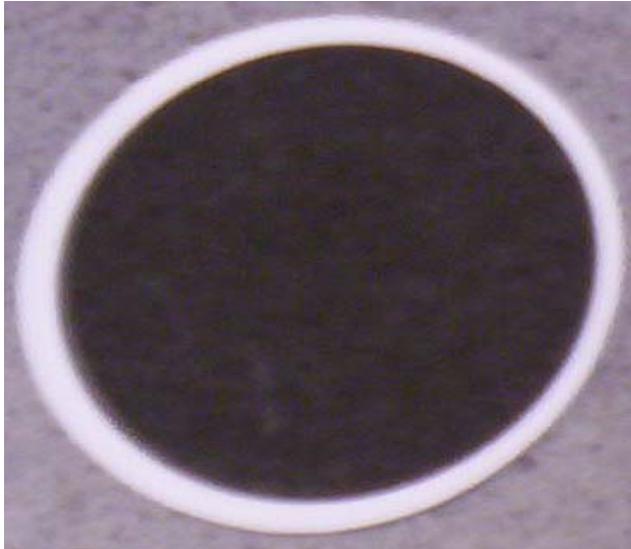
- ❑ **With background correction all tailpipe masses were zero**

Source of background contamination

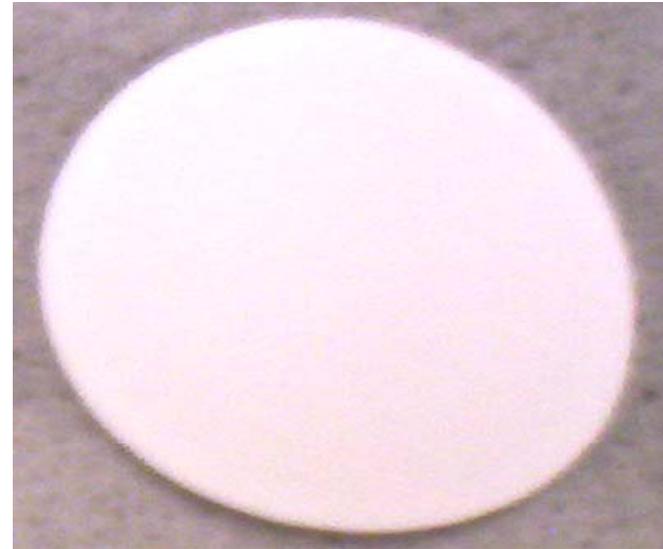


Engine-out and Tailpipe PM Filters – A visual comparison

Engine-out PM

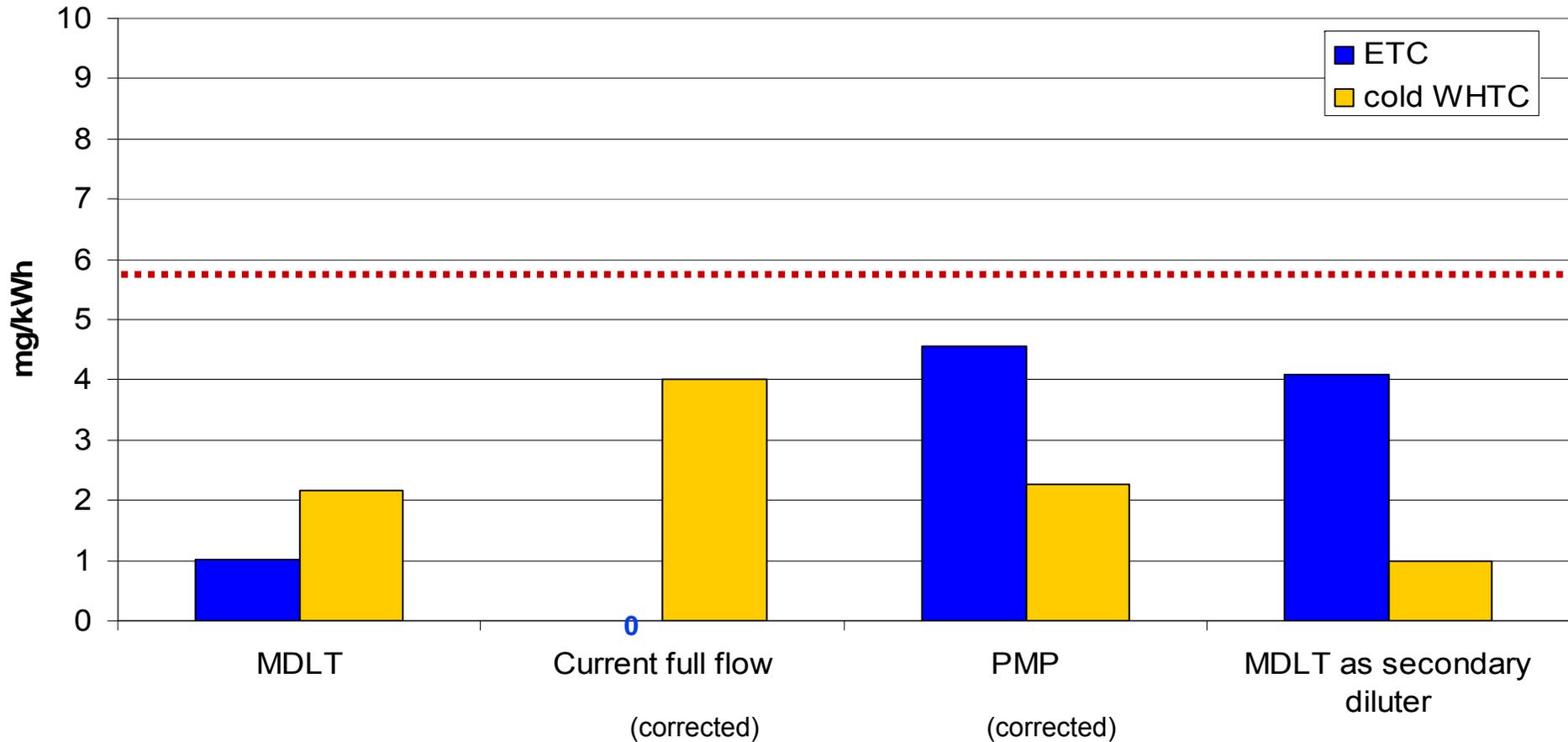


Tailpipe PM

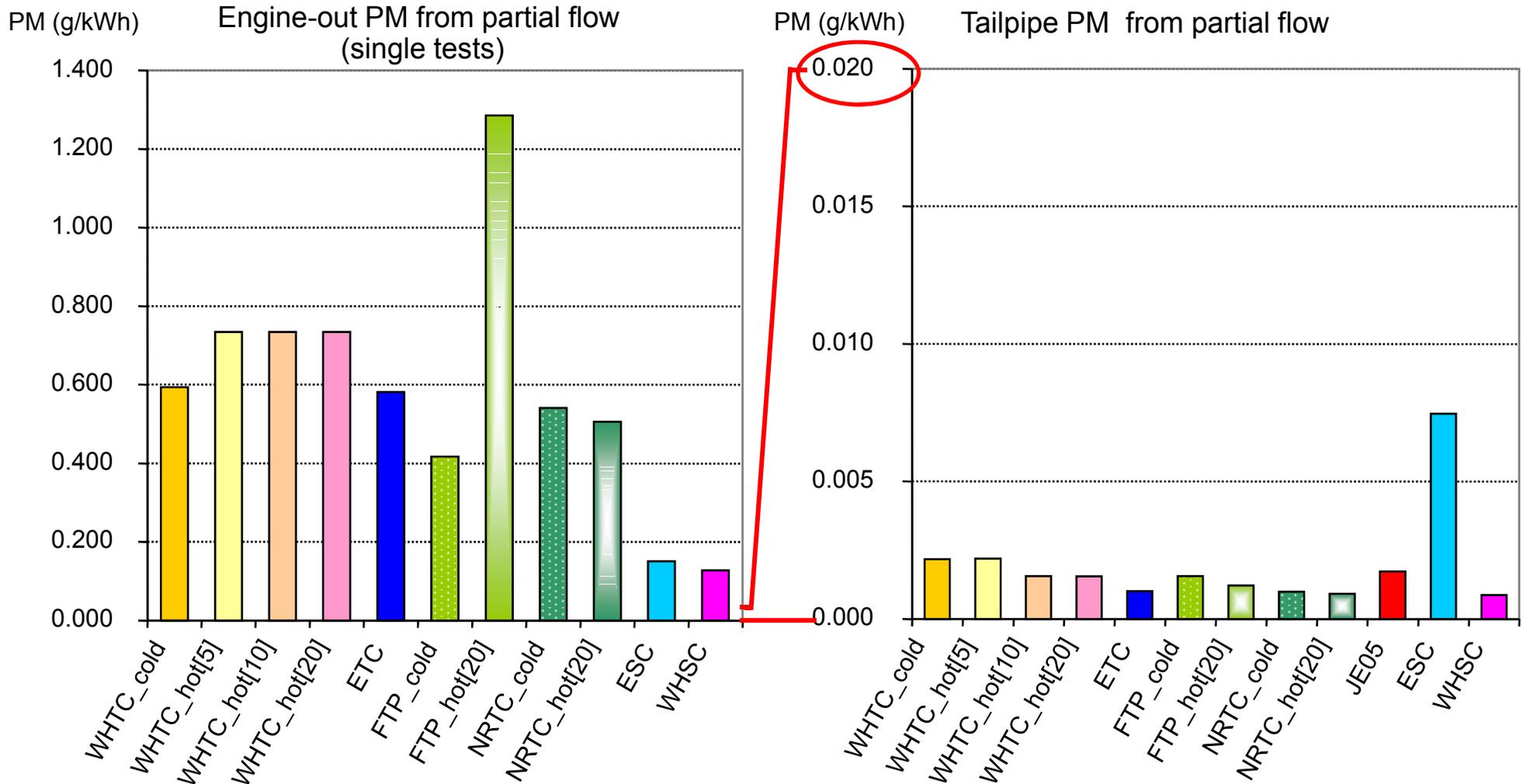


- ❑ Engine-out PM showed dense black PM material
- ❑ Post-DPF shows no indication of material sampled at all
- ❑ Post-DPF measurements with PMP, Standard and MDLT methods all showed filters indistinguishable from unused ones

Mean Tailpipe PM results using different approaches all show emissions <5mg/kWh for ETC and WHTC



Average PM results for engine-out and tailpipe

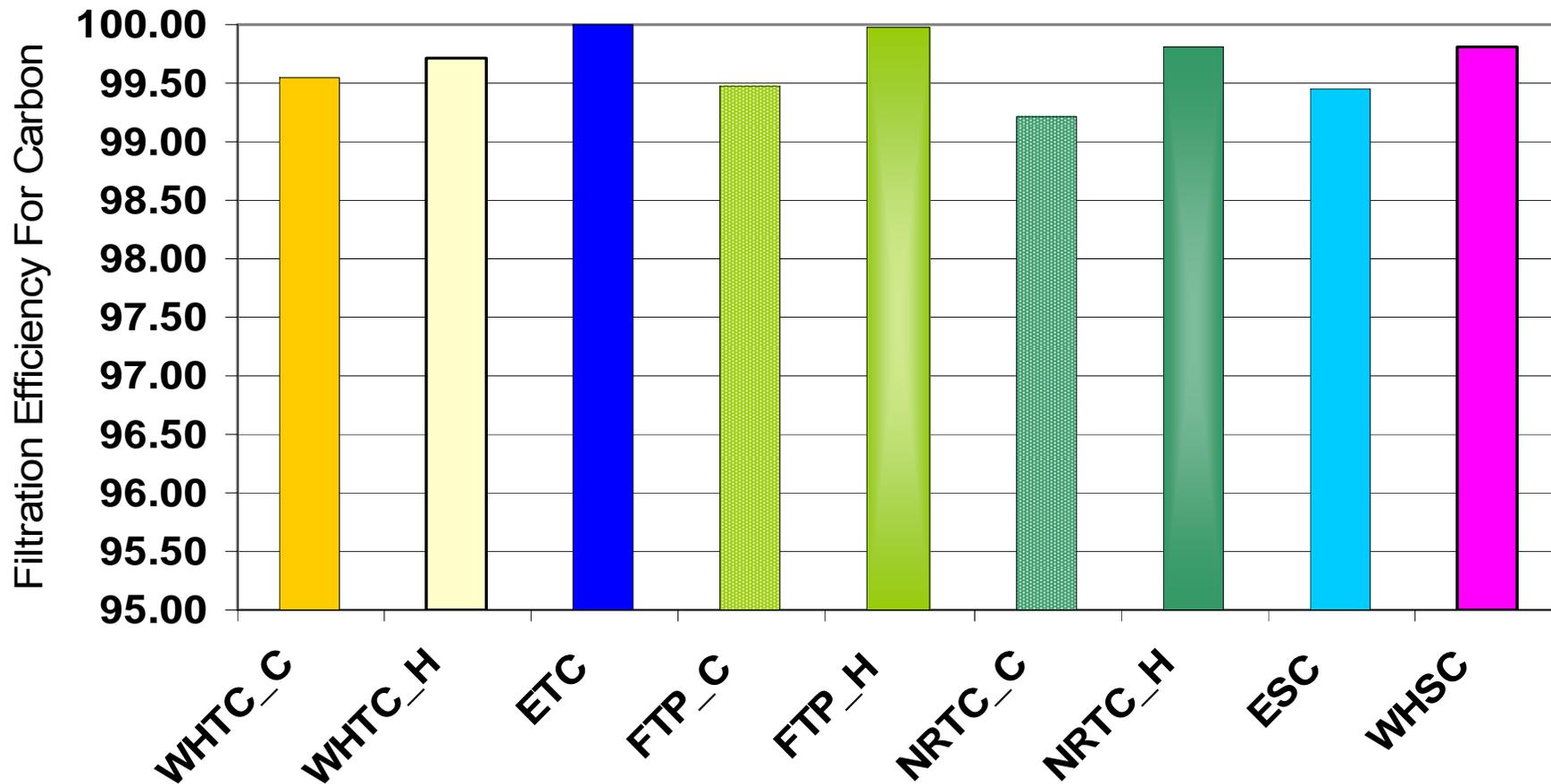


- Higher tailpipe ESC results were believed to be due to mode 10 desorbing low volatility materials
- Typical filtration efficiencies for PM typically 94 to 99%

Filtration efficiency for elemental carbon at >99%



- ❑ Particulate filter efficiency for removal of elemental carbon is > 99%.
- ❑ Efficiencies for particles and elemental carbon are very similar.



Summary of PM Measurement Results



- ❑ Particulate mass emissions from several regulatory transient cycles < 5mg/kWh.

- ❑ Measurements of PM from MDLT show very low mass levels
 - ESC: Maximum 41µg total mass on filter (ESC), typically 20µg and <8mg/kWh
 - ETC: <10µg filter mass and ~ 1 to 2 mg/kWh
 - All cycles masses at zero when background correction applied

- ❑ Measurements of PM
 - Without background subtraction PMP method collected filter mass levels typically <50% of levels measured by current method
 - All cycles masses at zero when background correction applied

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- ❑ The PMP particle number method proved very robust even at near-ambient particle emissions levels.
- ❑ Engine-out particle number data was in the range of 2.5 to 5×10^{14} /kWh.
- ❑ All transient cycles data showed tailpipe particle number emissions below 10^{12} /kWh.
- ❑ Particle numbers were essentially cycle-independent.
- ❑ Background-corrected PM from PMP method gave results below 5mg/kWh from several regulatory transient cycles
- ❑ PM levels from all approaches were consistent when background correction was applied
- ❑ The emissions control system reduced both solid particles and elemental carbon emissions by more than 99%.

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- ❑ Emissions levels for post-DPF mass and number using CVS and partial flow systems have been identified for ETC, ESC and WHTC cycles
- ❑ The following recommendations can be made to assist the development of the forthcoming PMP ILCE_HD Exercise
 - **MASS**
 - 47mm filters, heated dilution air and controlled face velocity led to a reduction in volatiles retained on sample filters.
 - This approach should be retained to limit artifacts
 - **NUMBER**
 - For simultaneous mass and number sampling from partial flow systems
 - the flow drawn by the particle number measurement system must be either corrected for or replaced to avoid errors in mass determination
 - It is advisable to use a CPC with a mass flow controller to ensure close flow control.
 - Measurements of particle numbers during ESC and other ‘stepped’ cycles must consider the effects on system pressure of switching between sample and bypass
 - These measurements will require specific processing to eliminate pressure effects on dilution and CPC function influencing measured particle numbers and particulate mass