

COMPARISON OF FULL FLOW DILUTION, PARTIAL FLOW DILUTION, AND RAW EXHAUST PARTICLE NUMBER MEASUREMENTS

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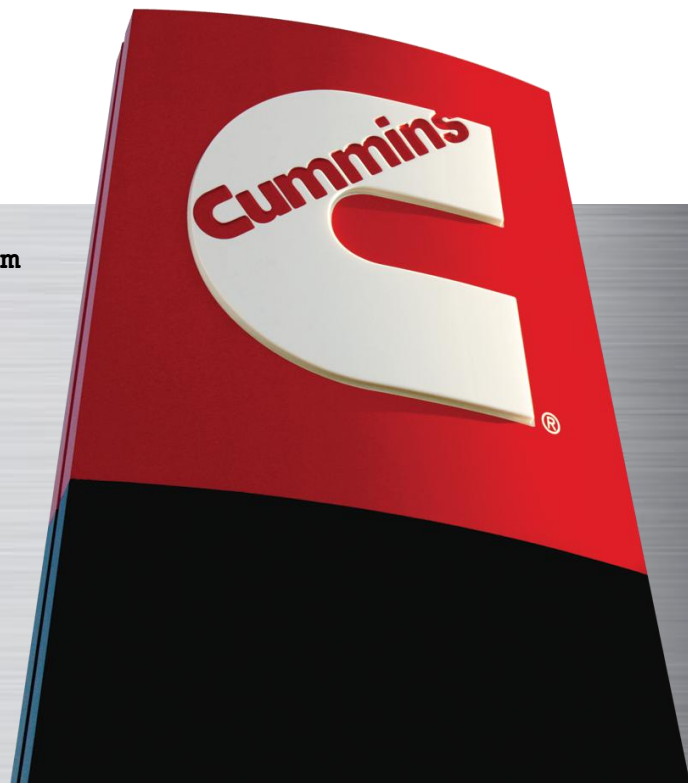
²HORIBA Automotive Test Systems

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Background

- Current EURO regulations allow Full flow & Partial flow dilution for PN measurements
- Studies have shown up to $\pm 15\%$ difference between CVS and Partial Flow
- Due to such variation, BSPN design target is set at least 50% lower than standards
- Most of the engine development occurs in raw test cells. Thus, there is a need of an instrument that can make PN measurement directly from raw exhaust
- **HORIBA MEXA-2100 Solid Particle Counting System (SPCS)** was identified which is compliant to PMP and can also measure raw PN emissions
- Therefore, Demo was conducted at Cummins Technical Center, Columbus, USA to evaluate the performance of the instrument



Overview of the HORIBA-2100 SPCS

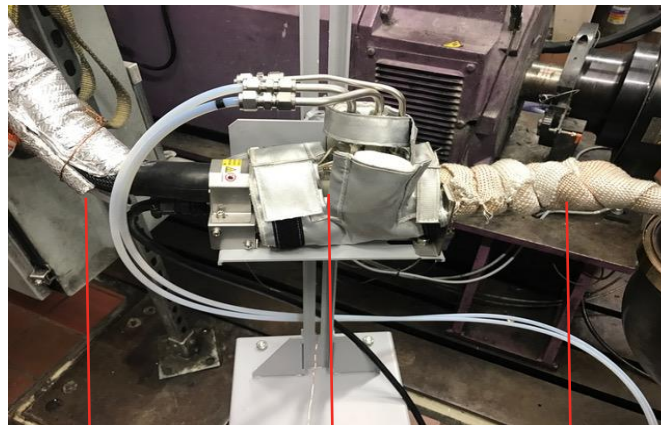
- Compliant to EU regulation requirements
- Additional Dilution sampling unit (DSU) for raw PN measurements (***Different PCRF values***)
- Can operate in the test cell temp. up to 45°C (113°F)
- Can handle up to 500°C of exh. Temp. and 100 kPa exh. Back press.
- 4 m heated sampling line
- Integrated Cyclone to remove particle larger than 2.5 µm
- CPC calibration up to 10,000 #/cm³ (TSI). Horiba internally confirmed linearity up to 30,000 #/cm³ with R² > 0.99



Front View



Rear View



Heated PTT

DSU

Probe



Objectives

- **PHASE 1:** Evaluate Repeatability, Short-term Reproducibility and the Impact of PCRF Selection for HORIBA 2100 SPCS
- **PHASES 2-5:** Compare HORIBA @ RAW or CVS against Reference @ PFSS or CVS for DPF & non-DPF engines

PHASE	ENGINE	DPF	PN # Level	HORIBA Location	APC* Location (Ref.)
1-2	A	NO	10^{13}	RAW	PFSS
3	B	NO	10^{13}	CVS	CVS
4	C	YES	10^{11}	RAW	CVS
5	D	YES	$10^{10}-10^{11}$	CVS	CVS

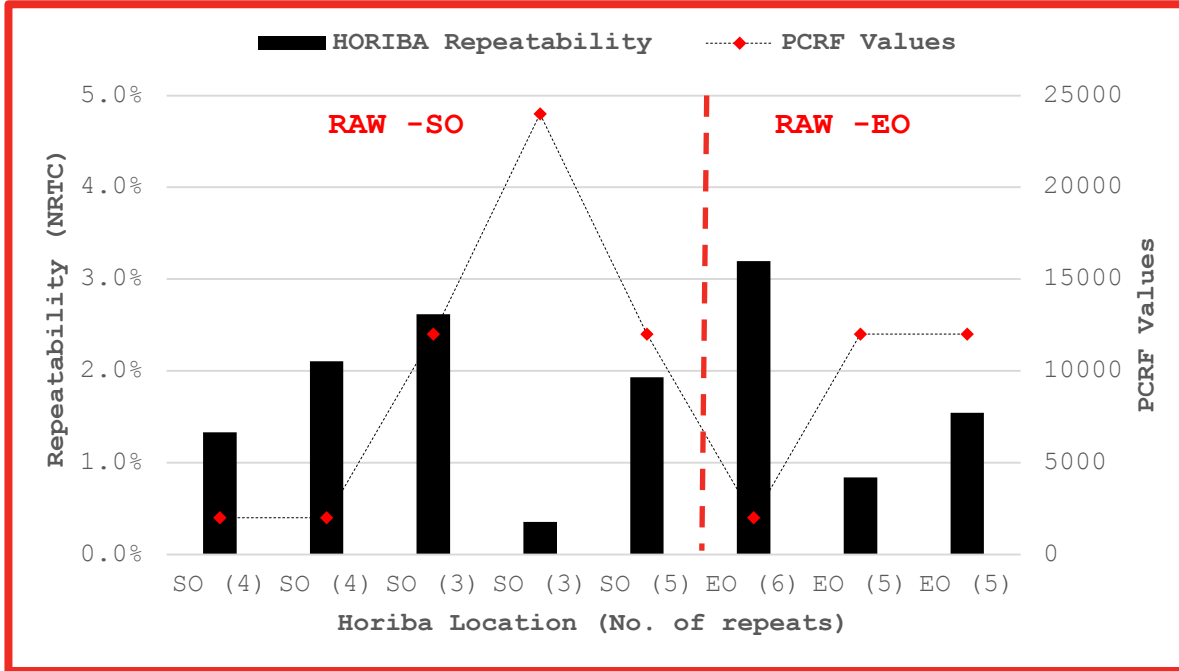
PHASE 1: Experimental Setup



Test Cell Location	Cummins Technical Center (CTC), Columbus, USA	
Test Cell Type	Raw Transient	
Engine A	Cummins 8.9 L, 380 HP, 6 Cylinder IL, SN: *****143 AT: DOC + SCR only	
Test Cycles	NRTC (51), RMCC1/NRSC (26)	
Instruments	HORIBA MEXA-2100 SPCS	APC (SN 285)
Location	Inside the Test Cell 202 (RAW EO & SO)	Test Cell 202 (PFSS SO)
Dilution ratio	DSU:10; PND1:10,50,100; PND2:15	PFSS:~15 (avg. NRTC); PND1: 100, PND2: 10

Engine with DPF was not used to exclude the impact of DPF conditioning on PN concentration

PHASE 1: Repeatability



Repeatability of HORIBA varied from 0.4-3.2%, respectively on NRTC cycles.

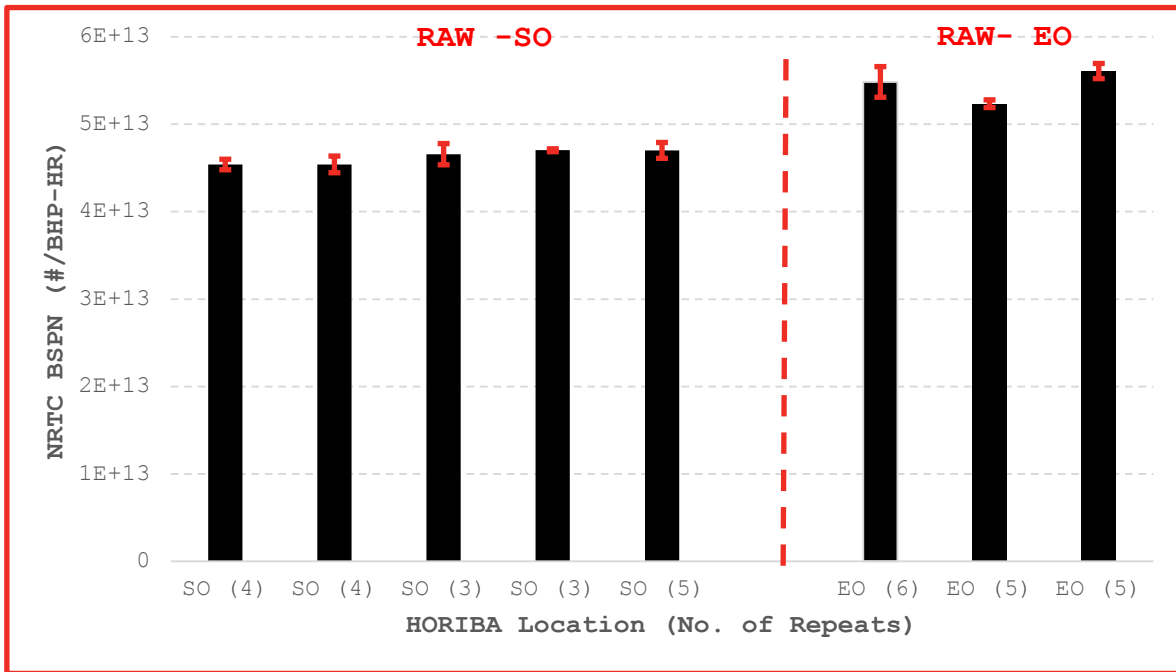
Insignificant difference in repeatability of HORIBA due to change in sampling location

Insignificant difference in repeatability due to change in PCRf values of HORIBA

Repeatability of APC varied between 0.3-1.2% at **PFSS SO**



PHASE 1: Short-term Reproducibility

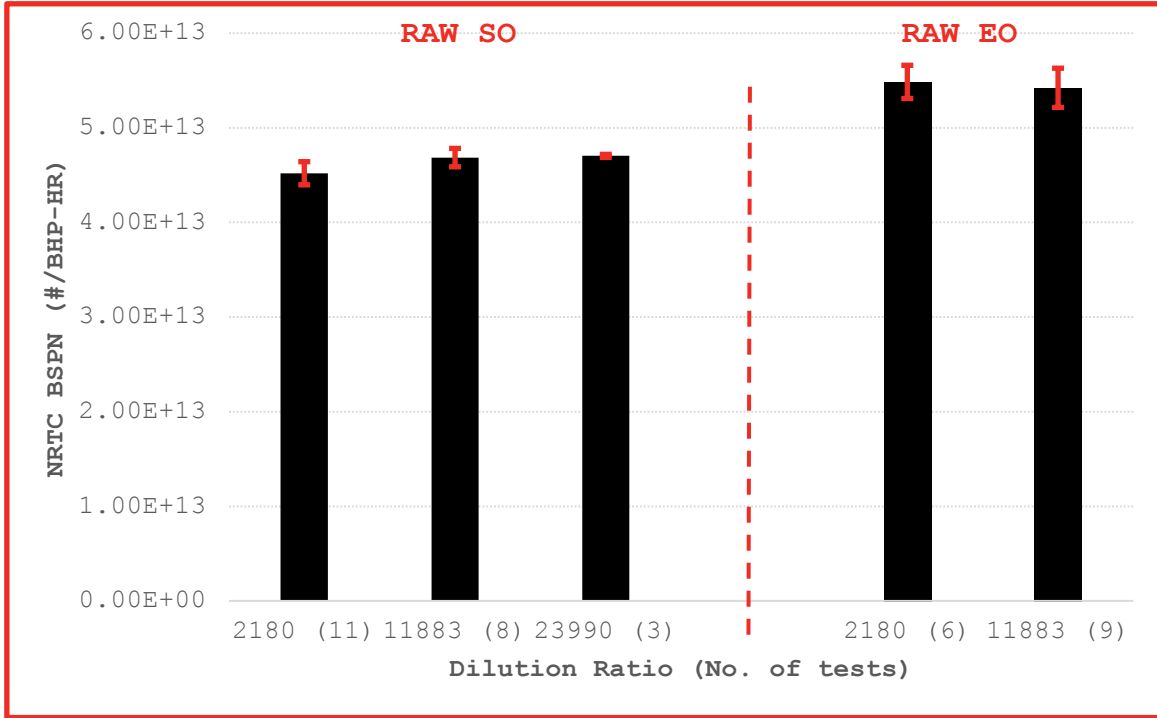


Short-term reproducibility at **SO** was 1.8%

Short-term reproducibility at **EO** was 3.5%

Short-term reproducibility of APC at **PFSS SO** was 1.2%

PHASE 1: Impact of PCRf Selection

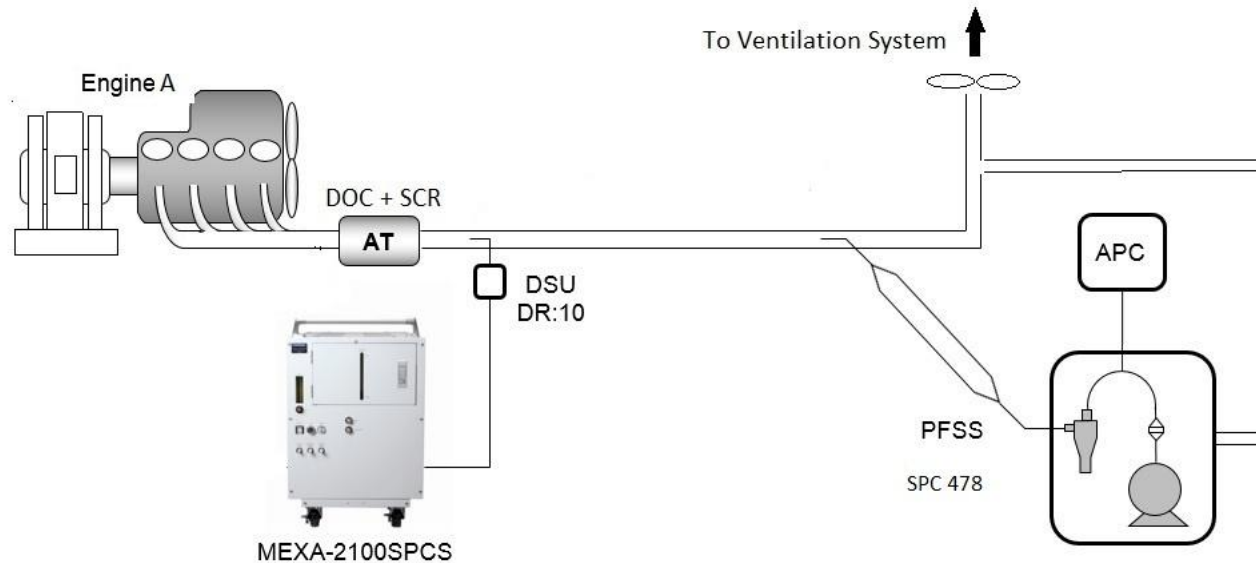


COV between dilution ratio settings ranging from ~2,000 to ~24,000 for **RAW SO** and **RAW EO** were 2.2% and 0.8% , respectively

PHASE 2: Engine A w/o DPF (RAW vs. PFSS)

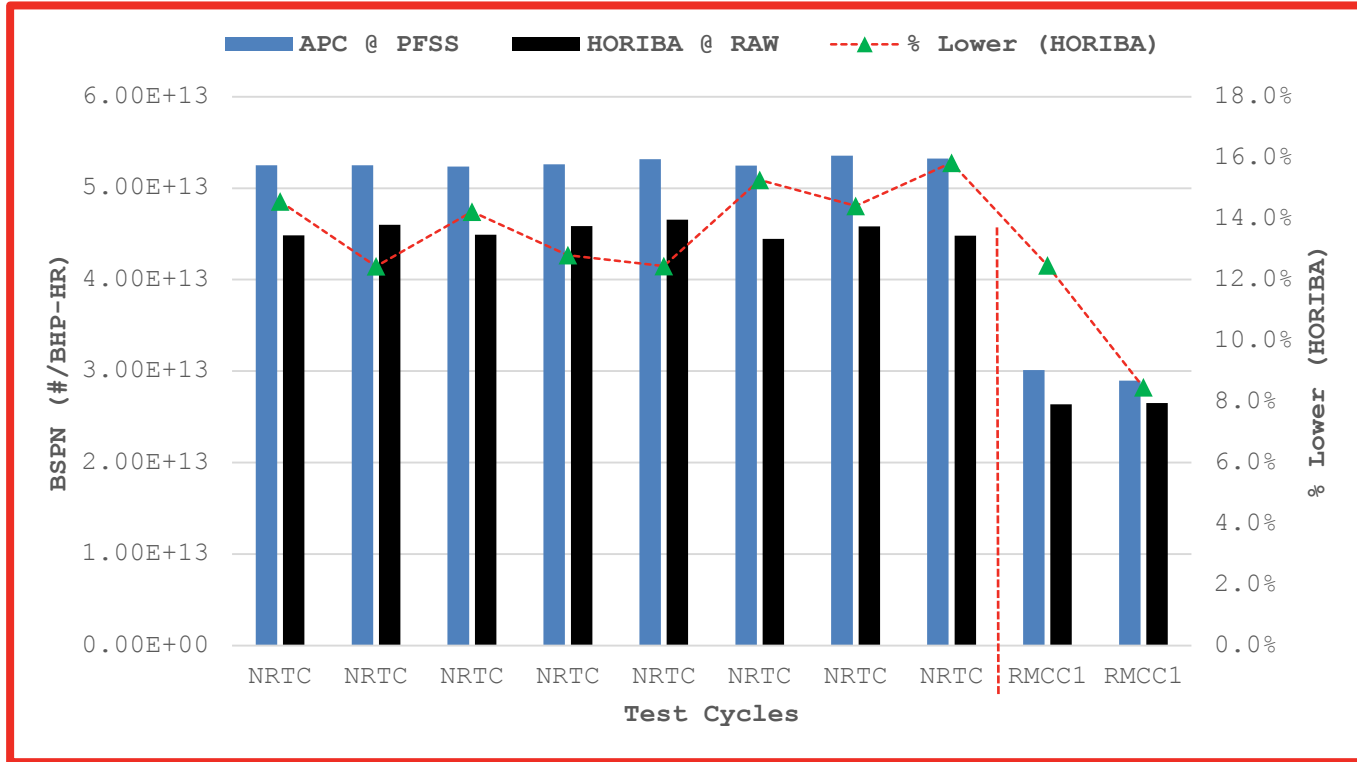


Instrument	SN	PCRF	Test Cell	Location
APC	285	1000	214	SO-PFSS
HORIBA SPCS	X	2180	214	SO-RAW





PHASE 2: RAW vs. PFSS @ 10^{13}

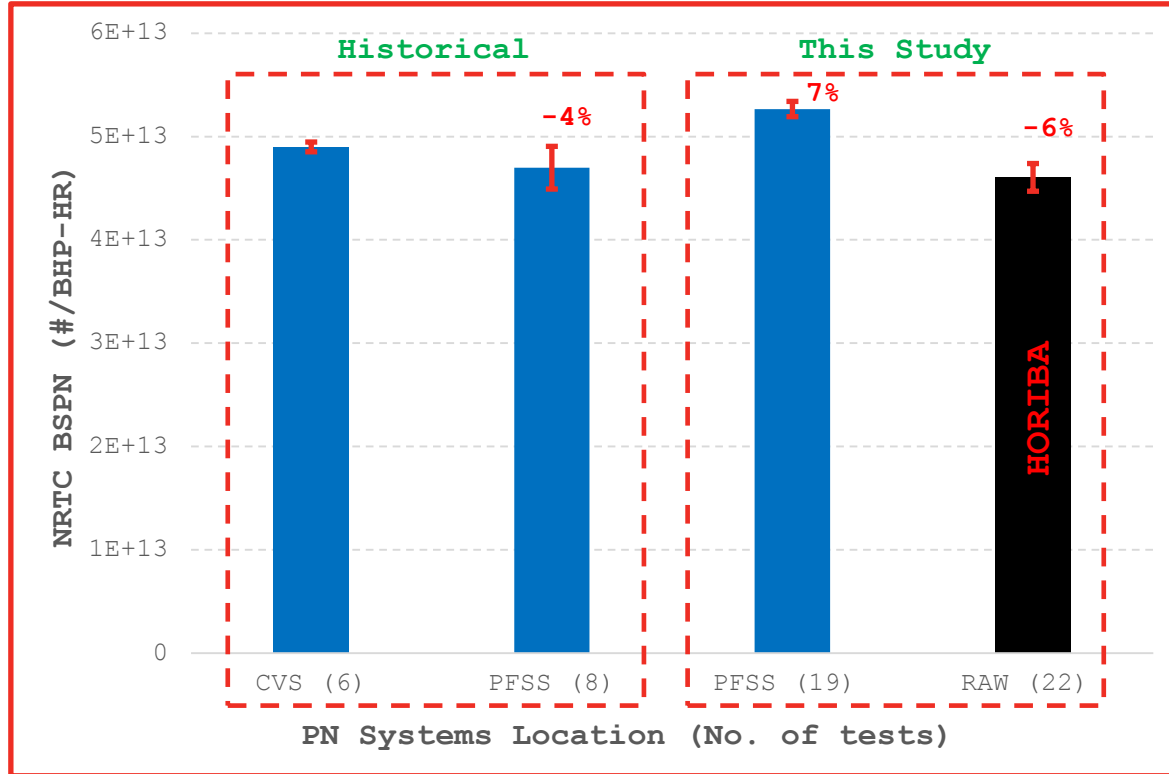


On average, HORIBA @ RAW was **~13% lower** than APC @ PFSS

For NRTC, this average was ~14% and for RMCC1 was ~10%



PHASE 2: CVS (Historical) vs. PFSS vs. RAW PN



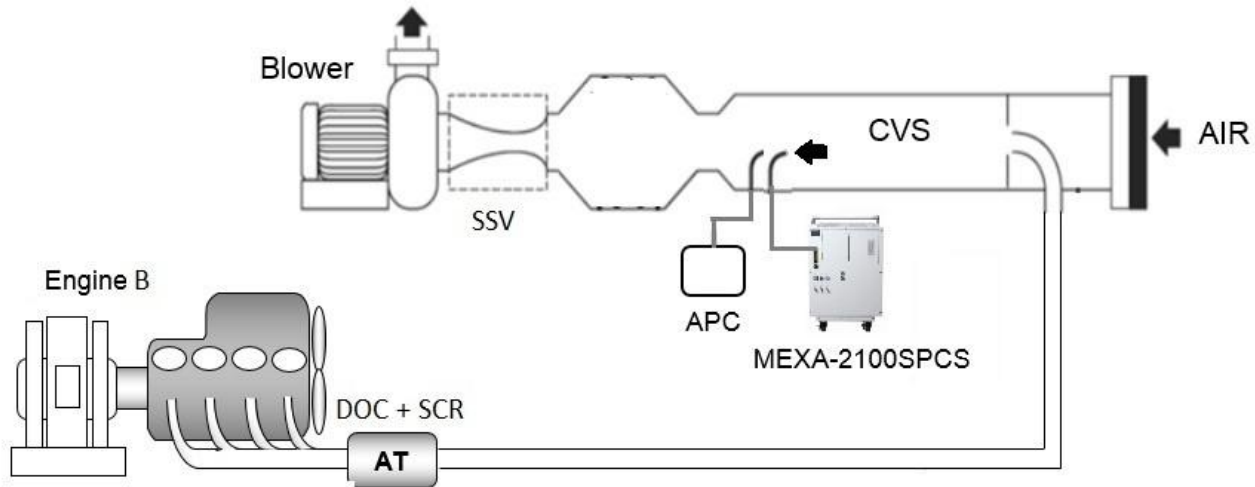
CVS PN measurements were 6% higher and 7% lower than RAW and PFSS (this study), respectively

Historical PFSS PN measurements (different test cell) differ by 11% from this study PN

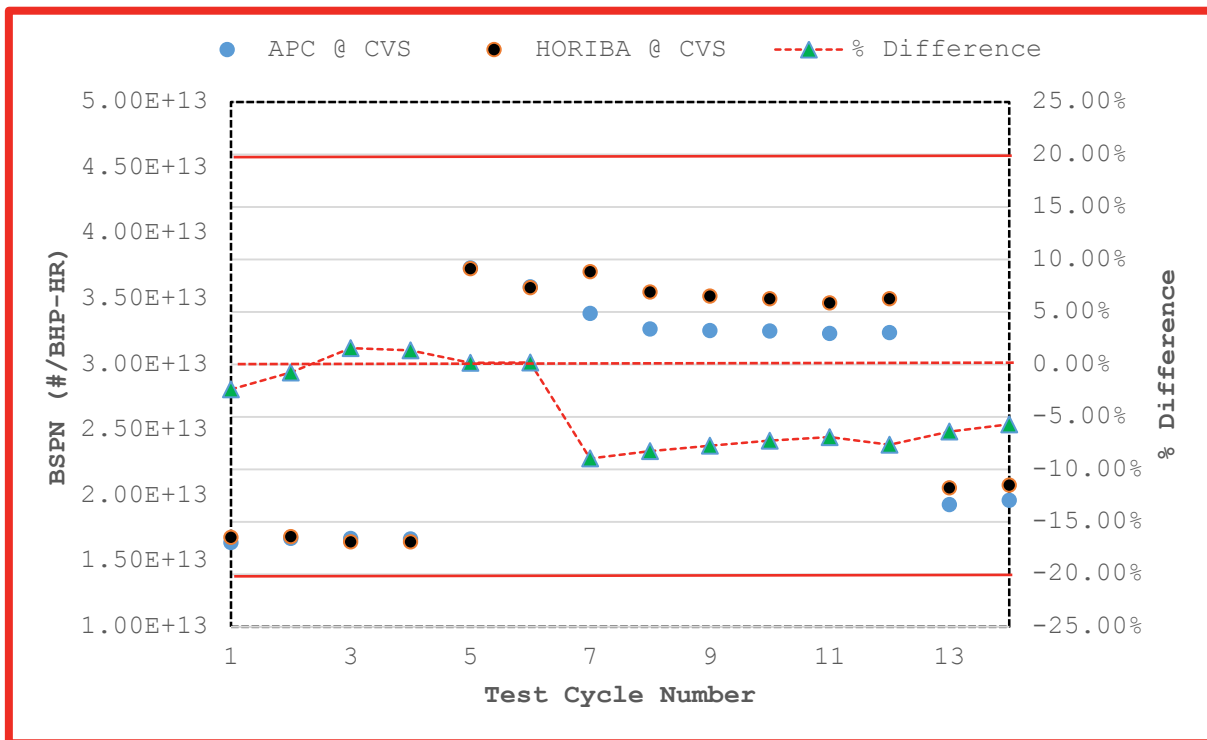
PHASE 3: Engine B w/o DPF (CVS vs. CVS)



Instrument	SN	PCRF	Test Cell	Location
APC	765	1000	212	CVS Tunnel
HORIBA SPCS	X	930	212	CVS Tunnel



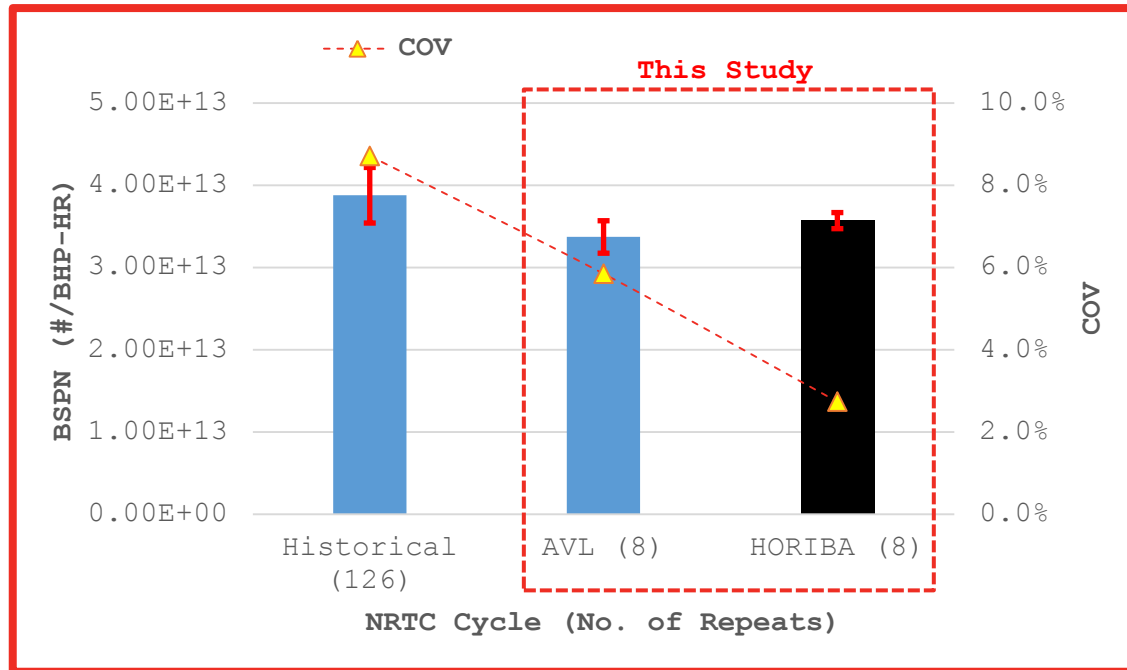
PHASE 3: CVS vs. CVS @ 10^{13}



% Difference is defined as the ratio of the difference between two BSPN values and the average of two BSPN values

On average, the % difference between two on different types of test cycles ranged between ~ **-9% to 2%** with average of **-4.21%**

PHASE 3: Historical vs. This Study



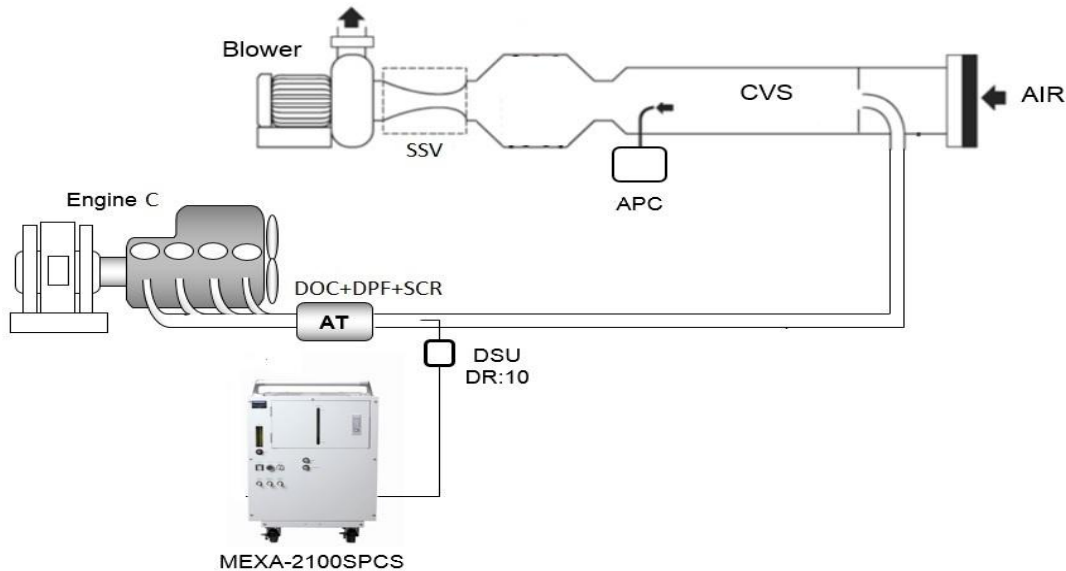
Historical data was 13% and 8% higher than APC and HORIBA measurements from this study.

In this study HORIBA showed better COV than APC (2.7% vs. 5.9%)

PHASE 4: Engine C w/ DPF (RAW vs. CVS)

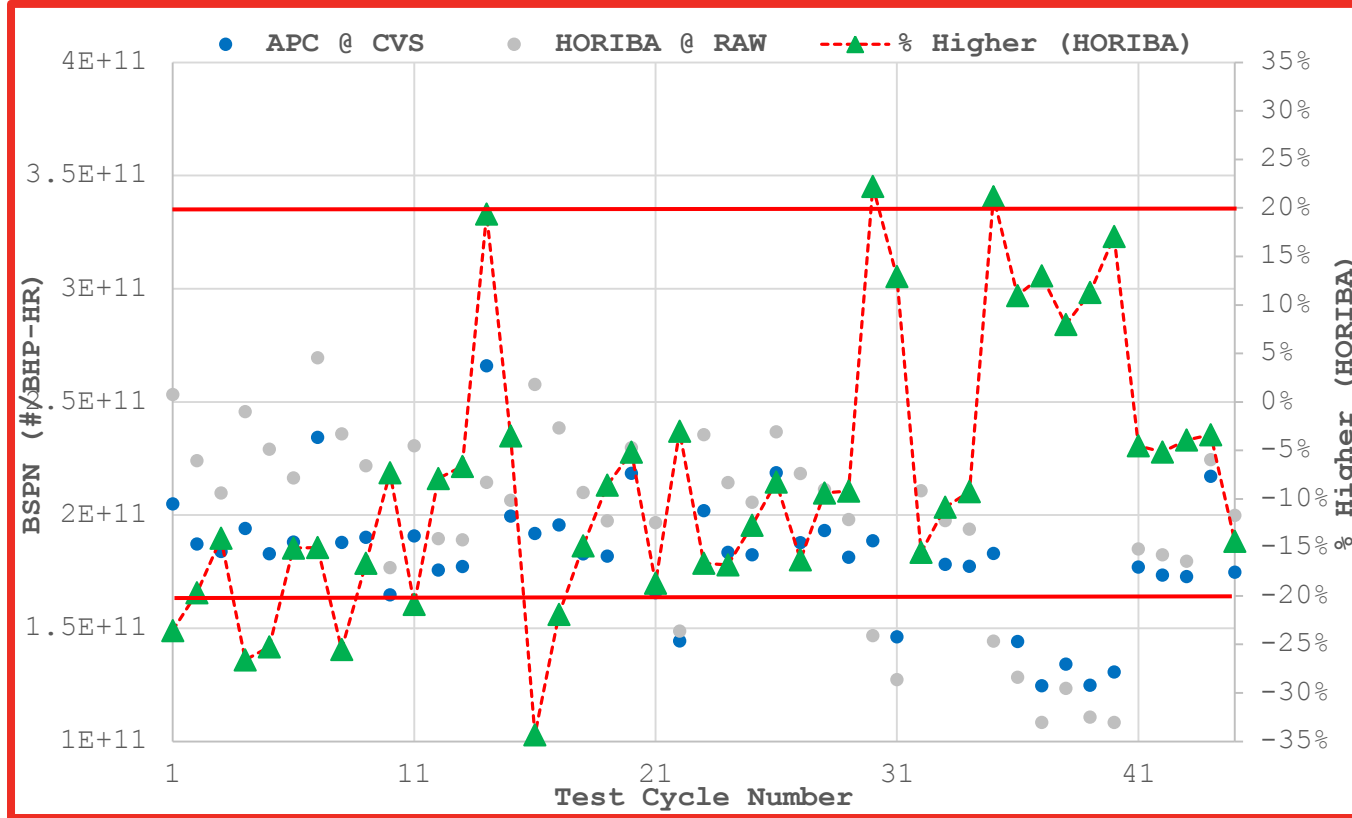


Instrument	SN	PCRF	Test Cell	Location
APC	285	1000	214	CVS Tunnel
HORIBA SPCS	X	2180	214	SO-RAW



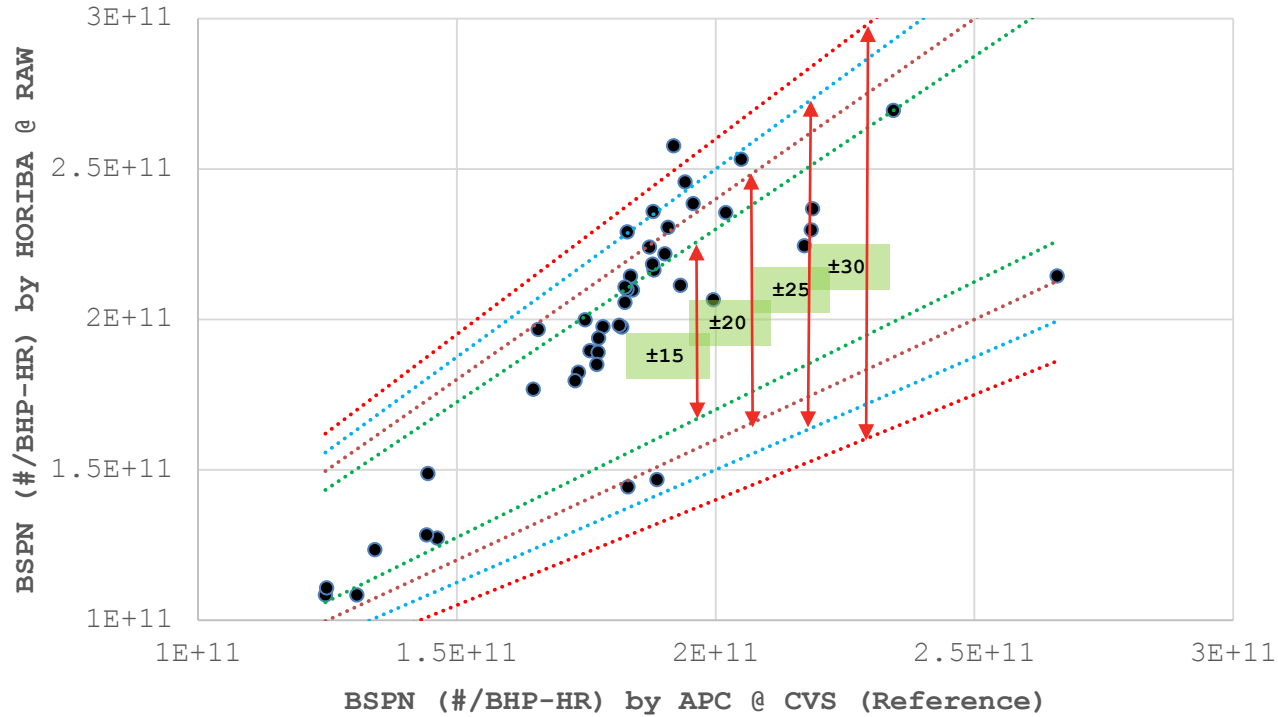


PHASE 4: RAW vs. CVS @ 10^{11}



On average, the RAW PN were **7.9±13.7 % Higher** than CVS (Reference) PN measurements

RAW vs. CVS @ 10^{11}

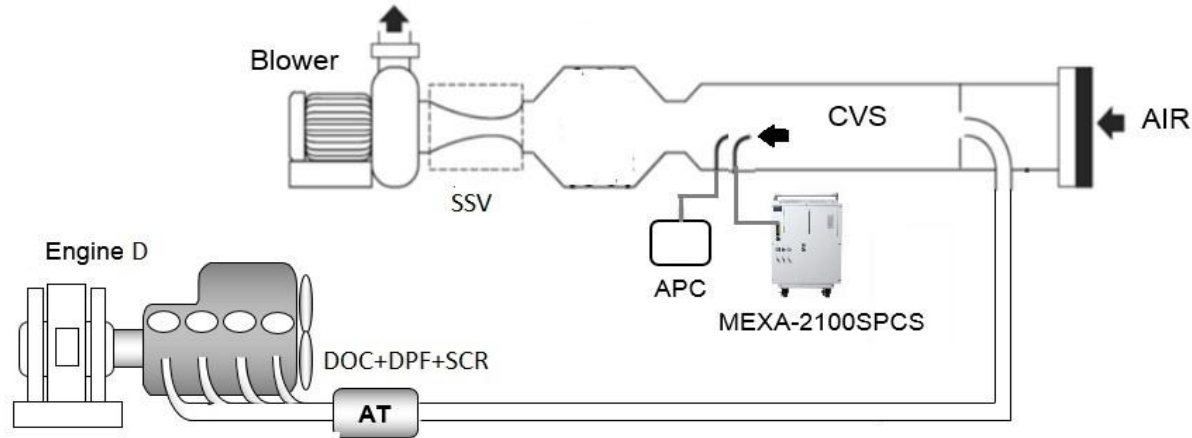


Out of 45 data sets: 56%, 78% and 87%, and 91% of RAW data were within $\pm 15\%$, $\pm 20\%$, $\pm 25\%$ and $\pm 30\%$ of the Reference, respectively

PHASE 5: Engine D w/ DPF (CVS vs. CVS)

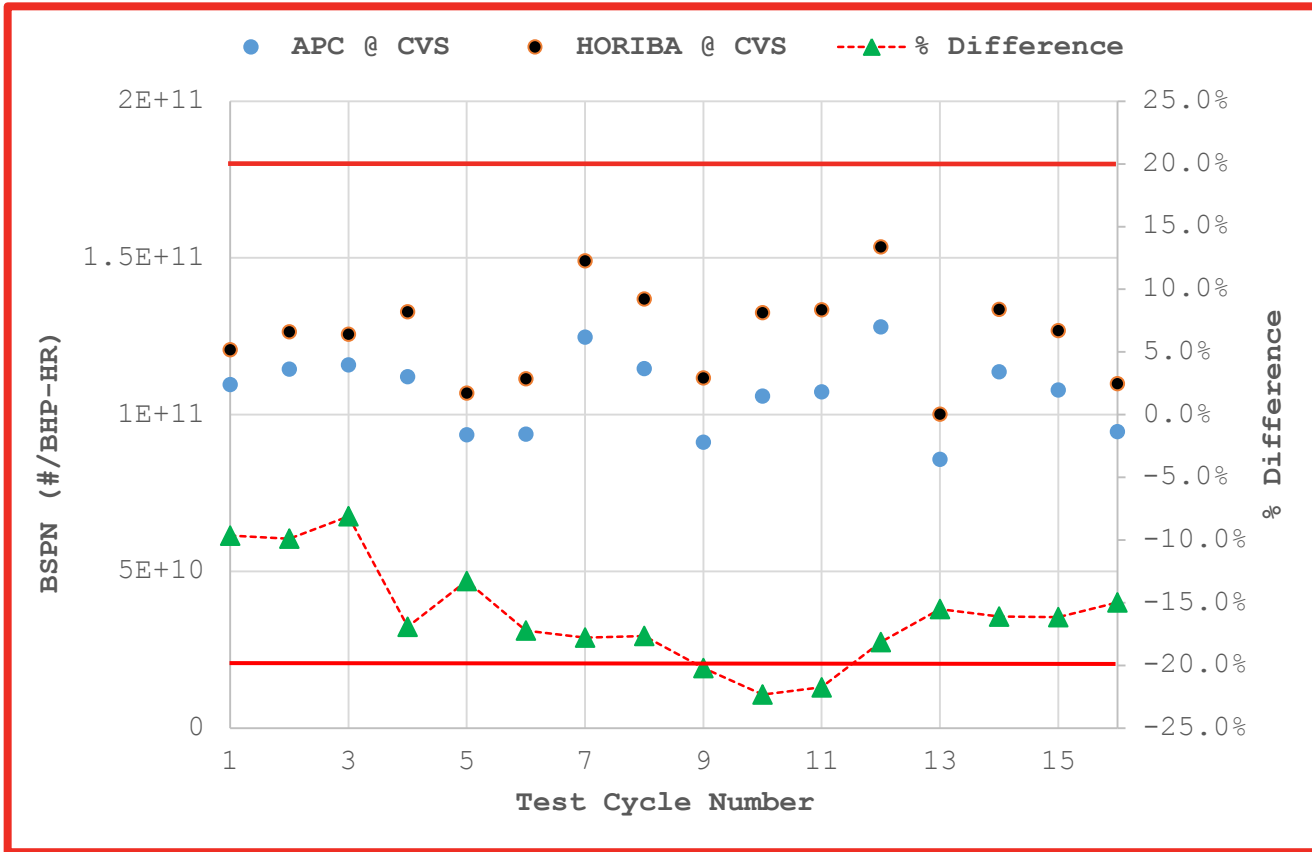


Instrument	SN	PCRF	Test Cell	Location
APC	765	1000	313	CVS Tunnel
HORIBA SPCS	X	930	313	CVS Tunnel





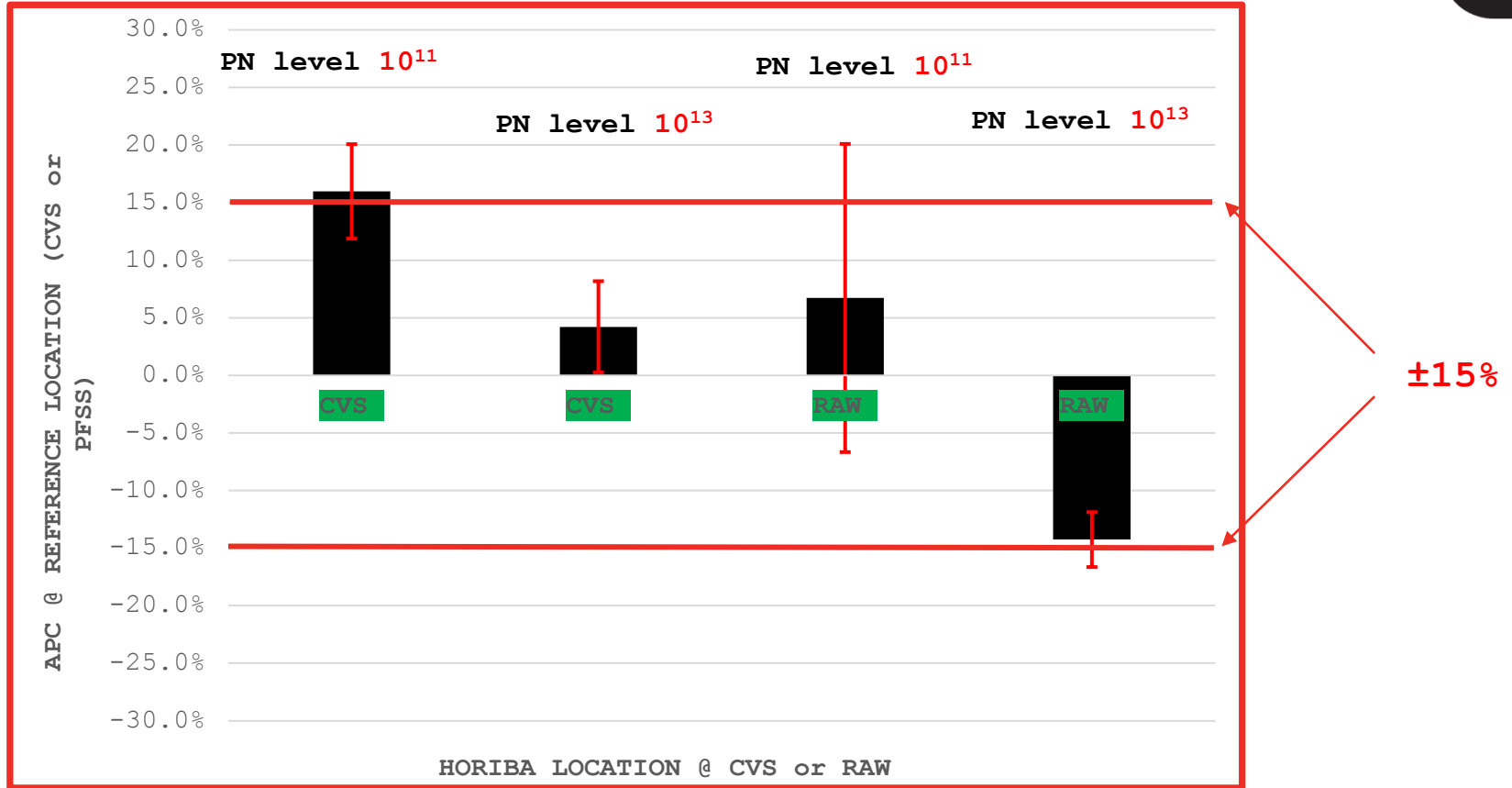
PHASE 5: CVS vs. CVS @ 10¹¹



On average, the % difference between APC and HORIBA at CVS was **-16%±4%**



OVERALL COMPARISON





Conclusions

- Instrument performed adequately under high Temp. (up to 460 °C) & high Pressure (up to ~43 kPa)
- BSPN Repeatability was observed between 0.4-3.2%
- BSPN Reproducibility was 1.8% and 3.5% for SO and EO, respectively
- No impact on BSPN due to change in PCRF values
- **At 10¹³ level Historical CVS vs. PFSS vs. RAW were within ~13%**
- **At 10¹¹ level RAW measurements were 7.9±13.7% higher than cvs**
- **For RAW testing, on average, the APC and HORIBA were between ~ ±15%**
- **60%, 84%, 93%, and 98% of all raw HORIBA measurements were within ±15%, ±20%, ±25%, and ±30%, respectively.**