Particle Emissions from a EU III Heavy-Duty Diesel Engine with a Catalyst-based Diesel Particulate Filter & Selective Catalytic Reduction System

Dirk Bosteels, Robert A Searles,

Association for Emissions Control by Catalyst (AECC)

Jon D Andersson, Carl A Jemma,

Ricardo Consulting Engineers Ltd

ETH conference - August 2003

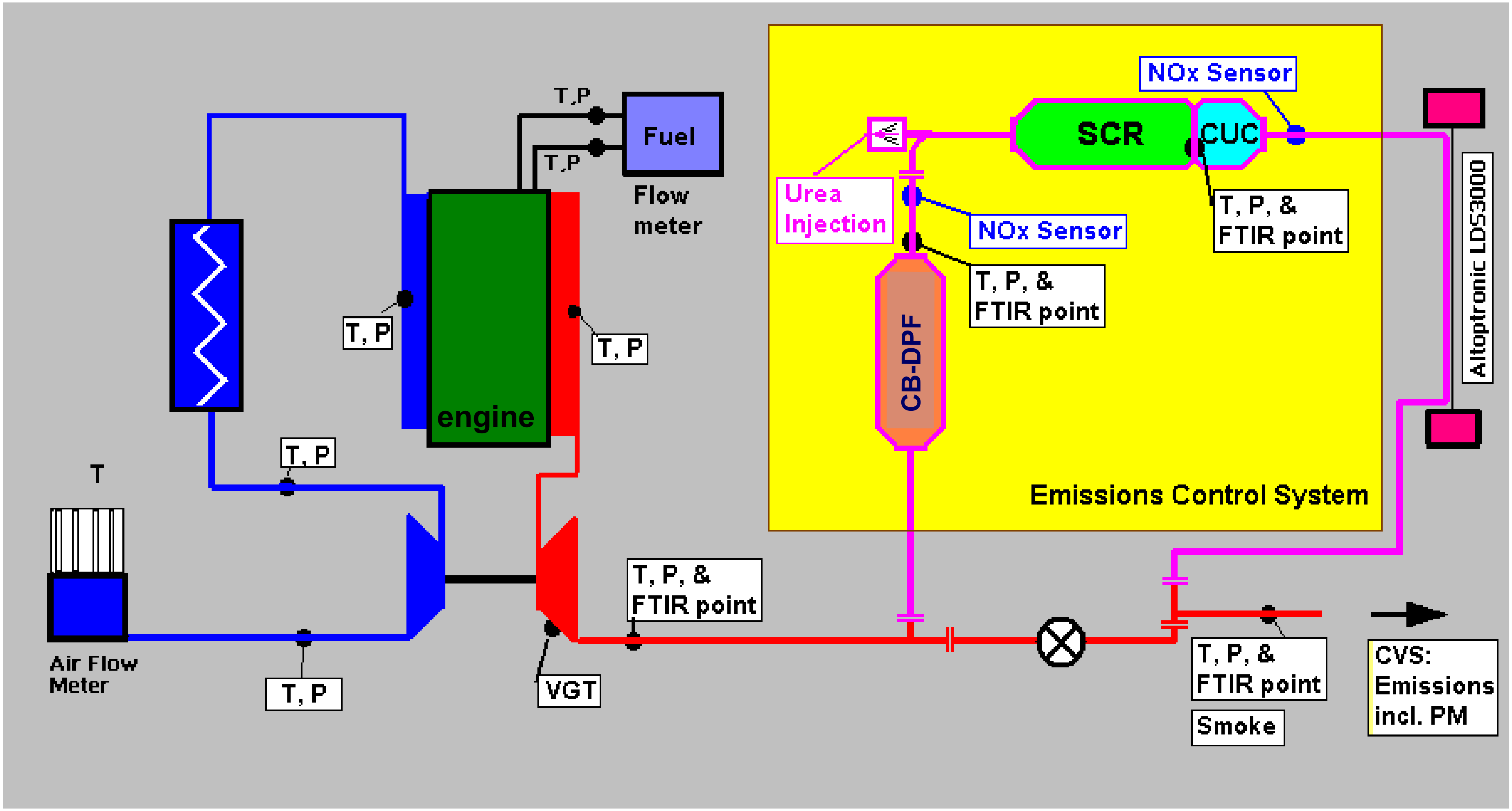
Objectives of the programme

- To demonstrate the capabilities of an integrated catalyst based diesel particulate filter (CB-DPF) system, an urea-based selective catalytic reduction (SCR) and clean-up catalyst to **meet the 2008 (EUV) emission limits**, when fitted to a EUIII production engine
- The **emission targets** at zero hours were set at 50% of EUV levels, namely
  - for **NOx** : **1.0 g/kWh**
  - for **PM** : **0.01/0.015 g/kWh (ESC/ETC)**
- To further assess the ability of the CB-DPF + SCR to **maintain the emissions targets after severe ageing** (1000h engine ageing on test bed designed to be representative of about 250000km real-world driving
- To address other issues including **Particle number, size and chemistry**

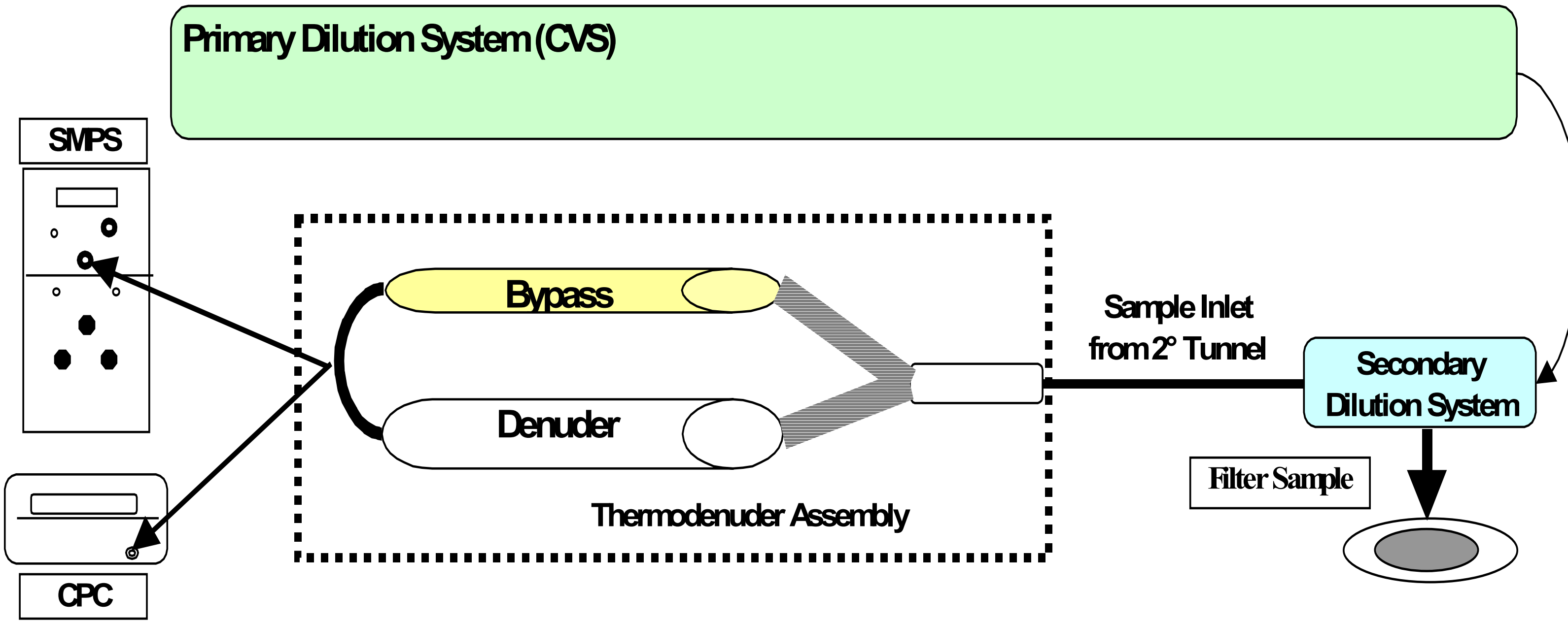
Test Fuels

		Emissions Tests	Ageing Test (900h)	Ageing Test (100h)
Sulphur	**ppm (wt)**	**8**	**40**	**250**
Cetane Number		55	54	54
Density	kg/dm^3	0.829	0.833	0.836
T10	°C	205	218	224
T50	°C	257	275	276
T90	°C	334	328	332
T95	°C	349	341	353
Aromatics	IP391 % (wt)	18.0	22.5	25.8

Schematic of Test Bed set up with Engine and Emissions Control System



Schematic of Particle and Particulate Sampling



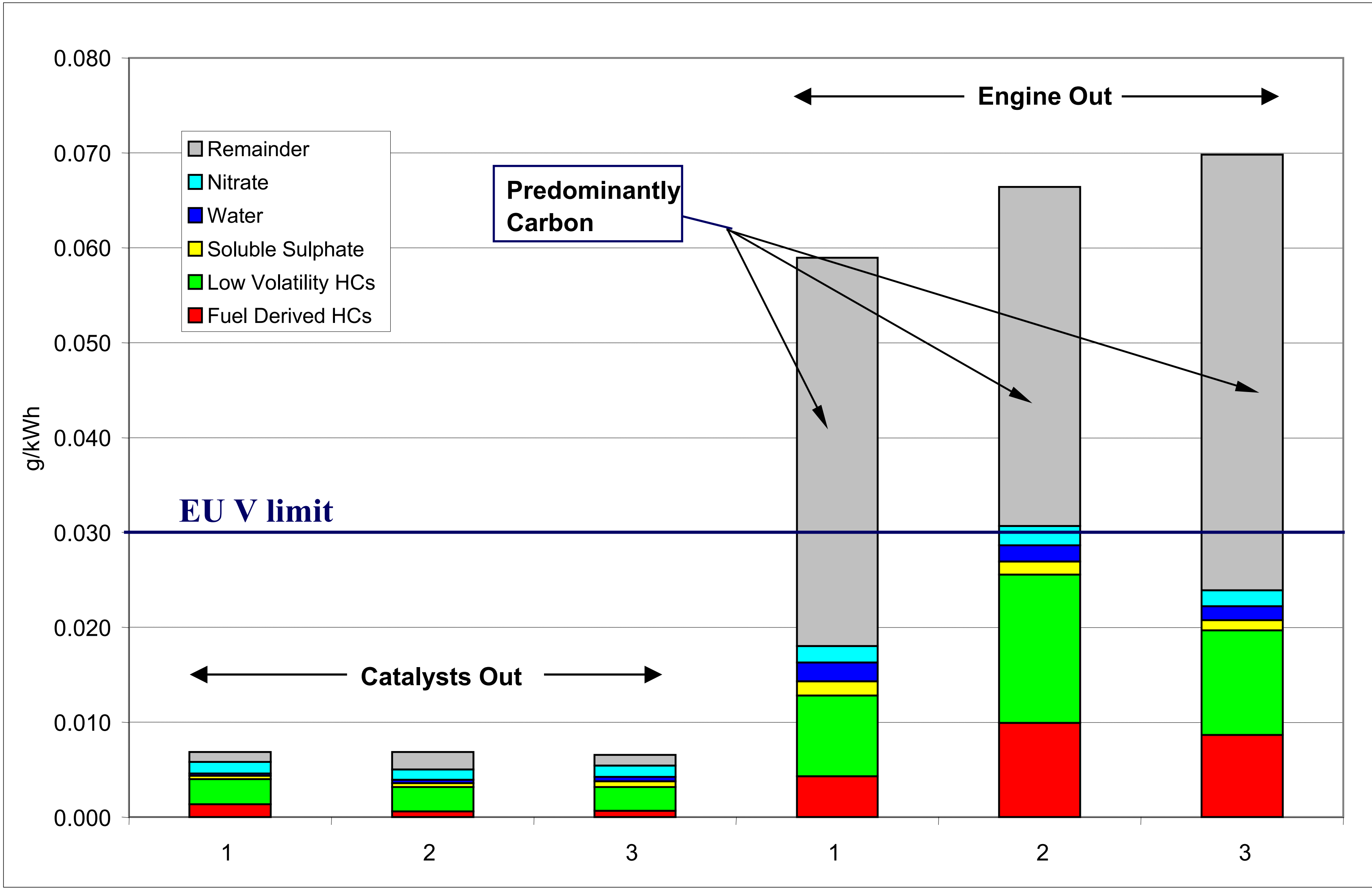
Summary of Emissions ETC/ESC Test Results

Legislation		0 hours			1000 hours		
ETC [g/kWh]	2008 (EU V) Limits	Before Ageing Test		Conversion Efficiency [%]	After Ageing Test		Conversion [%]
		Engine Ou	Catalysts Out		Engine Out	Catalysts Out	
HC	0.4	0.31	0.07	77*	0.29	0.07	76*
CO	3	0.8	0.03	96	0.78	0.01	99
NOx	2 (rev.)	5.89	1.06	82	5.83	0.85	85
PM	0.03	0.066	0.01	85	0.064	0.011	83

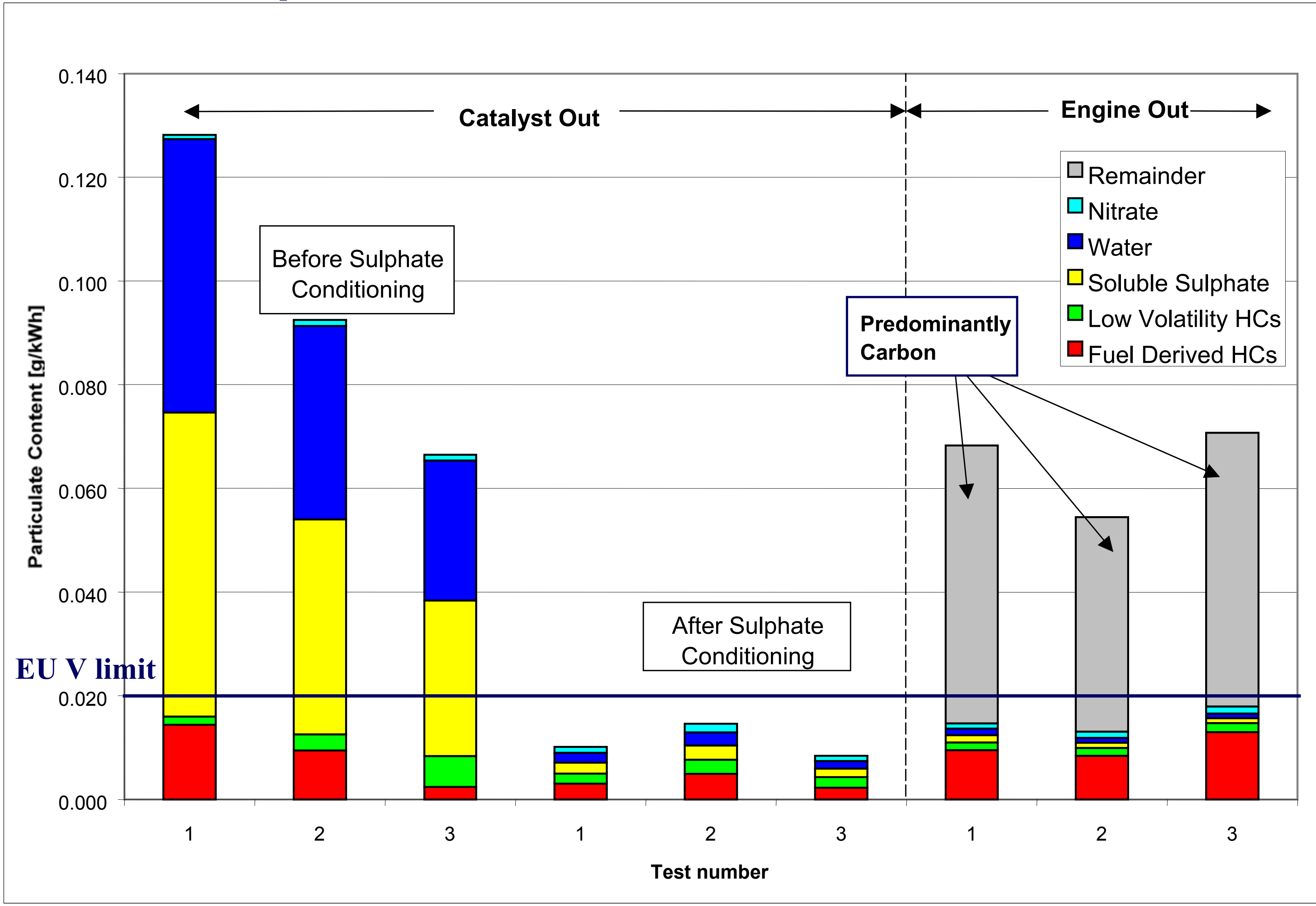
ESC [g/kWh]	2008 (EU V) Limits	Before Ageing Test		Conversion Efficiency [%]	After Ageing Test		Conversion [%]
		Engine Out	Catalysts Out		Engine Out	Catalysts Out	
HC	0.25	0.22	0.04	82*	0.2	0.05	75*
CO	1.5	0.5	0.03	94	0.53	0.01	98
NOx	2 (rev.)	5.27	0.89	83	5.28	0.8	85
PM	0.02	0.07	0.016	77	0.064	0.007	89

* apparently low HC conversion efficiencies stem from high ambient methane levels during testing. Correcting engine-out and post-catalysts data for this gives HC conversion efficiencies of >85%.

ETC Tests at 0h: Effect of Catalysts on Particulate



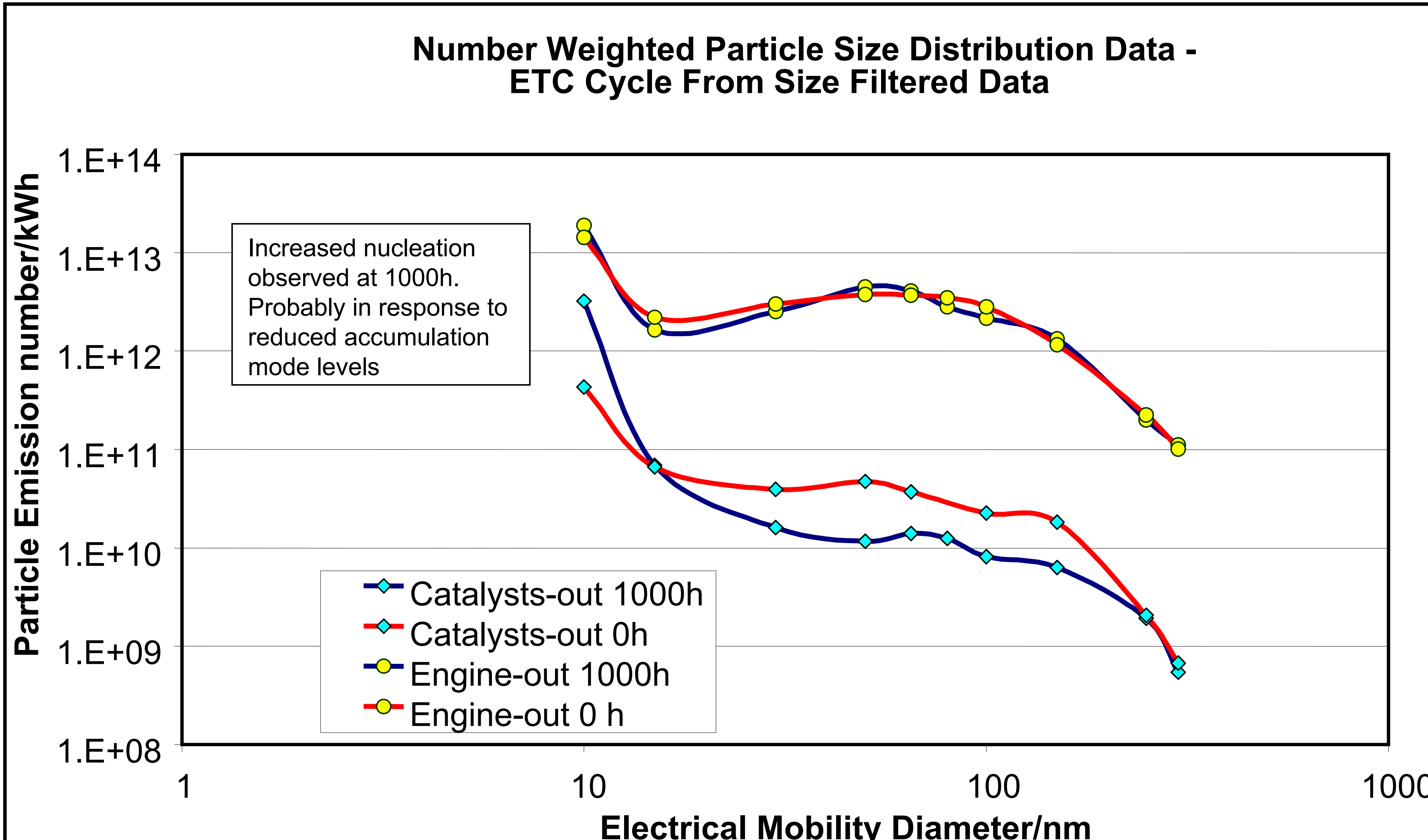
ESC data at 1000h: Particulate Analysis before and After Desulphation



Preliminary conclusions

- There was storage of sulphate in the catalysts during the ageing test due to the prevailing exhaust temperatures (300-400°C) and the fuels used. The sulphate was released during the initial emissions tests at 500h and 1000h when higher temperatures (450°C) were experienced, resulting in high levels of sulphate in the particulate.
- Conditioning the catalysts at high load (CB-DPF inlet 510°C) for 8h drove off most of the stored particulates and restored measured PM emissions to very low levels.
- Reduction in fuel sulphur to 10ppm will minimise the storage and release of sulphates.

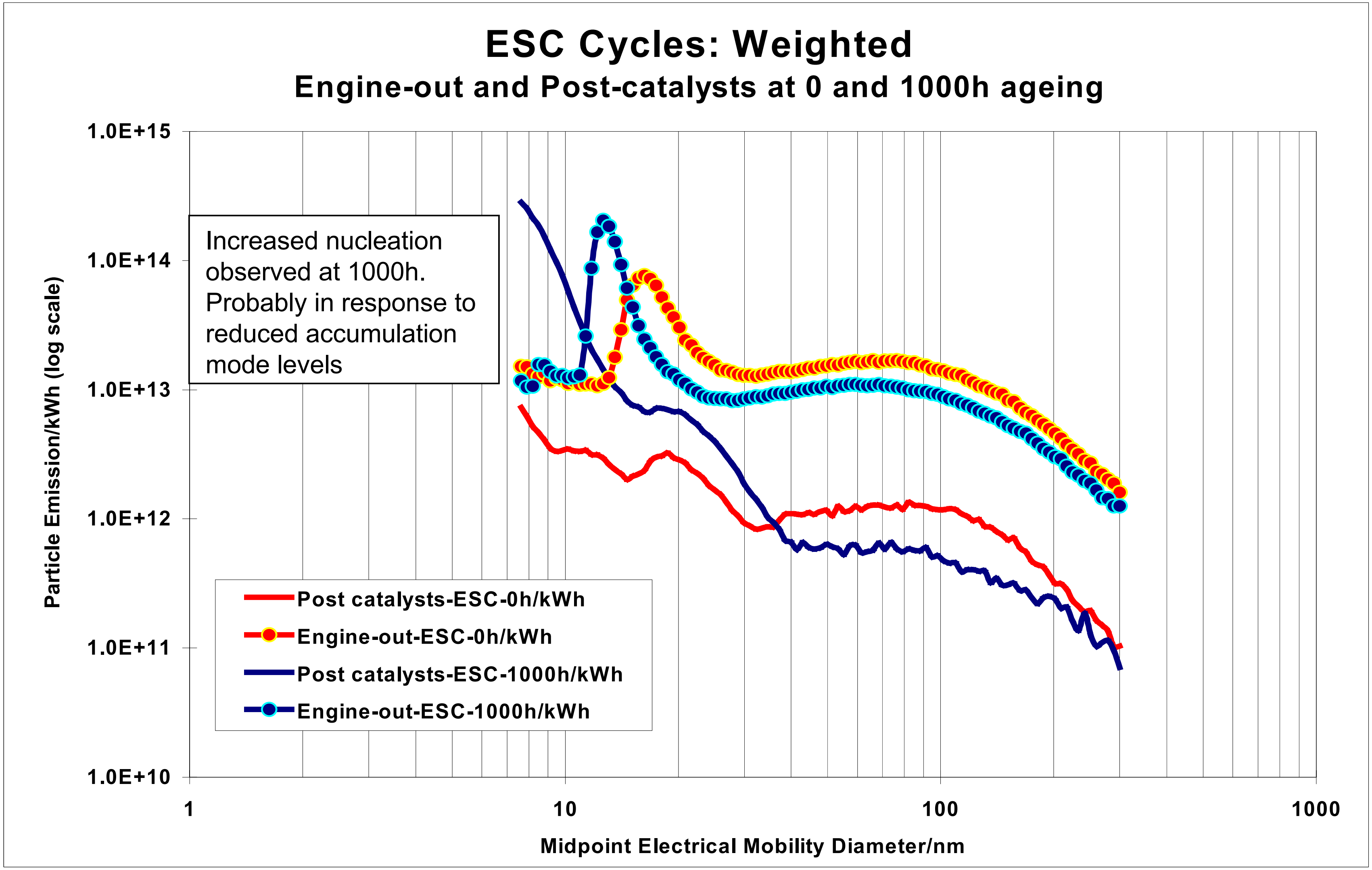
ETC Tests: Number Weighted Particle Size Distribution data



AECC Association for Emissions Control by Catalyst

RICARDO

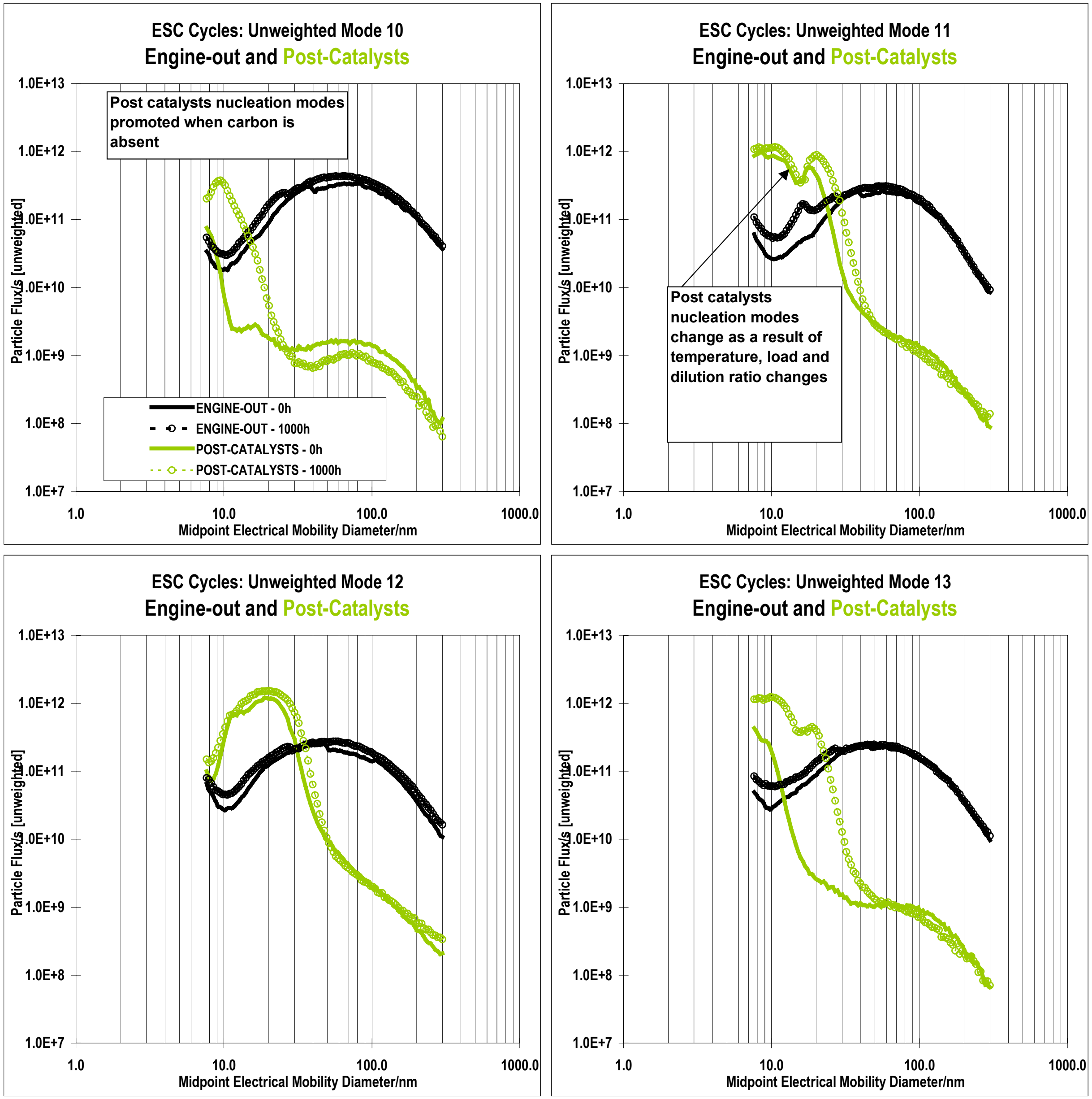
ESC Tests: Number Weighted Particle Size Distribution data



AECC Association for Emissions Control by Catalyst

RICARDO

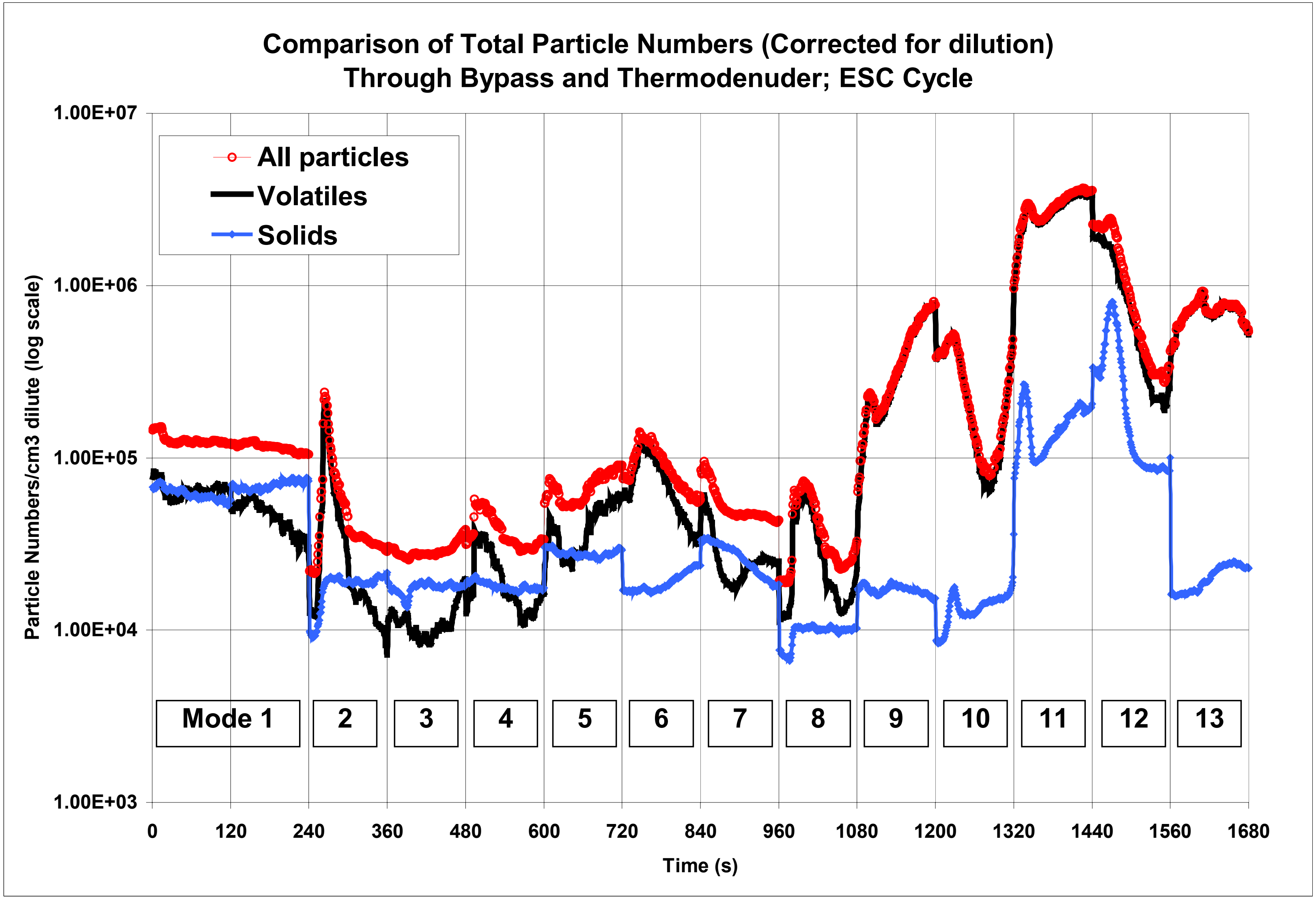
Nucleation Mode Formation during ESC Cycles



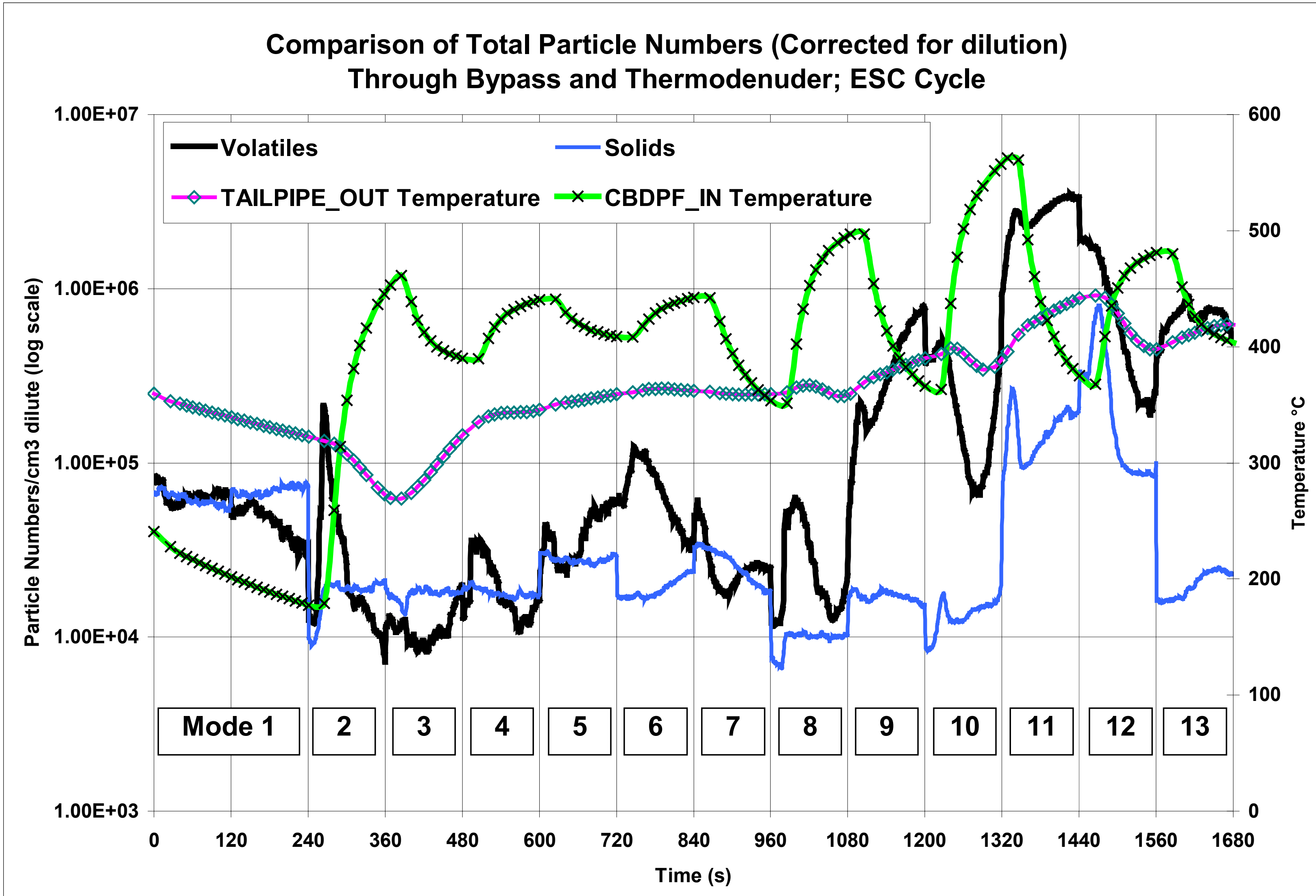
Particle Size Distributions - observations

- From ETC cycles, a reduction in Particle number concentration of ~100x was apparent between Engine-Out and Post-Catalysts measurements
- From ESC cycles, a reduction of only ~10x was observed
  - this was a consequence of
    - Enhanced nucleation promoted by Post-Catalyst reductions in carbonaceous accumulation mode
    - The power calculation artefact which enables idle to dominate the total cycle size distribution
- ESC individual modes showed a 100x reduction in accumulated mode levels with catalysts, but high nucleation mode emissions at speed C modes (10-13)
  - Nucleation enhanced by misfuelling at high S levels, 'favourable' dilution ratios and thermal release at high operating temperatures

Particle Number Emissions From ESC Cycle



Particle Emissions and Exhaust System Temperatures



ESC Particle Number production – Post-Catalysts

- Volatile particle emissions ~100x solid particle levels and show spiking with all mode to mode transitions.
- Solid particle production relatively flat except under high temperature operation.
- Emissions of volatile particles resemble pre-CB-DPF temperatures but with a ~100s lag.
- These observations suggest that emissions of both volatile and solid particles are associated with exhaust temperature rather than instantaneous operating condition or dilution conditions.
- These particles are therefore released from downstream of the catalytic system.
- Some, perhaps all, of the solids are volatile at high temperatures.

Emissions Cycle Effects on Particle Size and Number

- ETC tests
  - Few influences on particle formation.
  - Insufficient response time of SMPS.
  - Transient total particle production in nucleation and accumulation modes.
- ESC tests
  - Particle formation processes progress during ESC-mode to mode transitions.
  - Short term steady states in ESC are inappropriate for particle size and number measurements.

Conclusions (1)

- The emissions control system (CB-DPF + SCR + clean-up catalyst) applied to an unmodified heavy-duty EUIII series production engine enabled the 2008 (EUV) emissions limits to be achieved with a margin of more than 50% after 1000 hours ageing.
- There was no deterioration in emissions after ageing for 1000h using a cycle typical of severe continuous on-road operation with some high sulphur fuel misfuelling.
- NOx level was reduced to 1.0 g/kWh on ETC and ESC tests, corresponding to a reduction of 85% after 1000 hours ageing.

Conclusions (2)

- Particulate emissions were reduced by about 85% on both ETC and ESC tests after 1000 hours. Exhaust back pressure remained constant throughout the ageing test, in spite of deliberate misfuelling with 250ppm sulphur fuel for 100h.
- Total particle numbers were reduced by about two orders of magnitude over a size range of 10 to >100nm.
- There was storage of sulphate in the catalysts during the ageing test due to the prevailing exhaust temperatures and the fuels used.
- Reduction in fuel sulphur to less than 10ppm will minimise the storage and release of sulphates.

Conclusions (3)

- Volatile particle emissions dominate overall particle numbers.
- Particle emissions lag behind engine transients
  - Post-catalysts particle numbers are released in response to changes in exhaust temperature rather than changes in operating condition.
  - Occur from downstream of the catalysts.
- Solid particles appear to show volatile character at higher temperatures.
- Most, or all, post-catalysts particles may be semi-volatile
  - Implies very near 100% filtration efficiency for carbon.