

CHARACTERIZATION OF REPEATABILITY AND REPRODUCIBILITY OF BSPN MEASUREMENTS



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Background and Motivation

- Cummins is a global company that designs, manufactures, sells and services diesel engines and related technologies around the world.
- Particle Number (PN) limits were introduced in Europe.
- Cummins is interested in understanding PN measurement capability.
- Mamakos et al. R&R: **30-70%** when PMP's 'golden' engine was ran on cold/hot WHTC, WHSC and ETC.
- R&R worsened to 90-150% when engine was ran over ESC test cycle.
- This project characterized repeatability and reproducibility of BSPN measurements using three AVL particle counters and quantified variation in particle number measurement due to instrument and test process separately.

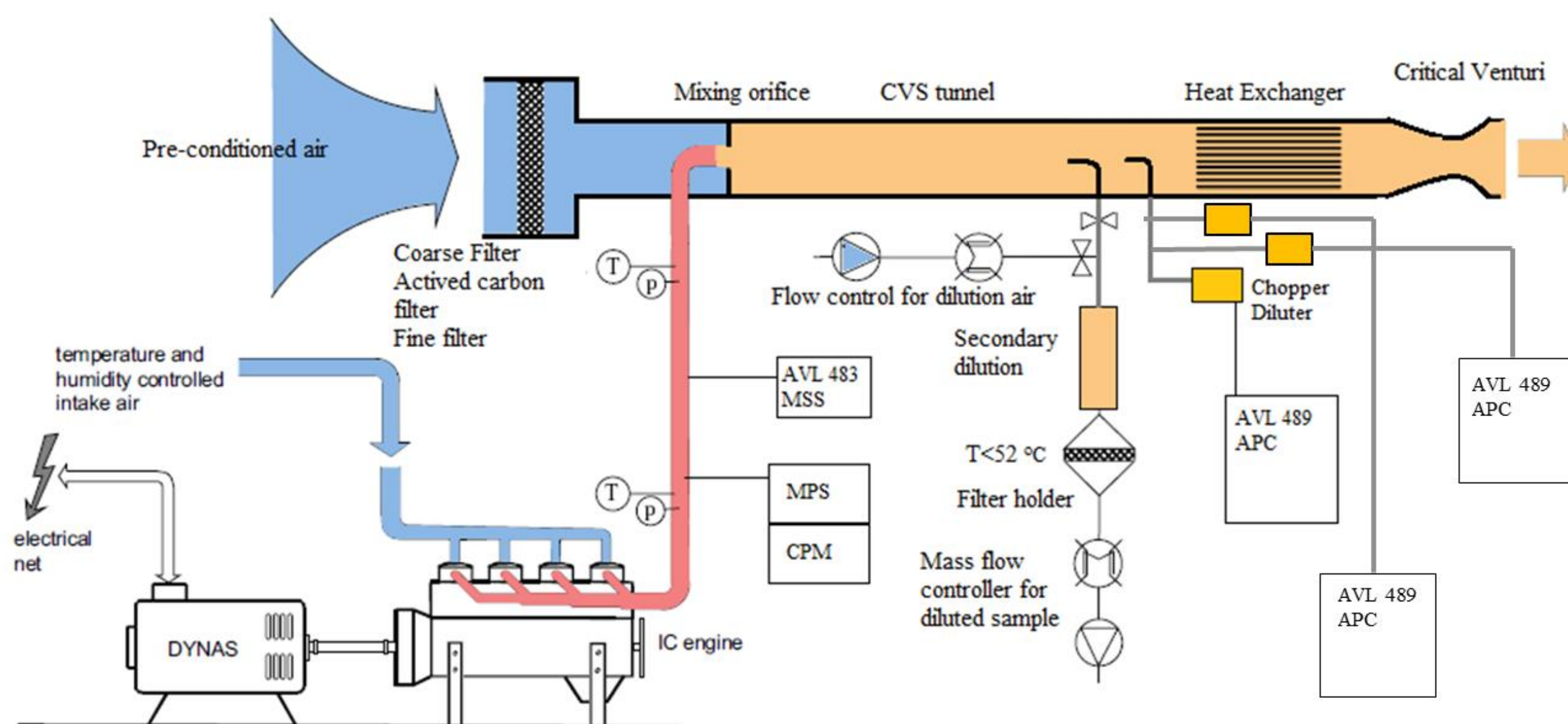
Experimental Design

- Test Site:** 1 (Cummins Technical Center, Columbus, Indiana)
- CVS Test Cells:** 5 (2 visits per test cells)
- Test Engine:** 1 (Cummins ISX 14.8 L, 425 HP)
- PN Instruments:** 3 (AVL Particle Counters)
- Test Cycles:** 2 (FTP & RMC)
- Test Operator:** 1
- Test Matrix:**

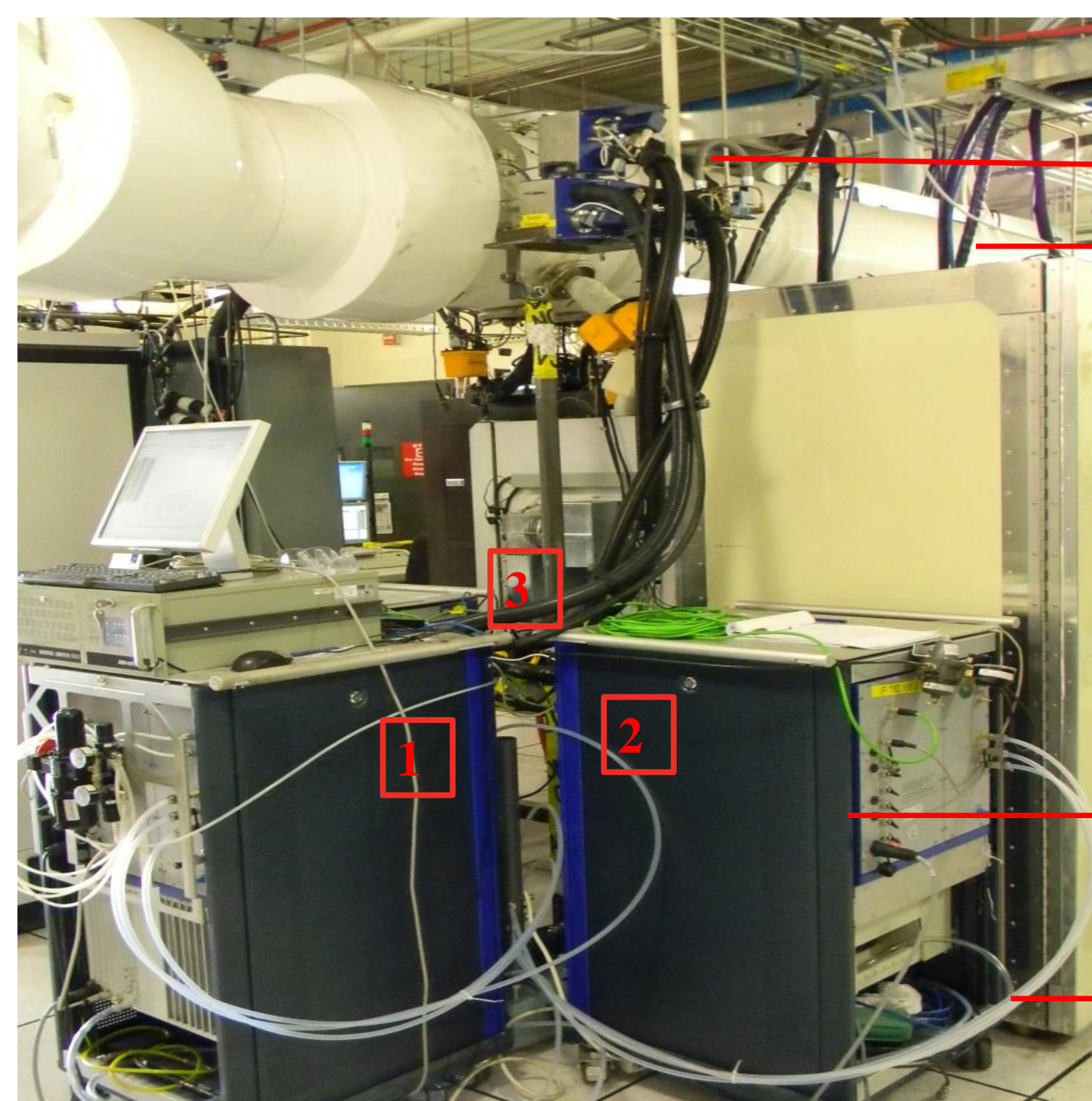
Sequence of Events

Regen	hotFTP (1 st Set)	Regen	RMC	hotFTP (II nd Set)
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Experimental Setup Schematic



AVL 489 Particle Counter Setup



Chopper Diluter (PND1)

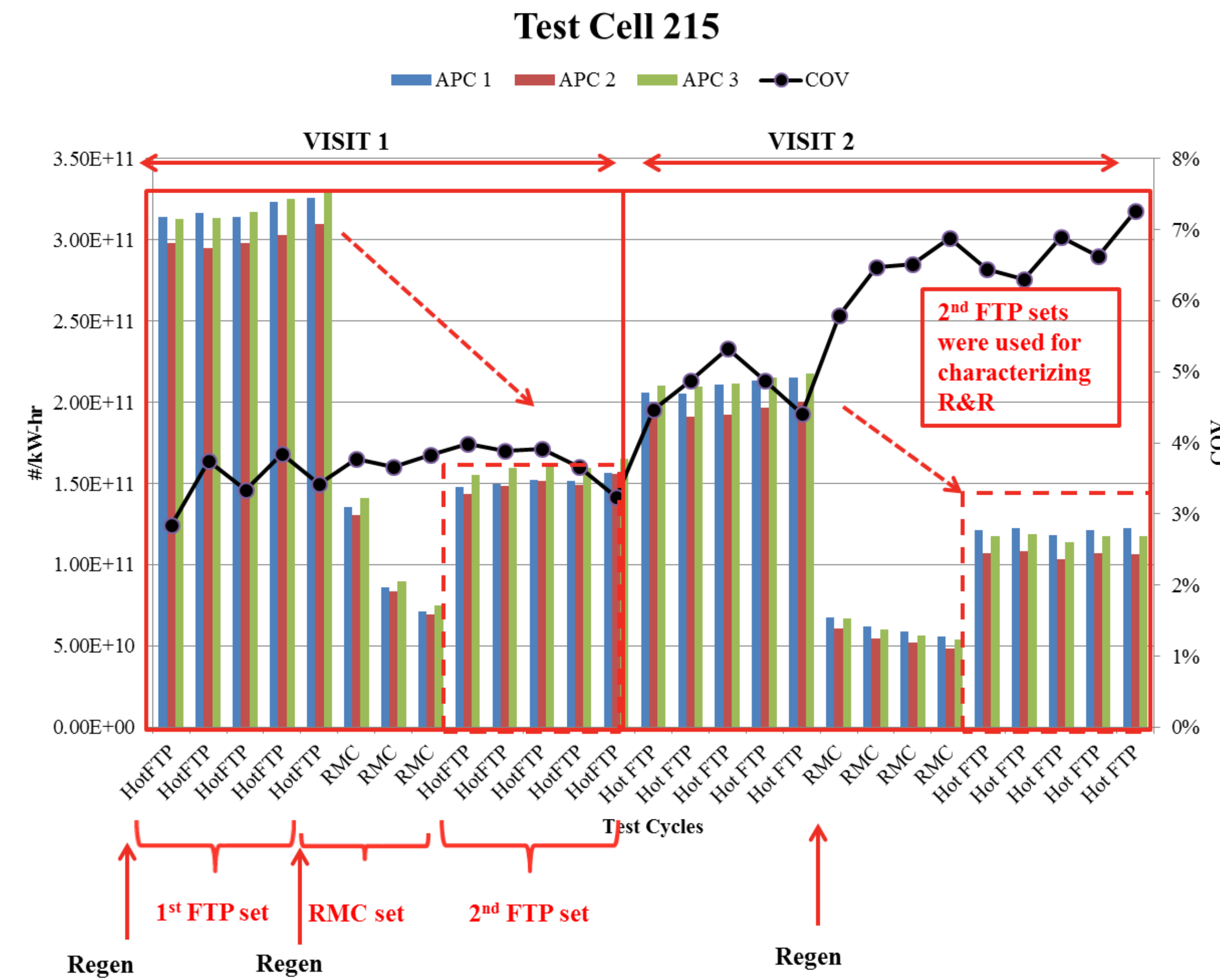
CVS

No Cyclone/Hatted Probe was used

ET, PND2 and PNC

Waste line (Butanol Mix)

Typical PN Measurements



Overall Variations

- Overall Variation = "part-to-part" + "repeatability" + "reproducibility"
- as only **one engine** was tested in this study
- Overall Variation = "repeatability" + "reproducibility"**
- Overall variation was computed based on **9 FTPs** sets of repeat tests irrespective of test cells
- Overall **53 test cycles** were analyzed and a total of **149 observations of BSPN** were made
- The **global (average) BSPN** throughout the testing period of **68 days** for hot FTPs was **1.39E+11 #/kW-hr**
- Global BSPN was used to calculate variation in BSPN due to *test process* and *measurement system (APC)* only

Repeatability

Repeatability	#/kW-hr	% of Global BSPN
Total	0.04E+11	2.54
APC	0.01E+11	0.69
Test Process	0.03E+11	2.45

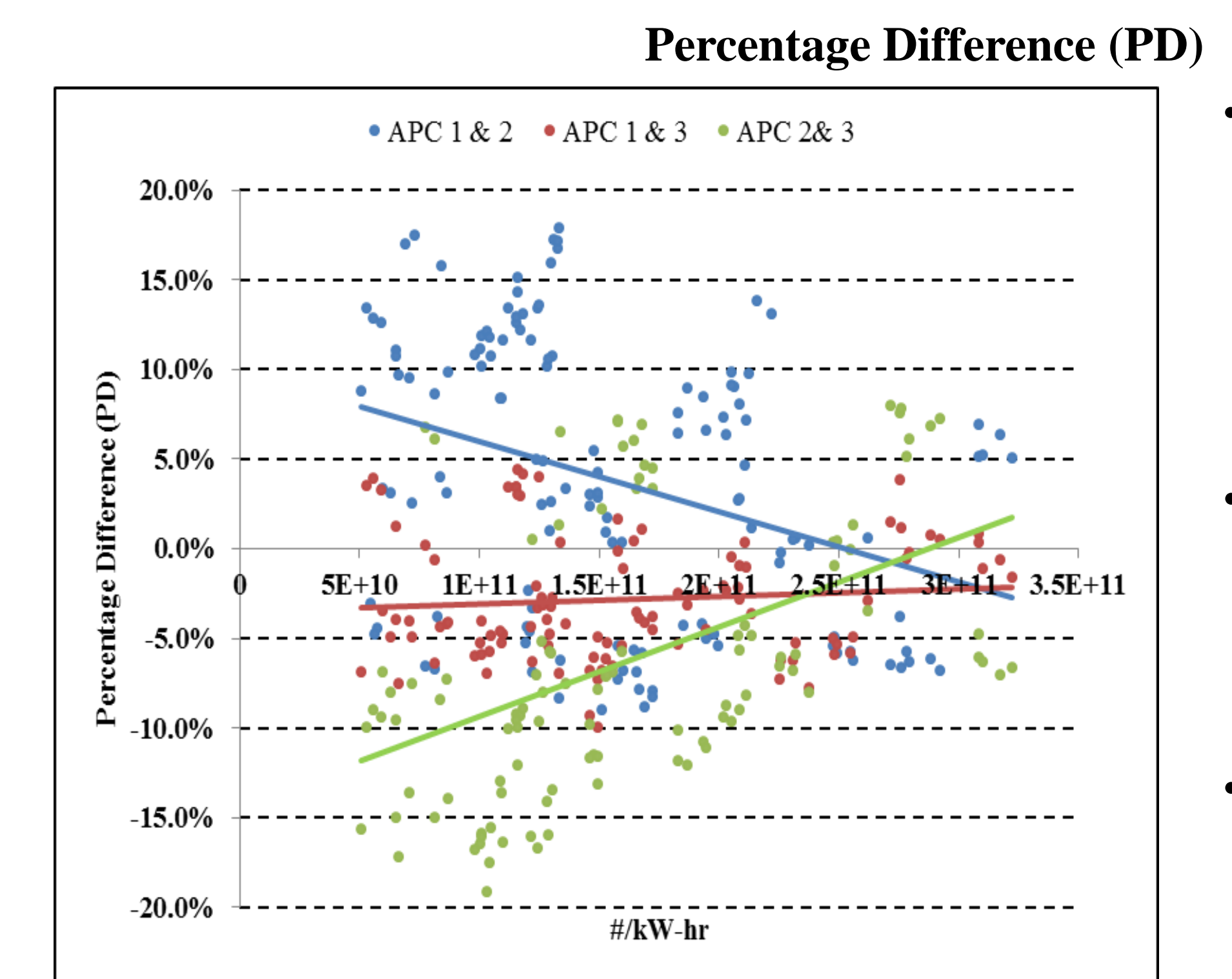
Reproducibility

Reproducibility	#/kW-hr	% of Global BSPN
Total	0.44E+11	31.7
APC	0.09E+11	6.2
Test Process	0.43E+11	31.1

- Reproducibility is High;
- Variation is mostly due to *Test Process*
- Total Variation** is defined as the sum of the variance of repeatability and reproducibility of BSPN measurements. Based on 149 BSPN measurements from three APC units, variation due to repeatability and reproducibility were found to be 0.6% and 99.4% of total variation, respectively.

Variation due to Repeatability	0.06%	APC	0.05%
		Test Process	0.59%
Variation due to Reproducibility	99.4%	APC	3.8%
		Test Process	95.6%
Total Variation	100%		

Variations within Test Cells



- Percentage Difference between BSPN measurements using any pair of APC units over the FTP and RMC test cycles (BSPN level: 5×10^{10} - 3×10^{11} #/kW-hr)
- On average, PD between APC 1 & 2, APC 1 & 3 and APC 2 & 3 were 3.8%, -2.8% and 6.3%, respectively.
- Typically, BSPN measurements from three APC units were within $\pm 10\%$

Repeatability of BSPN measurements over RMC test cycles

APC Unit	Repeatability Range (Visit 1)	Repeatability Range (Visit 2)
APC 1	8.2% - 28.4%	10.3% - 30.1%
APC 2	8.6% - 28.2%	8.3% - 31.1%
APC 3	7.6% - 32.4%	7.4% - 29.4%

Repeatability of BSPN measurements over FTP test cycles

APC Unit	Repeatability Range (Visit 1)	Repeatability Range (Visit 2)
APC 1	1.2% - 2.4%	1.4% - 2.6%
APC 2	0.7% - 3.3%	1.6% - 2.8%
APC 3	1.5% - 2.7%	1.7% - 2.7%

- Significant amount of time is required for PN to get stabilized

Reproducibility of BSPN measurements over FTP & RMC test cycles

APC Unit	Reproducibility Range	APC Unit	Reproducibility Range
APC 1	12.3% - 22.3%	APC 1	7.6% - 40.0%
APC 2	9.6% - 41.6%	APC 2	1.1% - 51.6%
APC 3	12.5% - 34.5%	APC 3	12.4% - 59.8%

- Reproducibility is poor

Conclusions

- Engine had very large variation in BSPN; attributed to the conditioning of the DPF. Therefore, second set of FTPs were used to characterize R&R of BSPN
- BSPN measurement repeatability was 2.5% of the global average
- Repeatability of APC unit was 0.69% of the global average
- BSPN measurement reproducibility was 31.7% of the global average
- Reproducibility of APC unit was 6.2% of the global average
- COV of BSPN among three APC units varied between -19.1 to 17.9% on 49 FTP test cycles
- Repeatability and reproducibility were found to be 0.6% and 99.4% of total variation, respectively.

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