A&D Technology

Real World Emissions Testing Based on FTIR Technology

TEST CELL AUTOMATION | LABORATORY MANAGEMENT | COMBUSTION ANALYSIS | SIMULATION | EMISSIONS
ENGINE | TRANSMISSION | ELECTRIC MOTOR | BATTERY/EV SYSTEMS | VEHICLE DYNAMICS

FAD-RDE Workshop 2014

Ron Tandy

Acknowledgements (Data Provided By):
Hong Kong Environmental Protection Department
Carol Wong

Contents

- FTIR Technology Overview
- Features and Benefits of FTIR for Automotive and PEMS use
- FTIR Accuracy and Correlation (Real World Data)
- Conclusions

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What is FTIR?

Multi-component gas analyzer based on **F**ourier **T**ransform **I**nfra-**R**ed technology.

Current FTIR technology allows for:

- Continuous measurement of up to 40 gases
- 5Hz data acquisition
- Fast response time ($T_{10\text{-}90}$ < 1.5sec)

FTIR is the ideal instrument for

- Engine development
- Aftertreatment calibration
- Catalytic converter development

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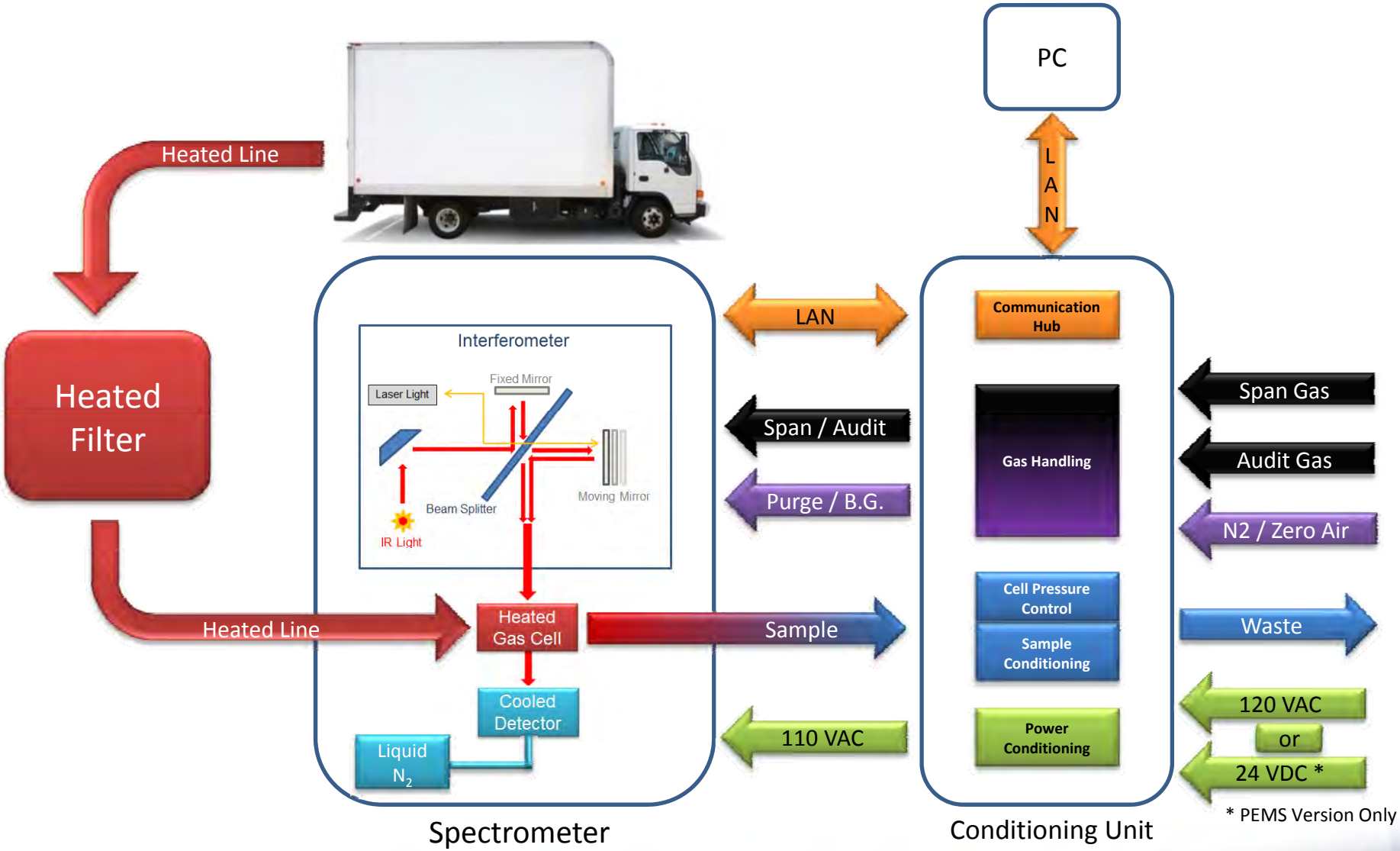
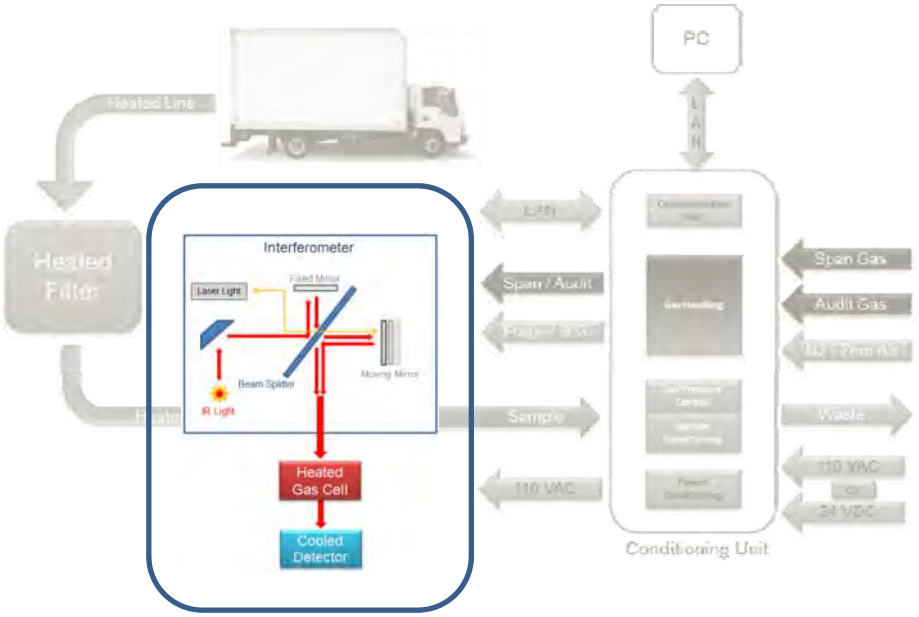
Typical FTIR System Configuration (Vacuum)



Spectrometer



Spectrometer

- The FTIR analyzer is an infrared spectrometer, configured as a dynamic multi-component gas analyzer
- FTIR Technology uses an interferometer, infrared light source, heated gas cell (191 ° C) and a cooled infrared detector
- MKS 2030HS Spectrometer – 16 micron, one-half wave number resolution (0.5CM^{-1}), LN_2 Cooled Detector

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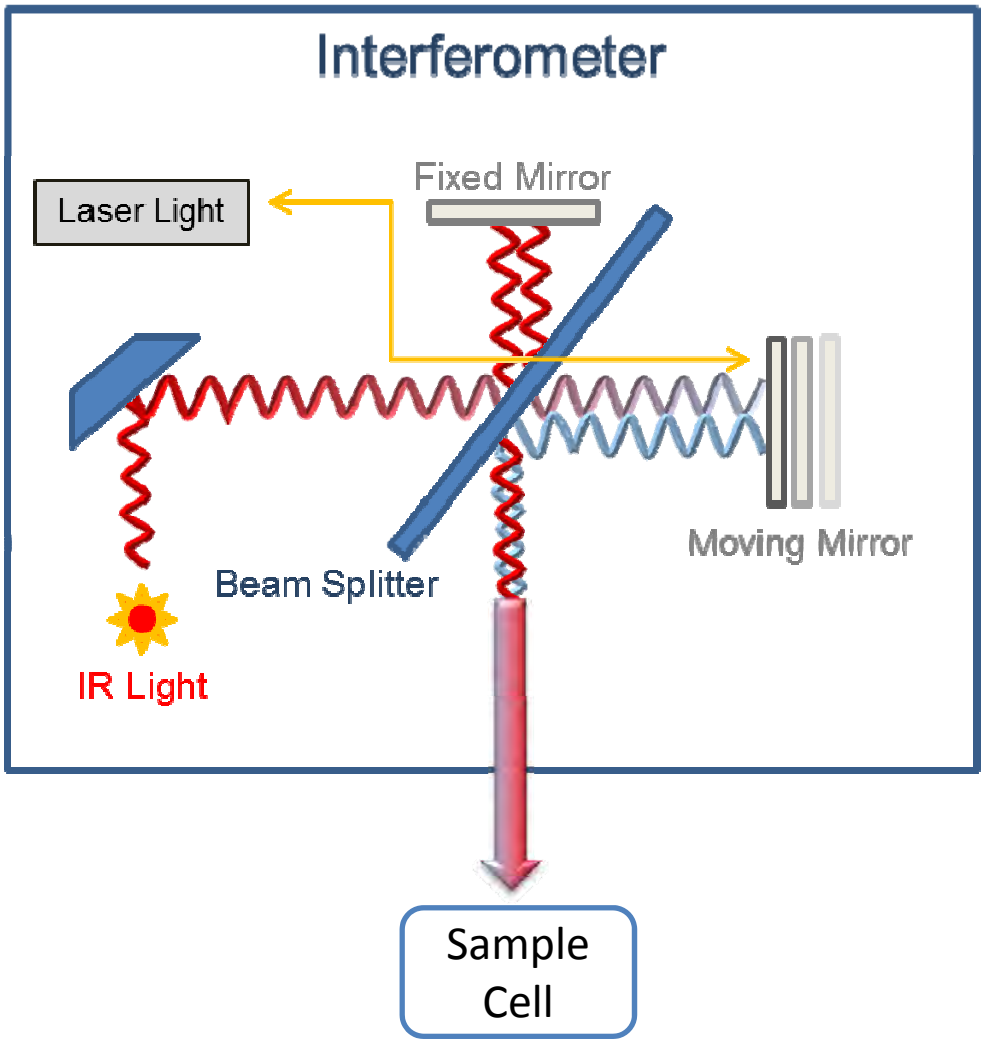
Interferometer Technology



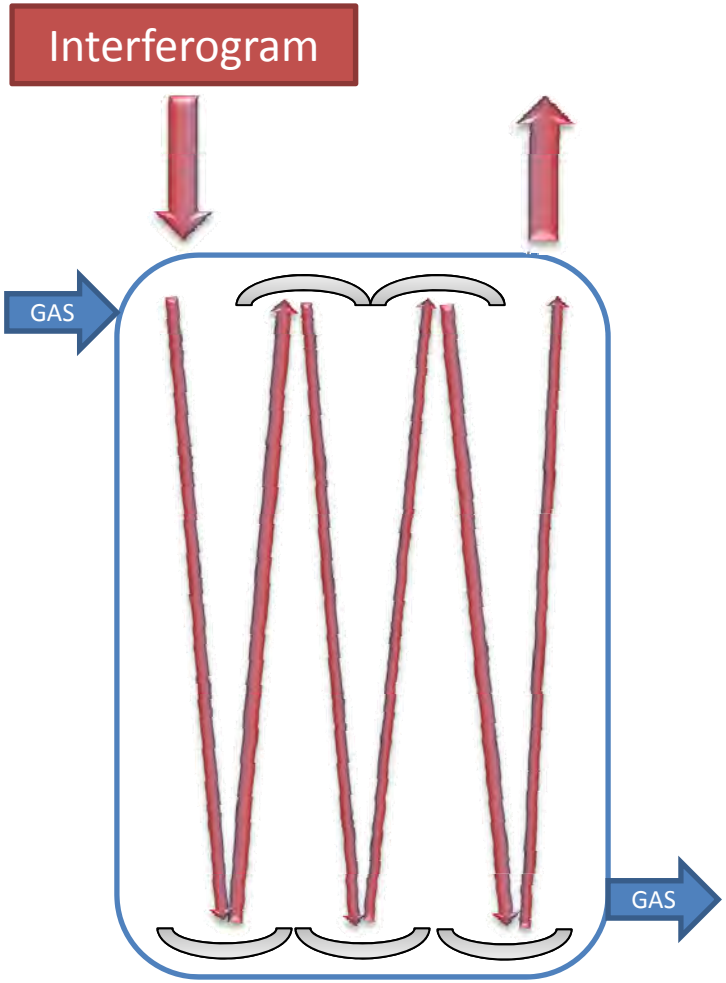
Michelson Interferometer creates interfering beams using:

- IR Light source
- Beam splitter
- Moving mirror
- Fixed mirror

A Helium Neon (HeNe) Laser determines mirror position, velocity and travel direction

The output is a Interferogram, containing information about all wavenumber frequencies within the mid-infrared spectral range

Sample Gas Cell



5.1 meter path (32 passes)

- **Heated to 191° C**
  Prevents condensation
- **5.1m Path**
  For high sensitivity
- **200 mL cell volume**
  For fast response time

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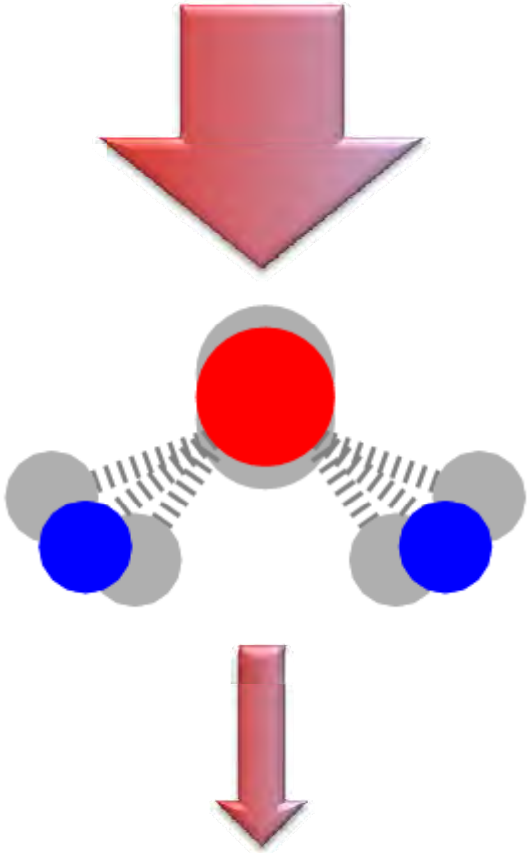
Frequency Absorption



Each molecule has a specific Infrared frequency where it absorbs the IR radiation.
(Bending, stretching, twisting , vibrating , etc. the molecule)

Because of the constructive (and destructive) interfering beams, the detector can read information about every wavelength in the infrared range simultaneously.

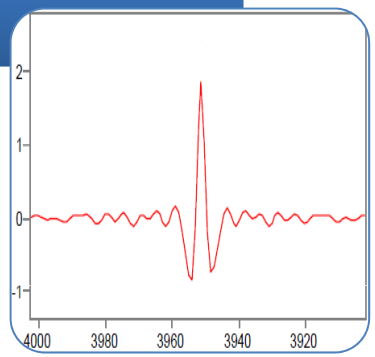
The interfering beams travel through the sample gas, where some energy is absorbed by gas molecules and some is transmitted to the detector.

The transmitted portion (not absorbed) reaches the detector.

The absorbed portion does not reach the detector, and is directly proportional to the amount of gas molecules in the sample.

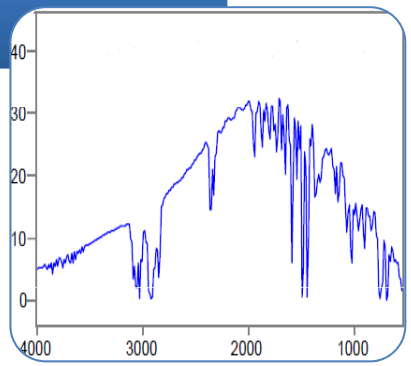
Interferogram to Gas Concentration

Interferogram



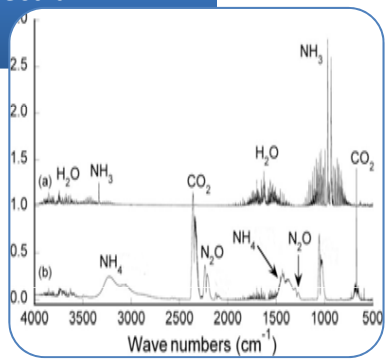
Signal as a function of time
(Position of Moving Mirror)

Single Beam

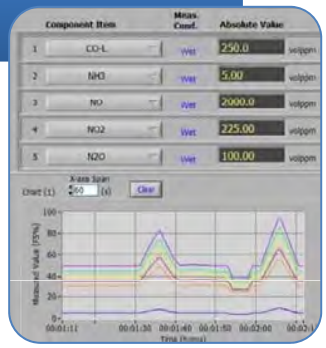


Signal as a function of frequency,
(with reference)

Absorbance Spectrum



Method Analysis



Fourier Transform algorithm

$$I(\tilde{\nu}) = \int_{-\infty}^{+\infty} I(x) D(\tilde{\nu}) \exp(2\pi \tilde{\nu} x)\, dx$$

Remove Background

A= -Log(I/Io)

Spectrum Analysis

- Method Determination
  (Gas, Diesel, CNG, Etc.)
- Analysis of absorption regions
- Speciation of gases

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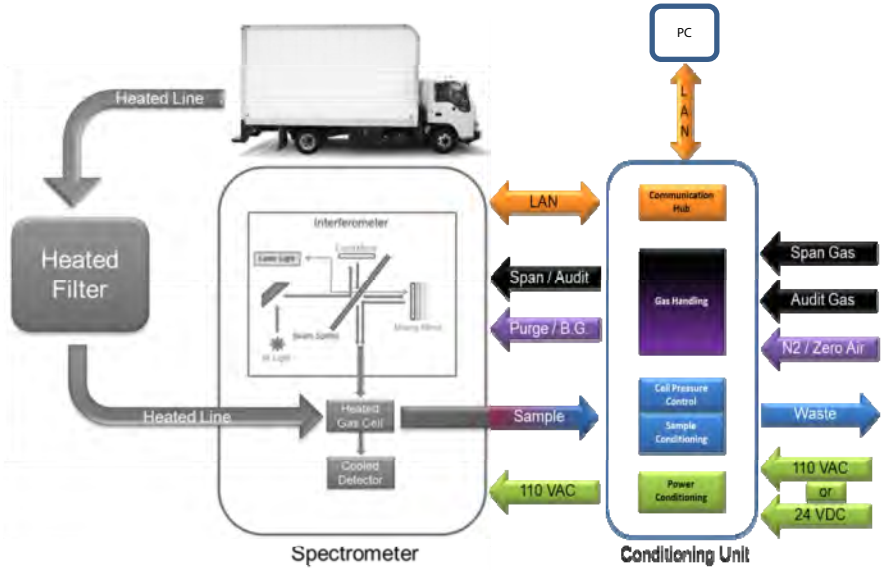
Conditioning Unit

- **Communication and Control** Spectrometer, PC, heated line & filter
- **Gas Handling**
  Zero and span gas regulation and distribution, for calibrations, purging and background
- **Cell Pressure Control**
  Controls the spectrometer cell pressure
- **Sample Conditioning**
  Cools sample and removes water (after spectrometer, prior to pump and mass flow meter)
- **Power Conditioning**
  Distributes power to spectrometer, HL, HF, and PC; accepts AC or DC (on-board only) input



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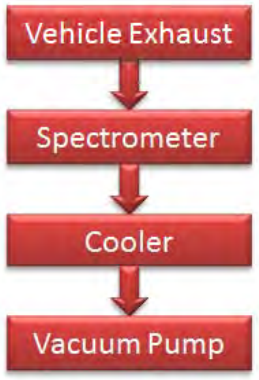
Cell Pressure Sampling

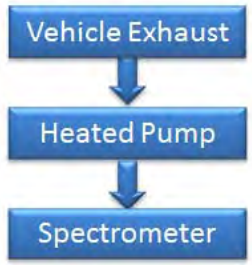
Vacuum Pressure

- Vacuum controlled cell
- Faster time response (T_{10}-T_{90} ~1.5 sec)
- Decreased consumption of exhaust gas

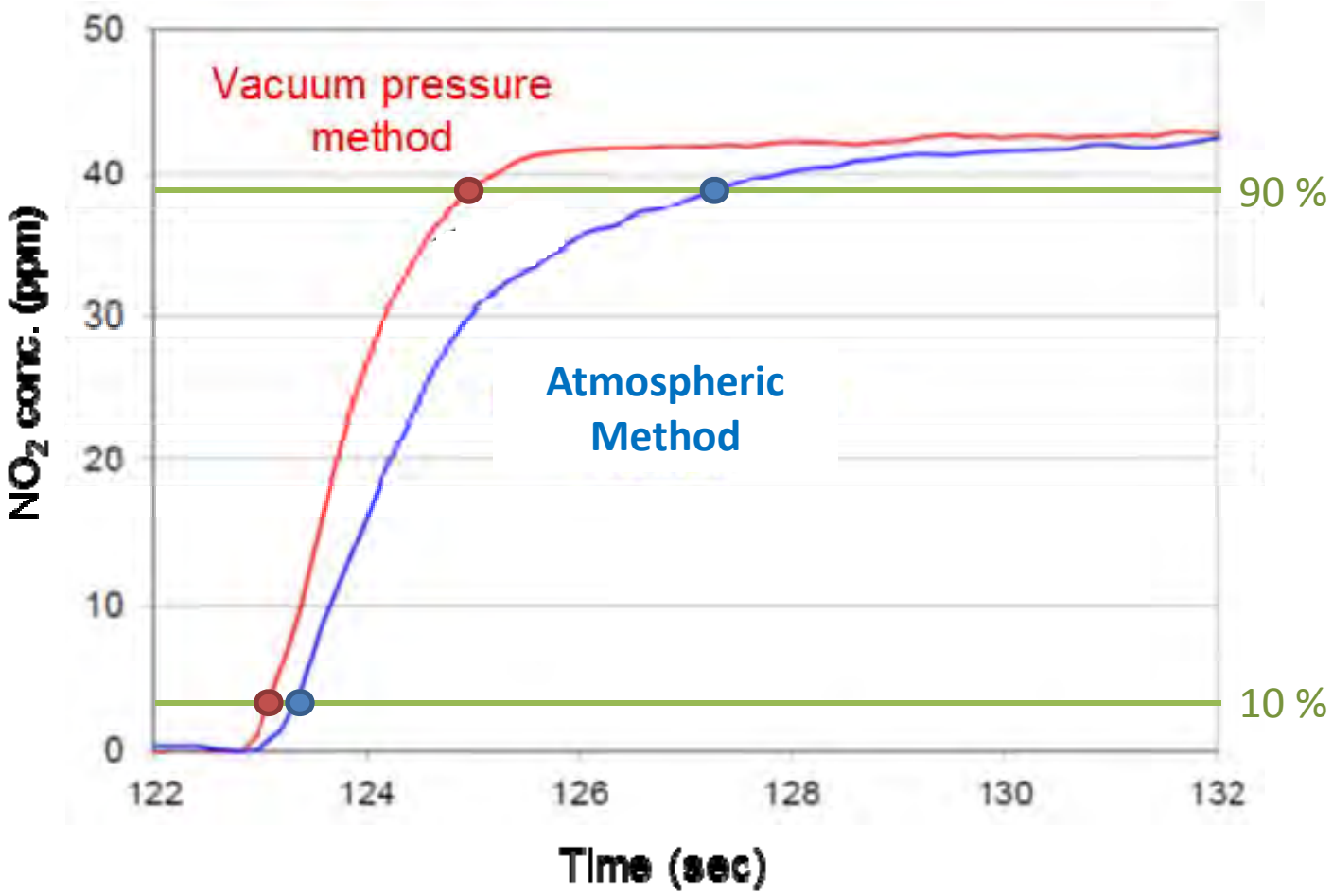


Atmospheric Pressure

- Allows for the availability of standard calibration libraries, methods and hundreds of gases/ranges
- Allows for easy integration, of systems already operating at atmospheric pressure



Vacuum Pressure Sampling



Vacuum pressure advantages:
Less gas degradation, decreased exhaust gas consumption, and significant reduction in the response time

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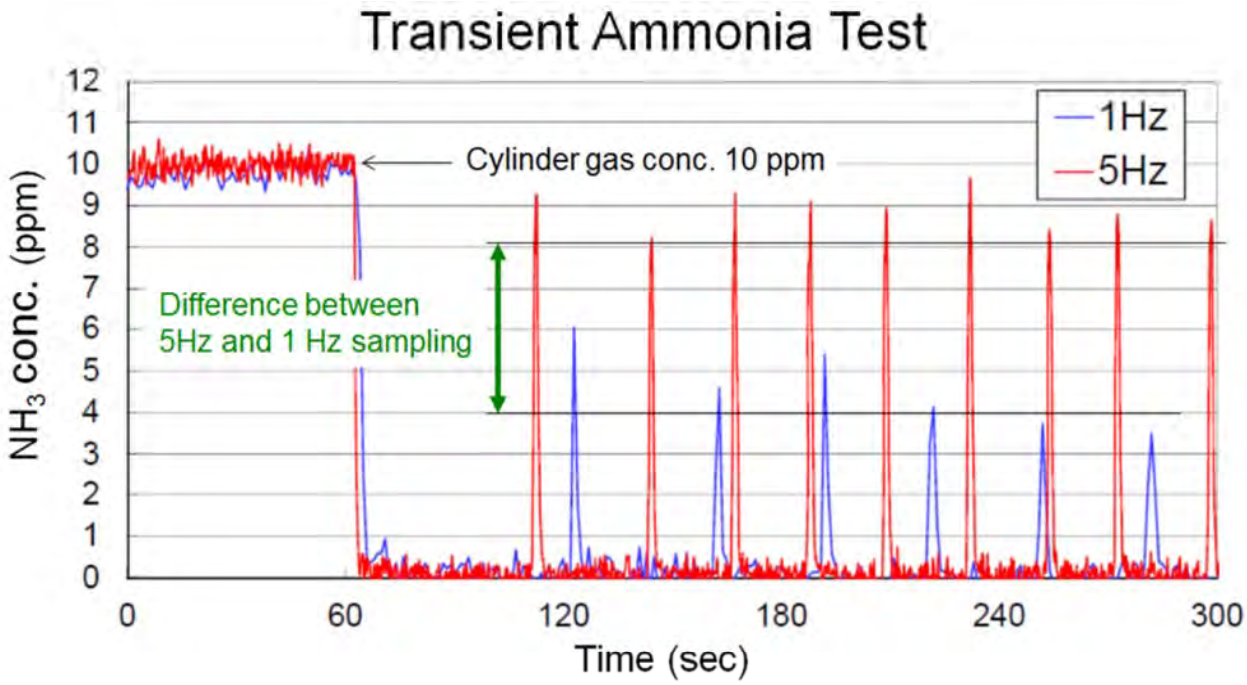
Sampling Rate

The FTIR spectrometer can sample at selectable rates, up to 5 Hz.

5 Hz sampling rates provide superior transient sampling, capturing more data fluctuations than 1 Hz.



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Messbare Gase

- Misst alle Gase die im mittleren Infrarot Spektrum absorbieren
- Messung aller regulierten Gases ausser THC*
- Mehrere konfigurierbare Messbereiche (z.B. CO_{Low} and CO_{High}).
- Investitionssicherung - Erlaubt Messungen von Gasen, die in der Zukunft von Interesse sein könnten.

*THC is calculated (sum of HC's) and based upon a FID correlation factor

Gas	Formula	Concentration	Units
REGULATED COMPONENTS:			
Carbon Monoxide (Low)	**CO (L)**	0 - 5000	ppm
Carbon Monoxide (High)	**CO (H)**	0 - 5	%
Carbon Dioxide (Low)	**CO_2**	0 - 4	%
Carbon Dioxide (High)	**CO_2**	0 - 20	%
Oxides of Nitrogen	**NO_X**	Calculated (sum of NO, NO_2)	
Hydrocarbons	**HC**	Calculated (sum of Carbons)	
NON-REGULATED COMPONENTS:			
Nitrogen Oxide (Low)	**NO (L)**	0 - 300	ppm
Nitrogen Oxide (High)	**NO (H)**	0 - 5000	ppm
Nitrogen Dioxide (Low)	**NO_2 (L)**	0 - 300	ppm
Nitrogen Dioxide (High)	**NO_2 (H)**	0 - 1000	ppm
Nitrous Oxide (Low)	**N_2O (L)**	0 - 100	ppm
Nitrous Oxide (High)	**N_2O (H)**	0 - 200	ppm
Ammonia	**NH_3**	0 - 500	ppm
Formaldehyde	**HCHO**	0 - 1000	ppm
Formic Acid	**HCOOH**		
Ethanol	**C_2H_6O**	0 – 1000	ppm
Methane	**CH_4**	0 - 2000	ppm
Methanol	**MeOH (CH_4OH)**	0 – 1000	ppm
Water	**H_2O**	0 - 30	%
Acetaldehyde	**MeCHO (CH_3CHO)**	0 - 1000	ppm
Sulfur Dioxide	**SO_2**	0 - 1000	ppm
Isocyanic Acid	**HNCO**	0 - 1000	ppm
Hydrogen Cyanide	**HCN**	0 - 1000	ppm
Carbonyl Sulfide	**COS**	0 - 200	ppm
DIFFERENTIATED HYDROCARBONS:			
Methane	**CH_4**	0 - 2000	ppm
Acetylene	**C_2H_2**	0 - 1000	ppm
Ethylene	**C_2H_4**	0 - 1000	ppm
Ethane	**C_2H_6**	0 - 1000	ppm
Propylene	**C_3H_6**	0 - 1000	ppm
Propane	**C_3H_8**	0 - 1000	ppm
1-3 Butadiene	**C_4H_6**	0 - 1000	ppm
Isobutylene	**C_4H_8**	0-500	ppm
Butane	**NC_4 (C_4H_{10})**	0 - 1000	ppm
Isopentane	**C5H12**	0 - 200	ppm
Benzene	**C_6H_6**	0 - 500	ppm
Octane	**NC_8 (C_8H_{18})**	0 - 1000	ppm

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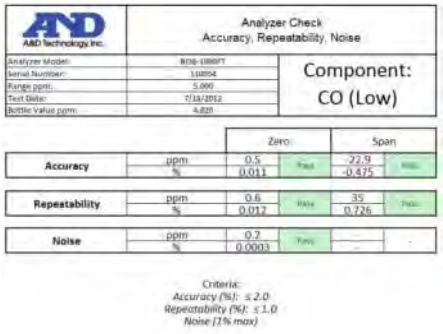
Evaluation by Regulatory Agencies

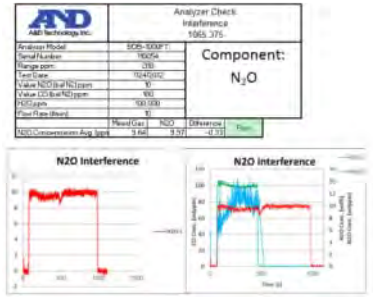
40 CFR Part 1065

System Response
40 CFR §1065.308

Linearity Verification
40 CFR §1065.307



Accuracy, Repeatability, Noise
40 CFR §1065.305



Interference Verification
40 CFR §1065.375

Meets or exceeds US EPA and
Euro Reg 49 verification requirements
(for regulated gases)

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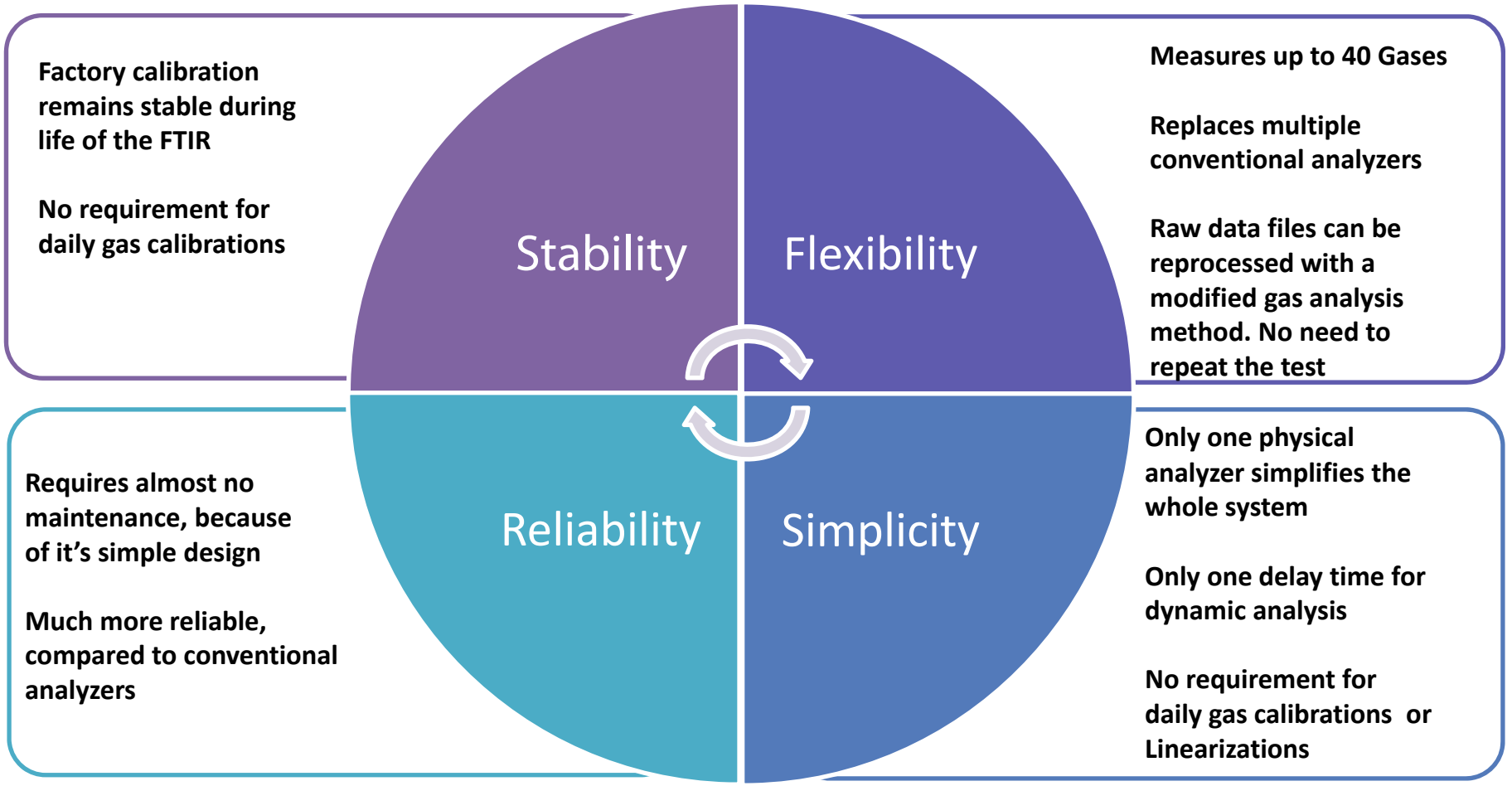
FTIR Customer Value



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Customer Benefits

- **Secure Investment**
  Gases that might be of interest in the future can be added without the need to integrate additional analyzers.

- **Low Total Cost of Ownership**
  Up to 40% lower operating cost compared to conventional analyzer systems due to less:
  - Maintenance
  - Operational work load (calibrations, diagnostics)
  - Required training
  - Span gas requirements

- **High Level of Flexibility**
  Can be utilized for many different applications and easily be moved between different test locations.

- **Excellent Correlation**
  With conventional gas analyzer systems.

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Benefits of FTIR - One Instrument

Replaces	Does Not Require
NDIR	CVS / Dilute
NDUV / CLD	Dry to Wet Conversion
GC Instruments	Time Align Gas Instruments
Impinger Systems	Daily Calibrations
Cutter FID	Linearization
Laser Diode or QCL	Drift Correction

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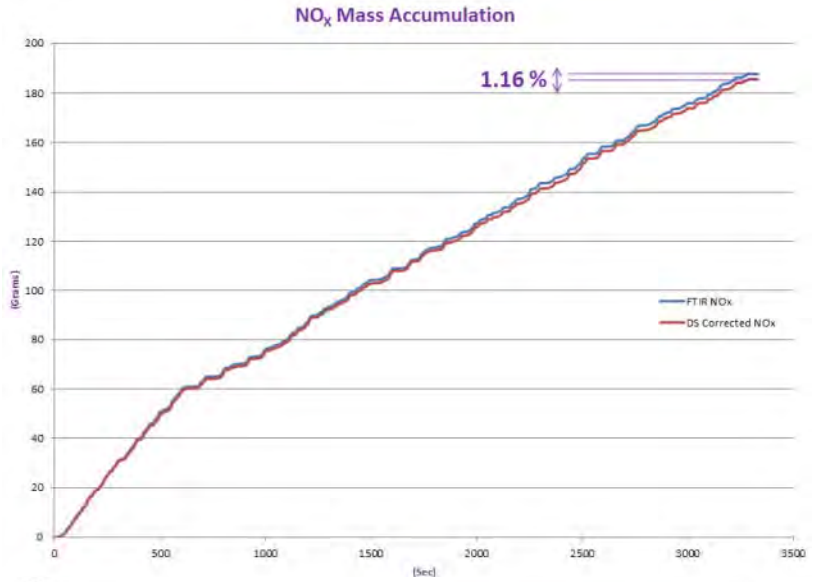
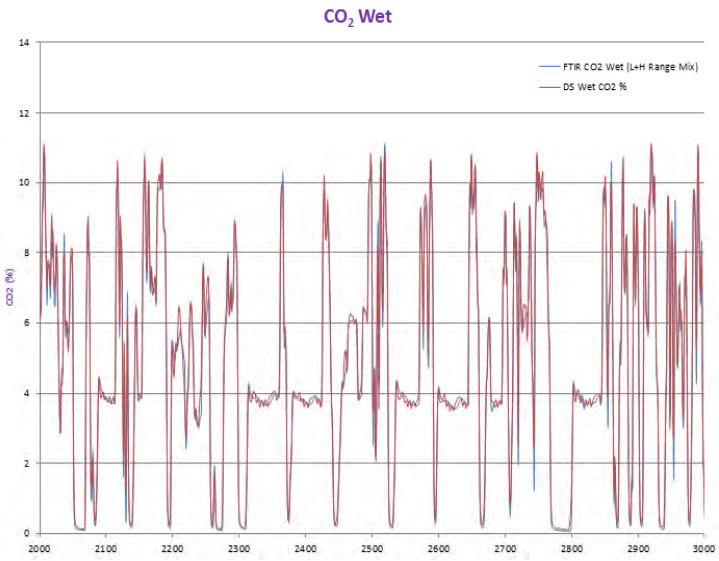
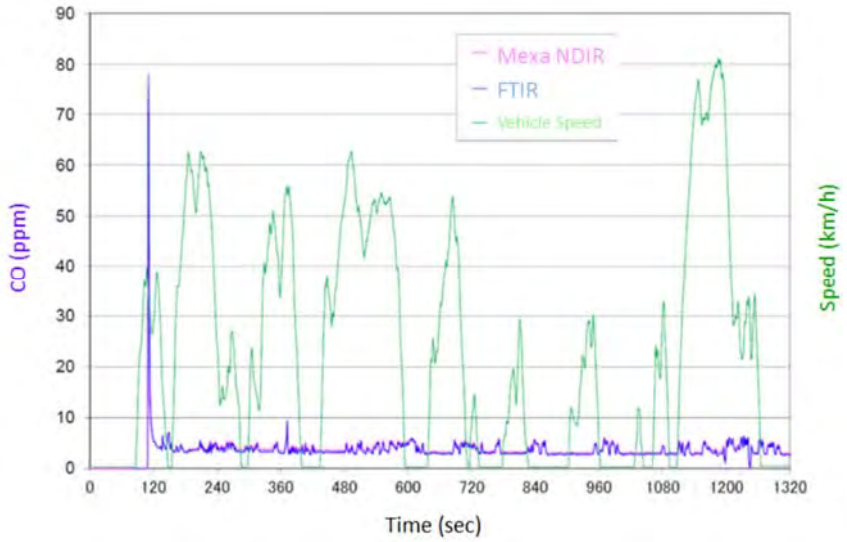
Correlation with Conventional Analyzers







Our testing shows FTIR correlation is Approx. ±2%, when comparing to conventional analyzers

(NO, NO_2, CO, CO_2, CH_4)

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Typical Applications (On-Board)

- Testing under Real-World Driving conditions
- Testing in harsh environments and high altitude
- Catalyst Development
- Evaluation of fuel additives without the need for a chassis dynamometer
- Correlation between test cell and real-world test results
- Emissions modeling in actual vehicle operational locations

PEMS FTIR Application

Problem		Solution
AC power availability	→	DC power inlet (24V)
Road vibration	→	Vibration dampening system
Pressure changes (altitude)	→	Pressure control system
Weather conditions	→	Environment control box
Battery charge level	→	Charge indicator with alarm

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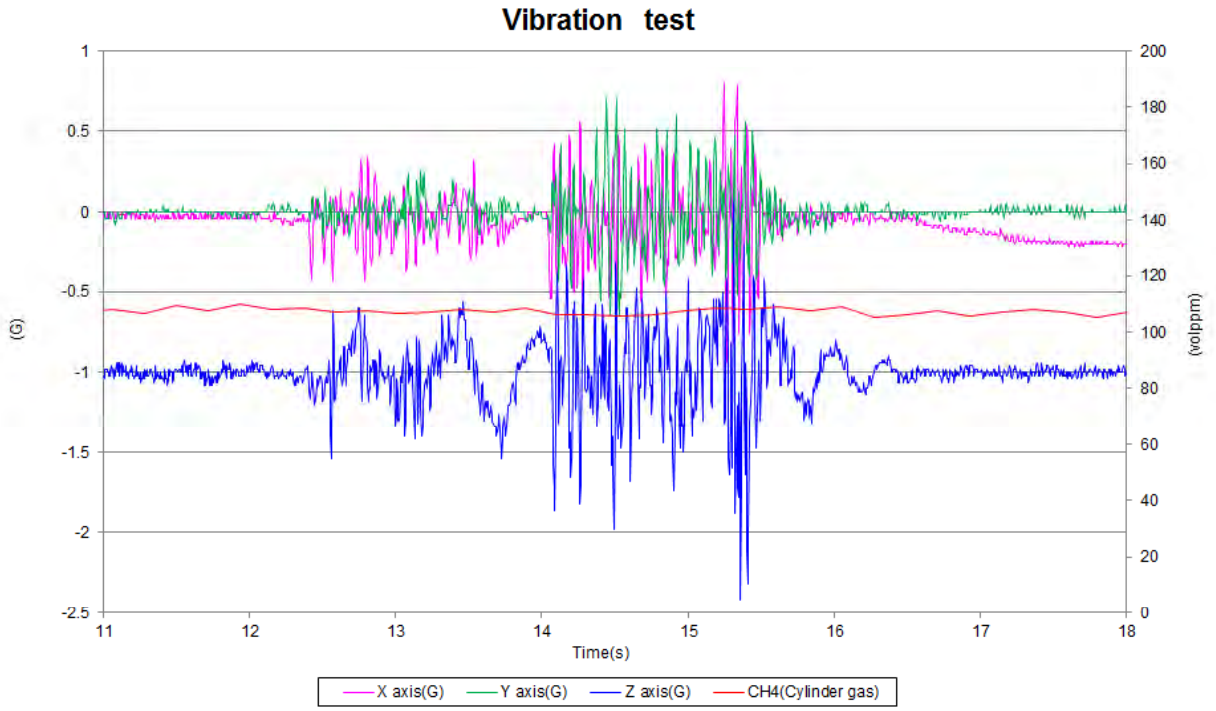
On-Board Vibration Dampening



No deflection on the gas concentration, during G-Force deflections from major road vibration

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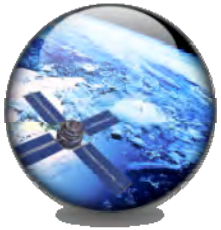
Typical FTIR PEMS Components



GPS Acquisition Unit and Software
Allows for GPS data (latitude, longitude altitude and speed), to be recorded and time-aligned with the emissions data.

ECU Acquisition Unit and Software
Allows for the vehicle ECU data to be recorded and time-aligned with the emissions data.

Video Camera Monitoring System and Software
Allows for live on-road video recording, time aligned with emissions data, GPS and ECU vehicle data .

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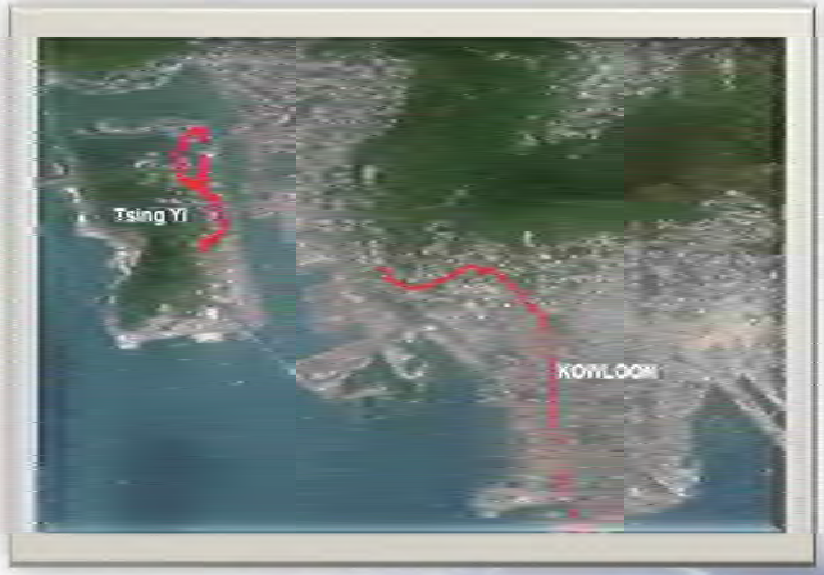
PEMS FTIR In-Use

Hong Kong EPD On-Road Testing

- **Coach Vehicle**
  Tsing Yi – Stop & Go
  7.14L Diesel
  12-DEC-2012

- **Double Decker Bus**
  Kowloon – Urban
  10.8L Diesel
  08-JAN-2013

"One of the most dense streets in the world"



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In-Use Hong Kong EPD Coach

Gaseous Measurement

A&D BOB-1000FT and Sensors SEMTECH-DS

HK-EPD Defendable Data Methods

- SEMTECH-DS: 1065 verification tests current
- 1065 In-use recommendations (e.g. drift corrections, etc.)
- Linearity Verification, Span (pre and post) and 3-hr Audit's

Span and audit conc. for SCR equipped Vehicle

	FTIR & Low CO/THC analyzer for CO				Low CO / THC analyzer for THC				FTIR		
	CO2, %	CO, ppm	NO, ppm	NO2, ppm	THC, ppmC	THC, ppmC3			N2O, ppm	NH3, ppm	NH3, ppm
Span	9.60	238.20	460.00	219.33	762.00	254.000			9.5	26.09	
Audit	4.80	119.10	230.00	99.76	381.00	127.000			4.8	13.05	476
Points in linearity check	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0			
	1.2	60	24.6	10.0	76.2	25.4	76.2	25.4			
	2.4	179	73.8	29.9	152.4	50.8	152.4	50.8			
	3.6	299	123.1	49.9	228.6	76.2	228.6	76.2			
	4.8	478	196.9	69.8	304.8	101.6	304.8	101.6			
	6.0	598	246.1	99.8	381.0	127.0	381.0	127.0			
	7.2	1014	309	144.9	457.2	152.4	457.2	152.4			
	8.4	2028	463.5	193.2	533.4	177.8	533.4	177.8			
	9.6	3042	618	241.5	609.6	203.2	609.6	203.2			
	10.8	4056	827.2	338.1	685.8	228.6	685.8	228.6			
	12.0	5070	1034.0	434.7	762.0	254.0	97.2	32.4			
Statistics from Trial on the SCR equipped Vehicle											
mean	5.2	129.1	228.5	98.9	9.6	3.2			2.3	0.2	
median	5.4	81.4	204.6	74.7	2.2	0.7			2.0	0.2	
max	12.4	5108.2	923.2	395.0	252.6	84.2			27.6	0.5	
99%	11.2	1203.3	756.0	359.7	79.3	26.4			13.7	0.5	
95%	9.9	222.1	587.0	281.2	36.3	12.1			4.6	0.5	
75%	7.2	112.2	363.6	151.1	14.7	4.9			2.5	0.3	
25%	3.3	59.4	32.6	14.7	1.0	0.3			1.5	0.0	
5%	0.2	15.8	11.0	8.8	-0.4	-0.1			0.5	0.0	
50% Max	6.2	2554.1	461.6	197.5	126.3				13.8	0.2	
37.5% Max	4.6	1915.6	346.2	148.1	94.7				10.3	0.2	
50% of 99th percentile	5.6	601.7	378.0	179.8	39.6				6.8	0.2	
37.5% of 99th percentile	4.2	451.2	283.5	134.9	29.7				5.1	0.2	
50% of 95th percentile	5.0	111.1	293.5	140.6	18.2				2.3	0.2	
37.5% of 95th percentile	3.7	83.3	220.1	105.5	13.6				1.7	0.2	
span	9.3	166.6	440.3	210.9	27.2				3.443475	0.35325	

User:
The higher concentration used is due to expected occurance of DPF regeneration

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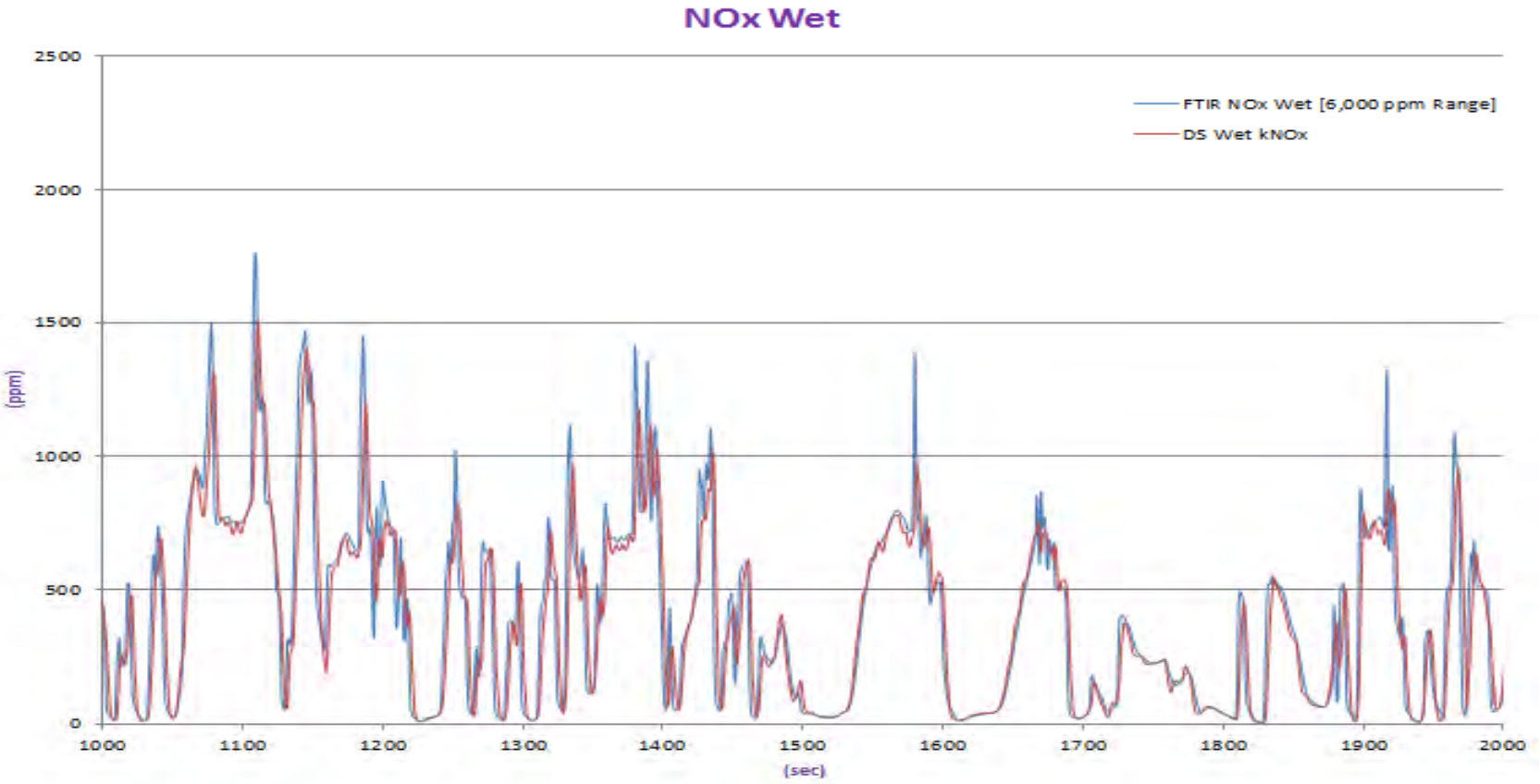
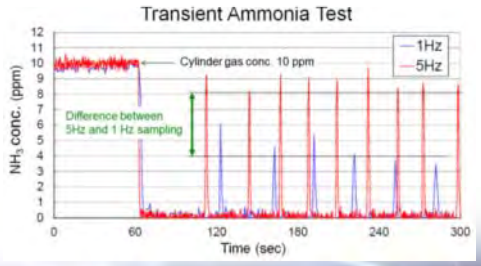
Hong Kong EPD Coach – NO_x Data



FTIR Readings Slightly Larger

- 5Hz (FTIR) vs 1Hz (DS) higher transient peaks
- NDUV Chiller Loss (5% allowed per 1065.376)

*SEMTECH-DS wet (Calculated)



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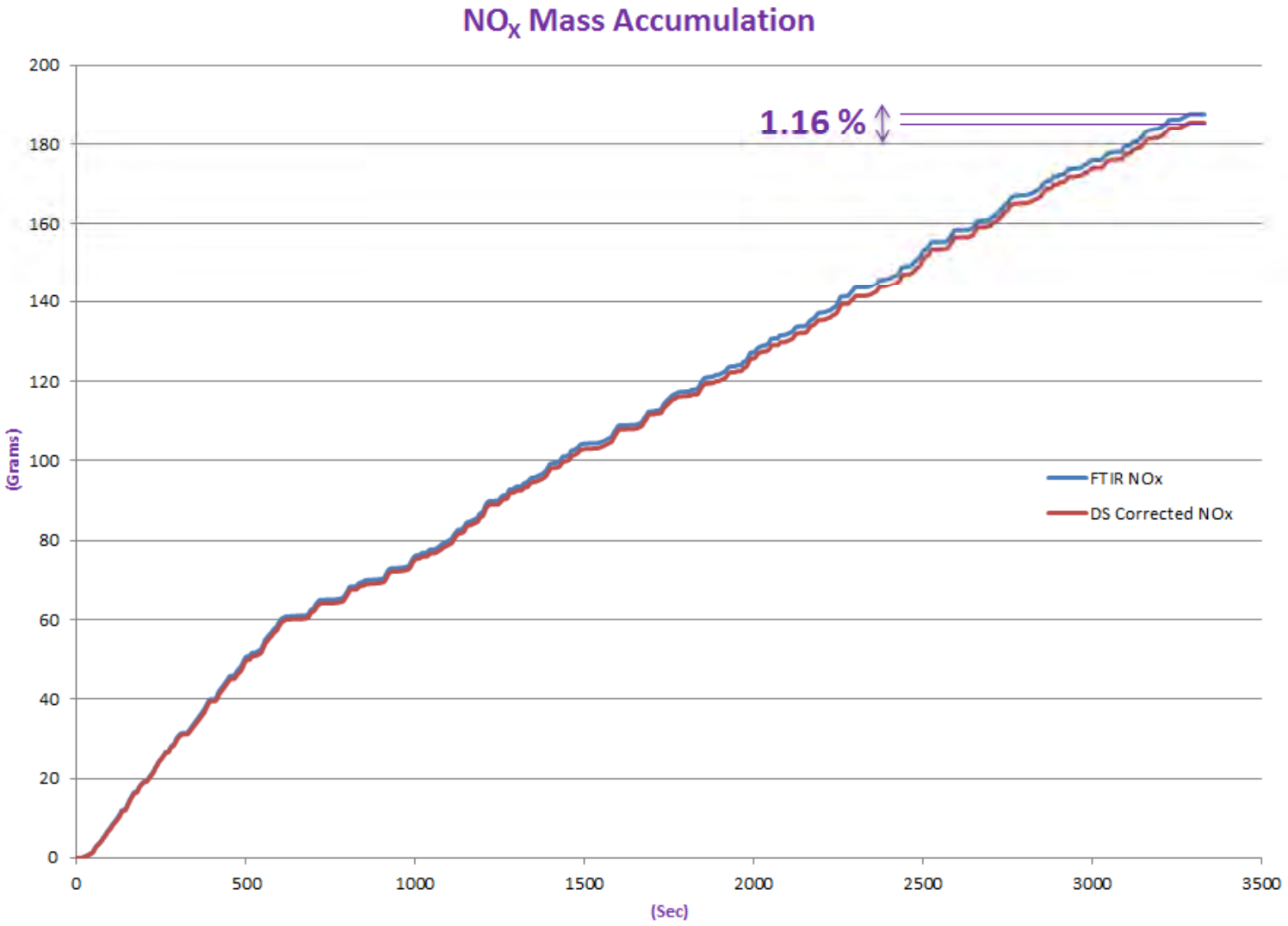
Hong Kong EPD Coach - NO_X Data



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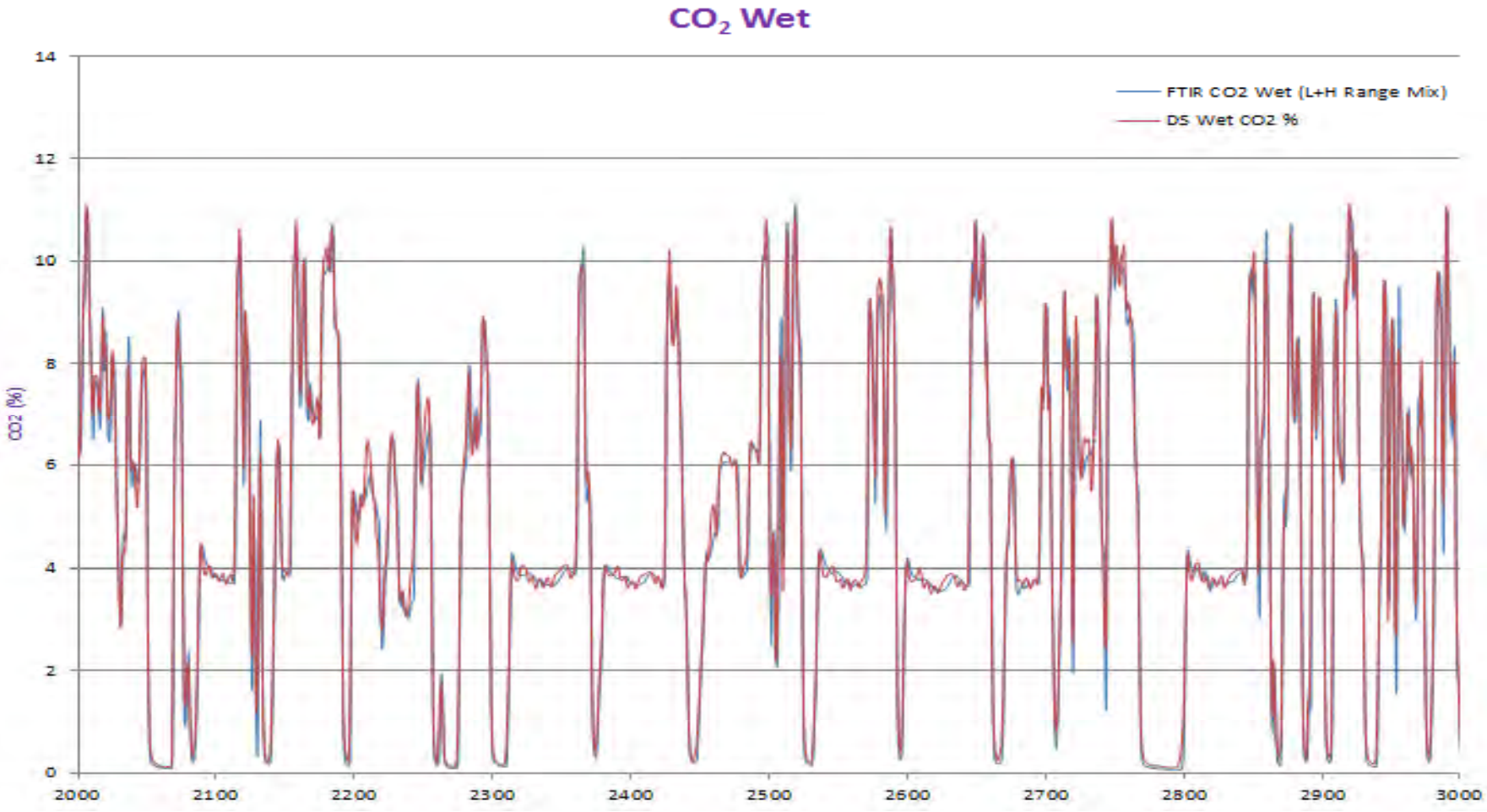
Hong Kong EPD Coach – CO_2 Data



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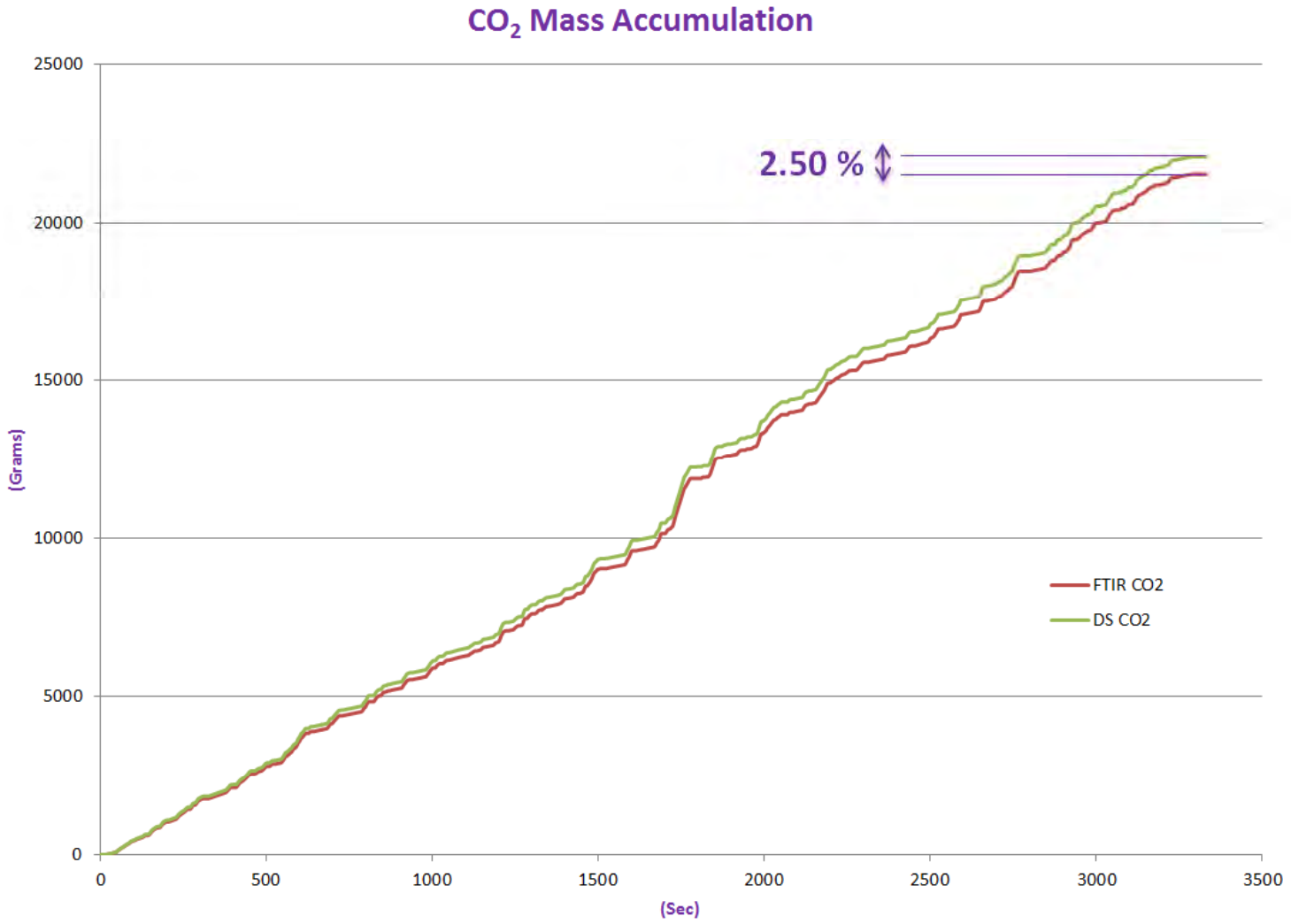
Hong Kong EPD Coach – CO_2 Data



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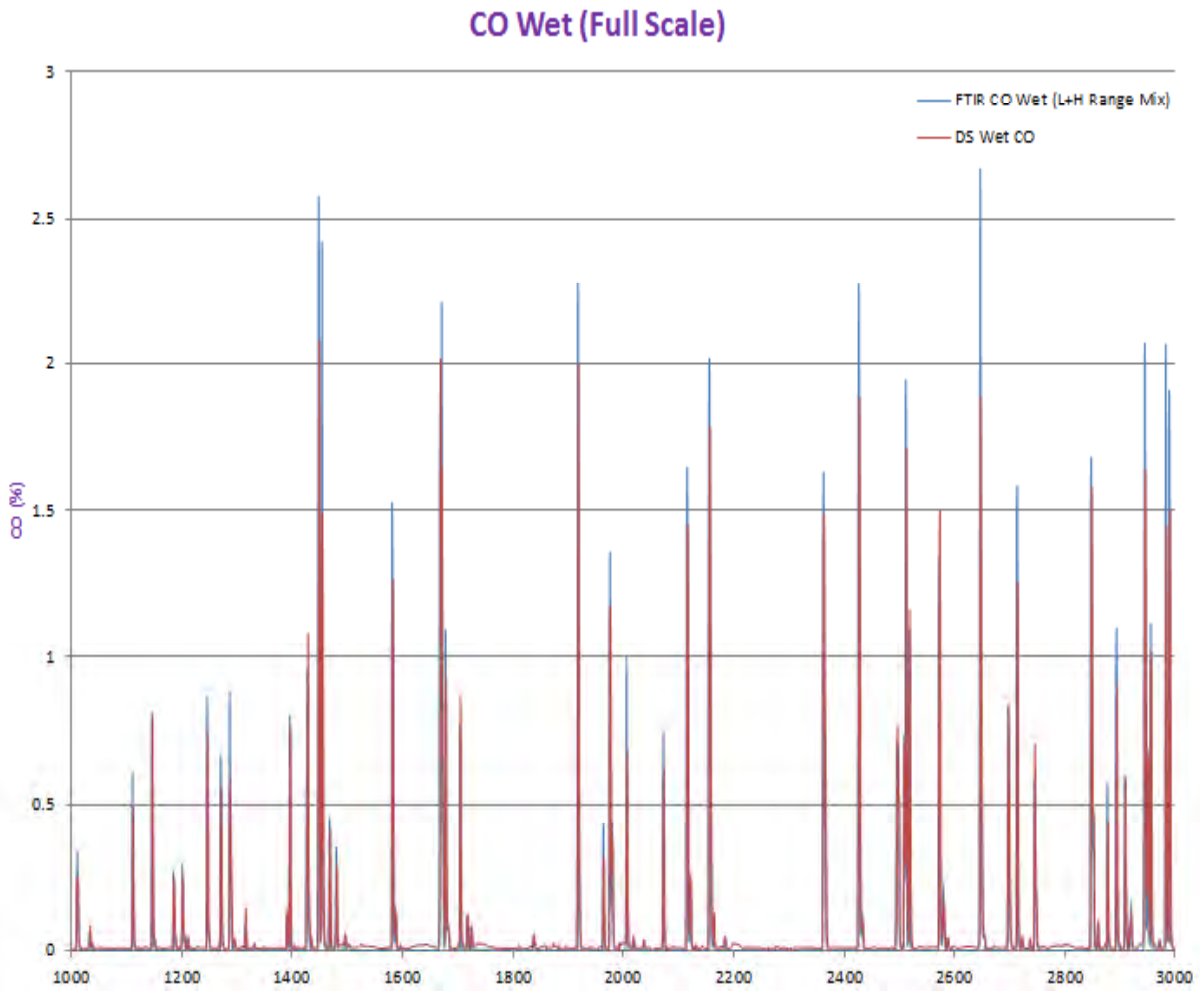
Hong Kong EPD Coach – CO Data



CO peaks generally agree but FTIR peaks are larger

Reasons:

- 5Hz (FTIR) vs 1Hz (DS) (higher transient peaks)
- FTIR high Range @ 4% CO
- Peaks significantly above NDIR-DS Span Calibration Value (200 ppm)

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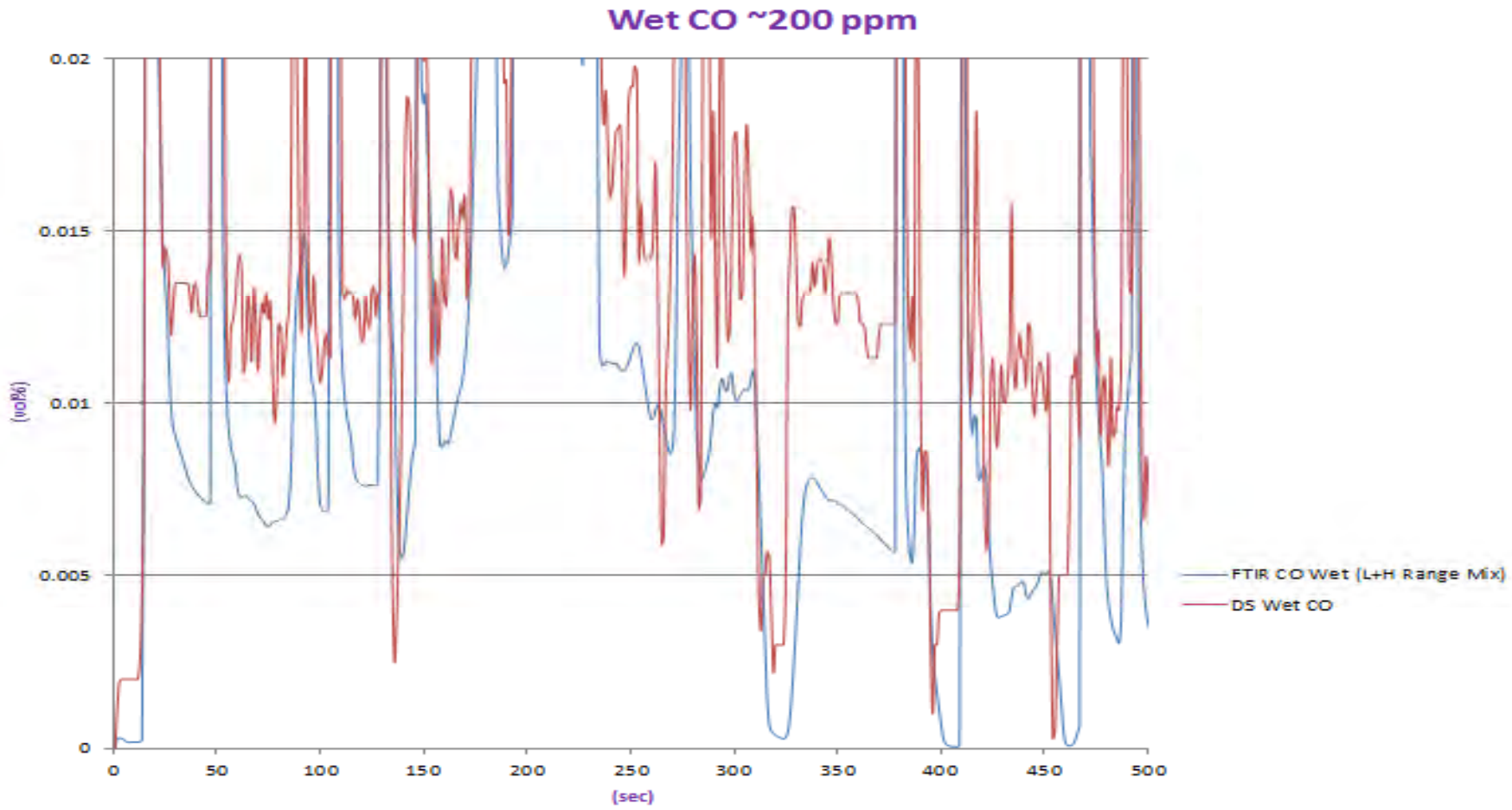
Hong Kong EPD Coach – CO Data



- At low concentrations CO follows same trend
- FTIR readings approximately ~50-75ppm lower
- Detection limit of DS-NDIR ~ 50ppm

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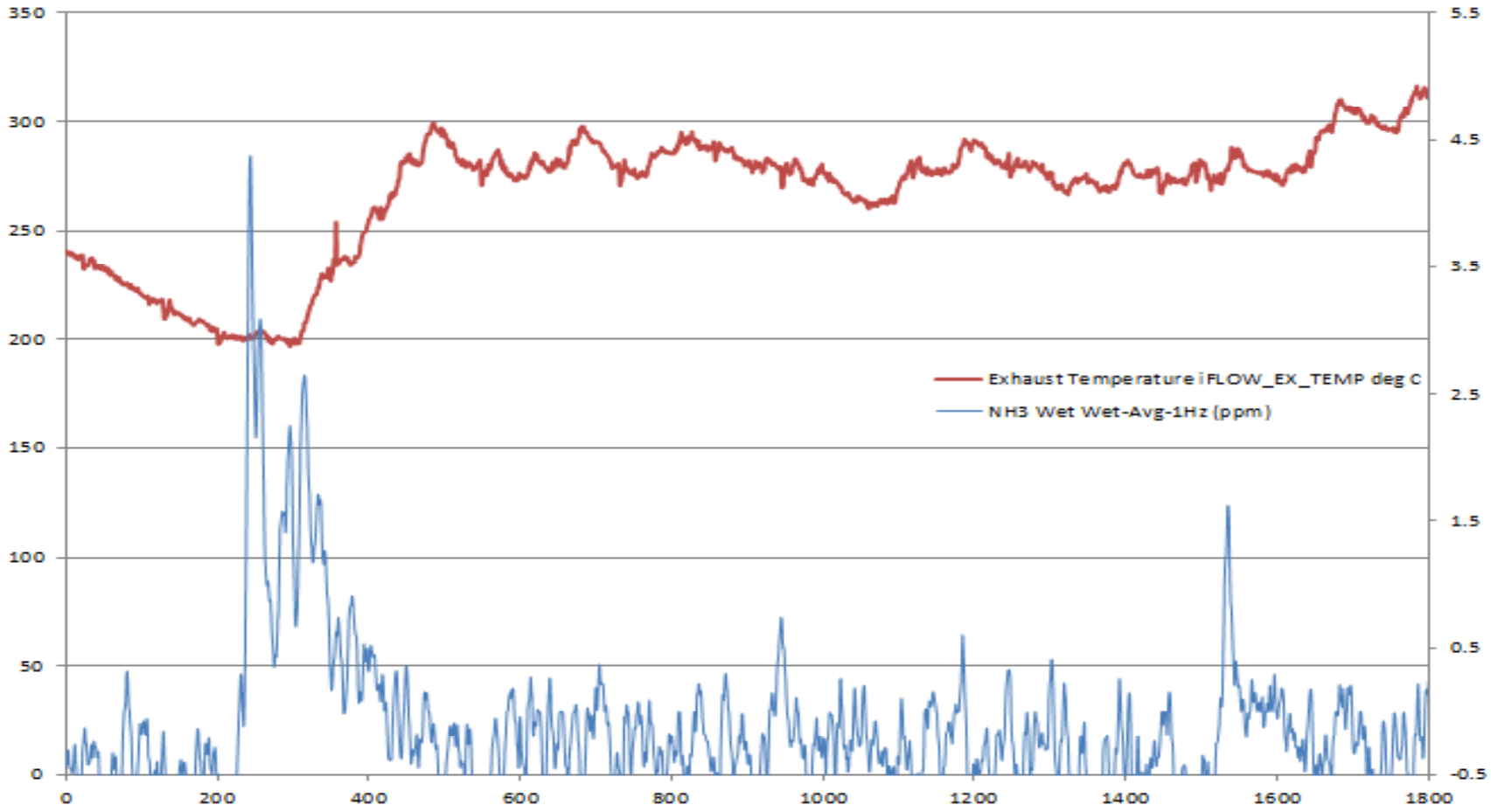
Amonia (NH_3) Slip



FTIR can detect NH_3 slip (SCR) when exhaust temperature drops

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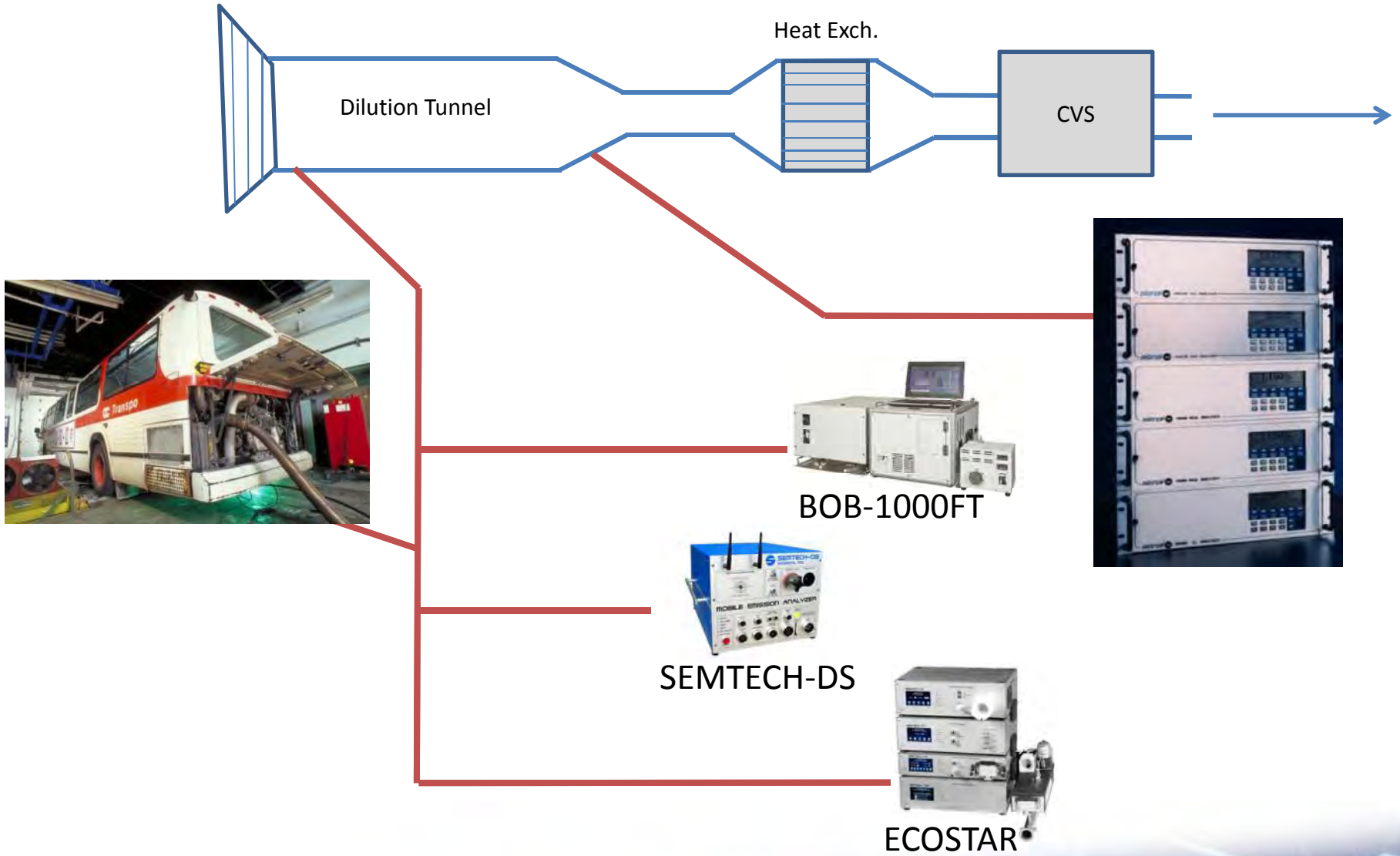
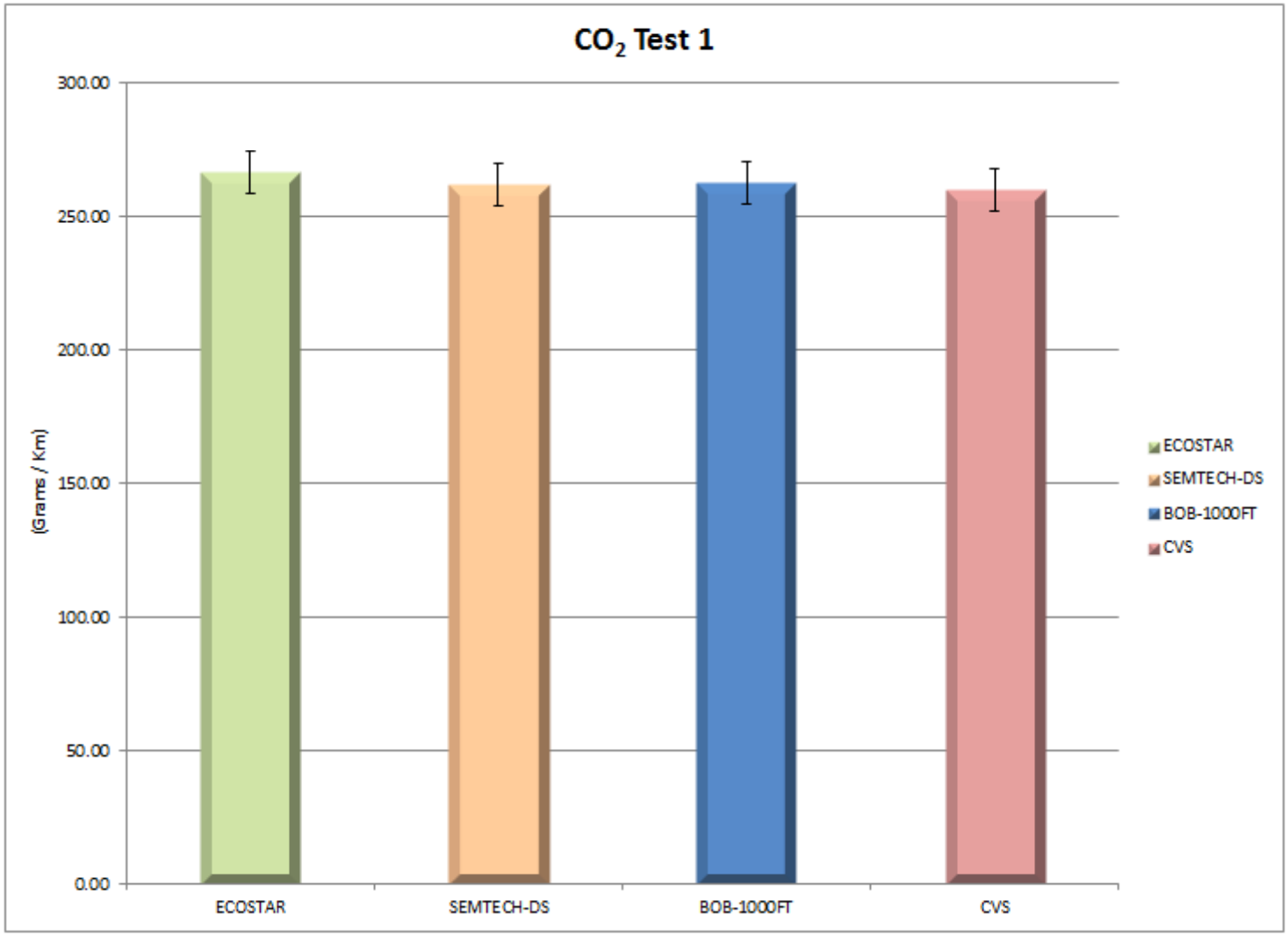
Hong Kong EPD Chassis Dynamometer Test Bed



Cold Start Test 1



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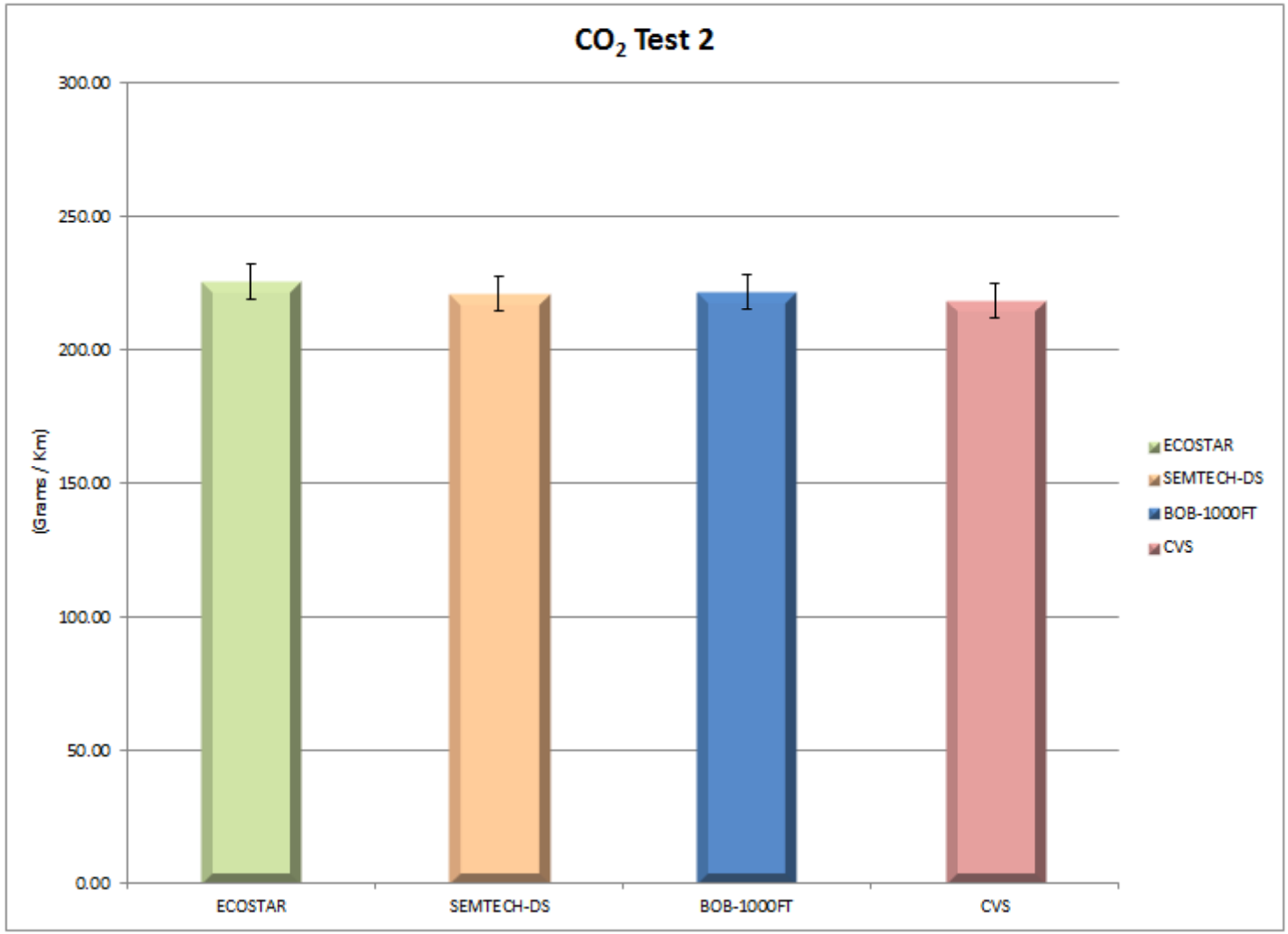
Warm Start Test 2



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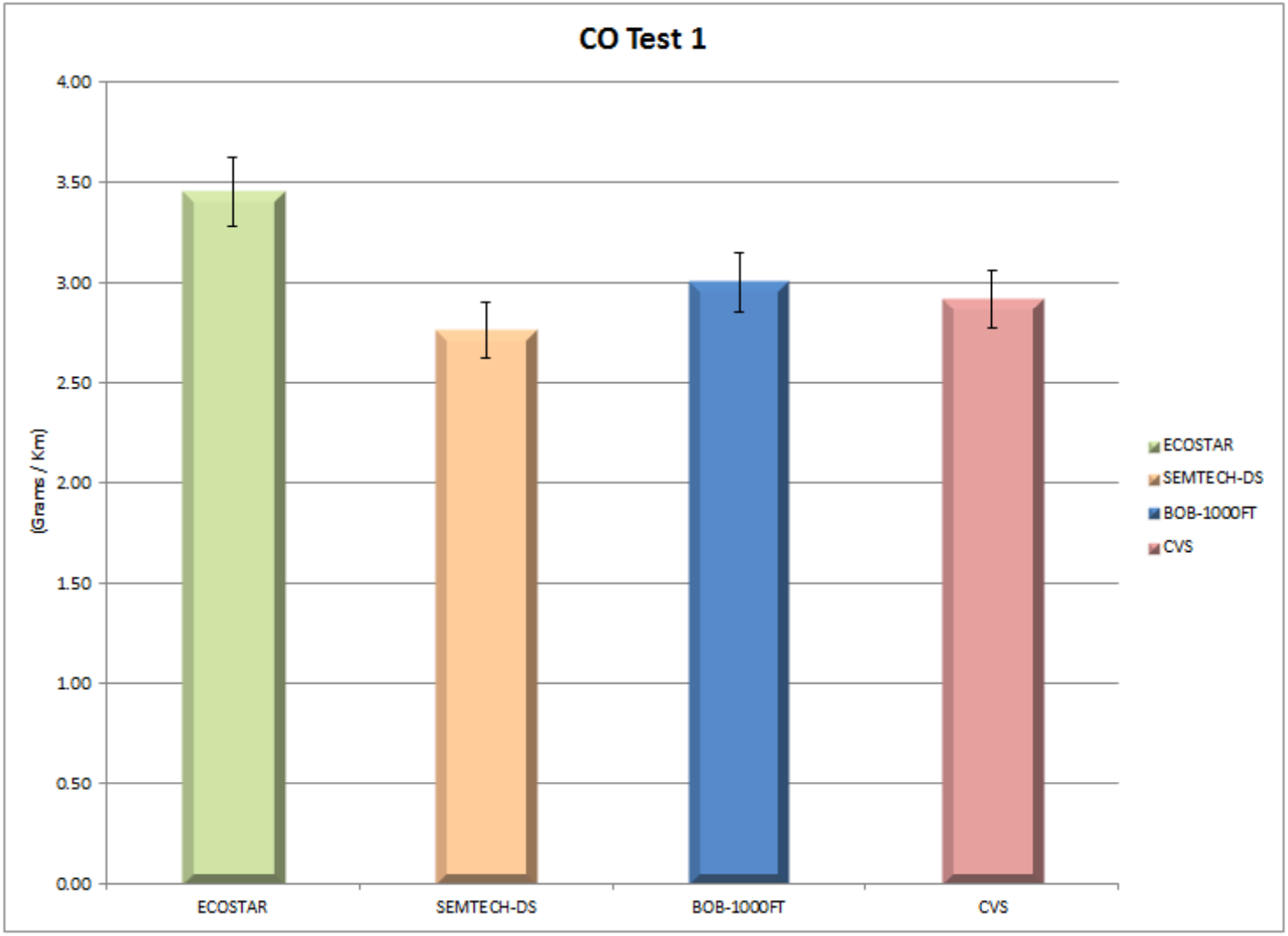
Cold Start Test 1



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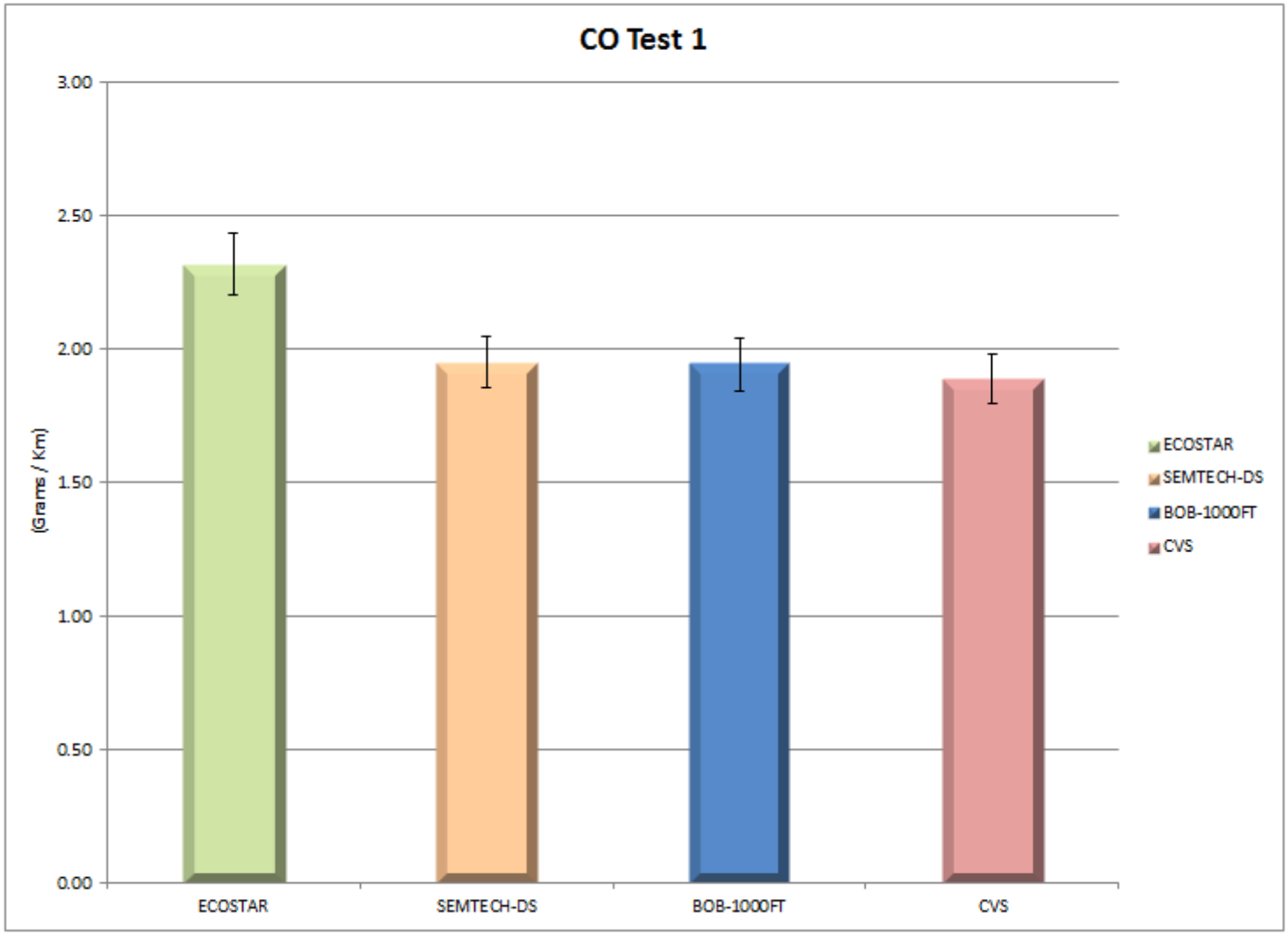
Warm Start Test 2



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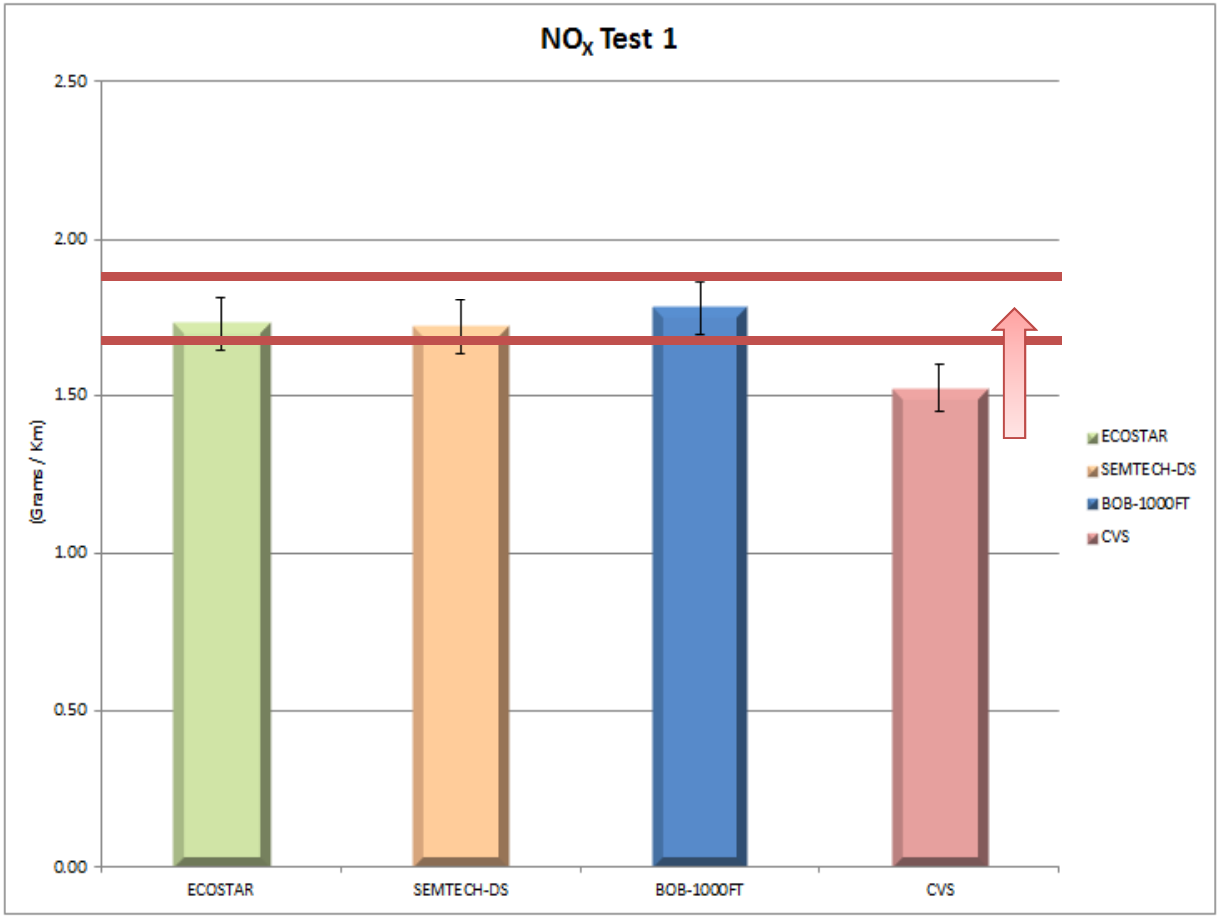
Cold Start Test 1



After evaluation, Hong Kong EPD determined an issue with the contractors CVS/CLD system.

Hong Kong EPD is on record stating that they believe the PEMS NOX is accurate, not the CVS NOX (~ + 20%)

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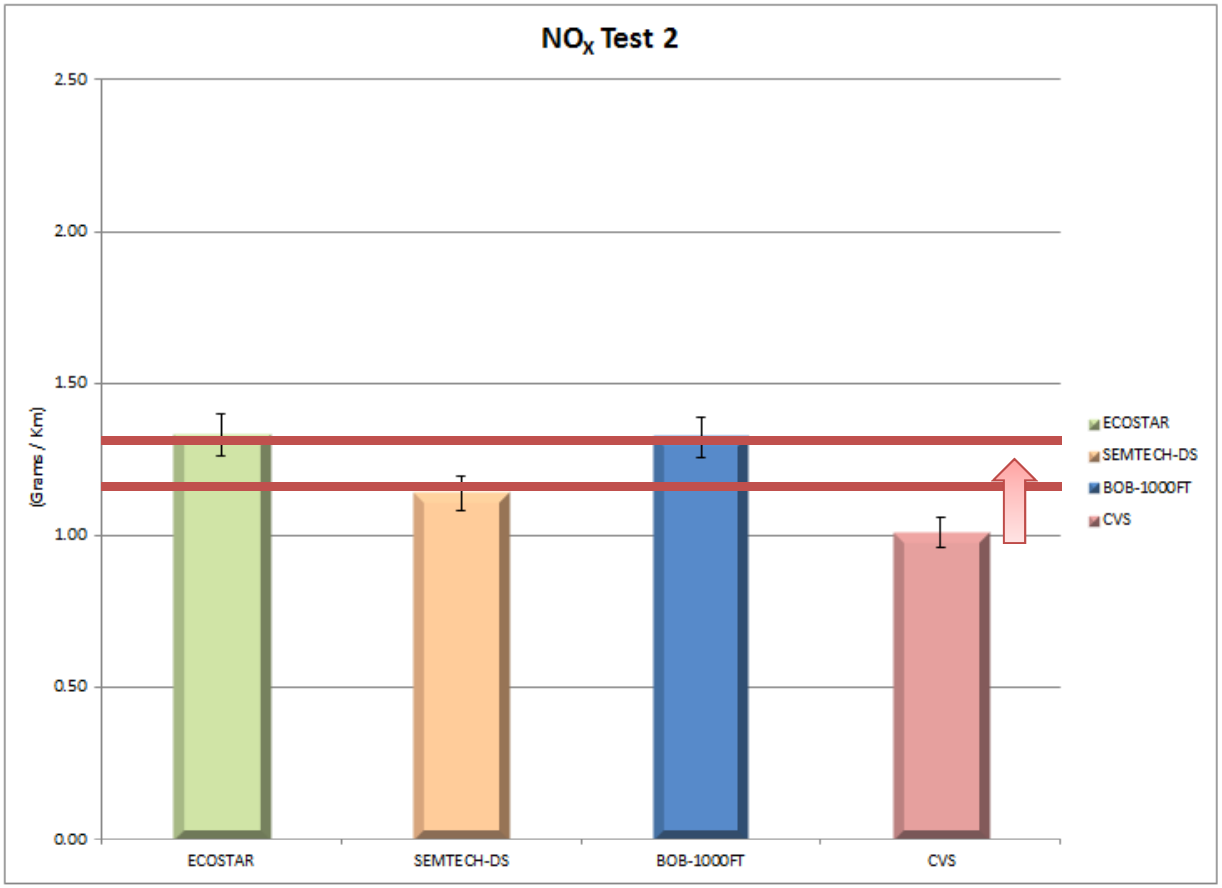
Warm Start Test 2



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Climbing Mount Fuji

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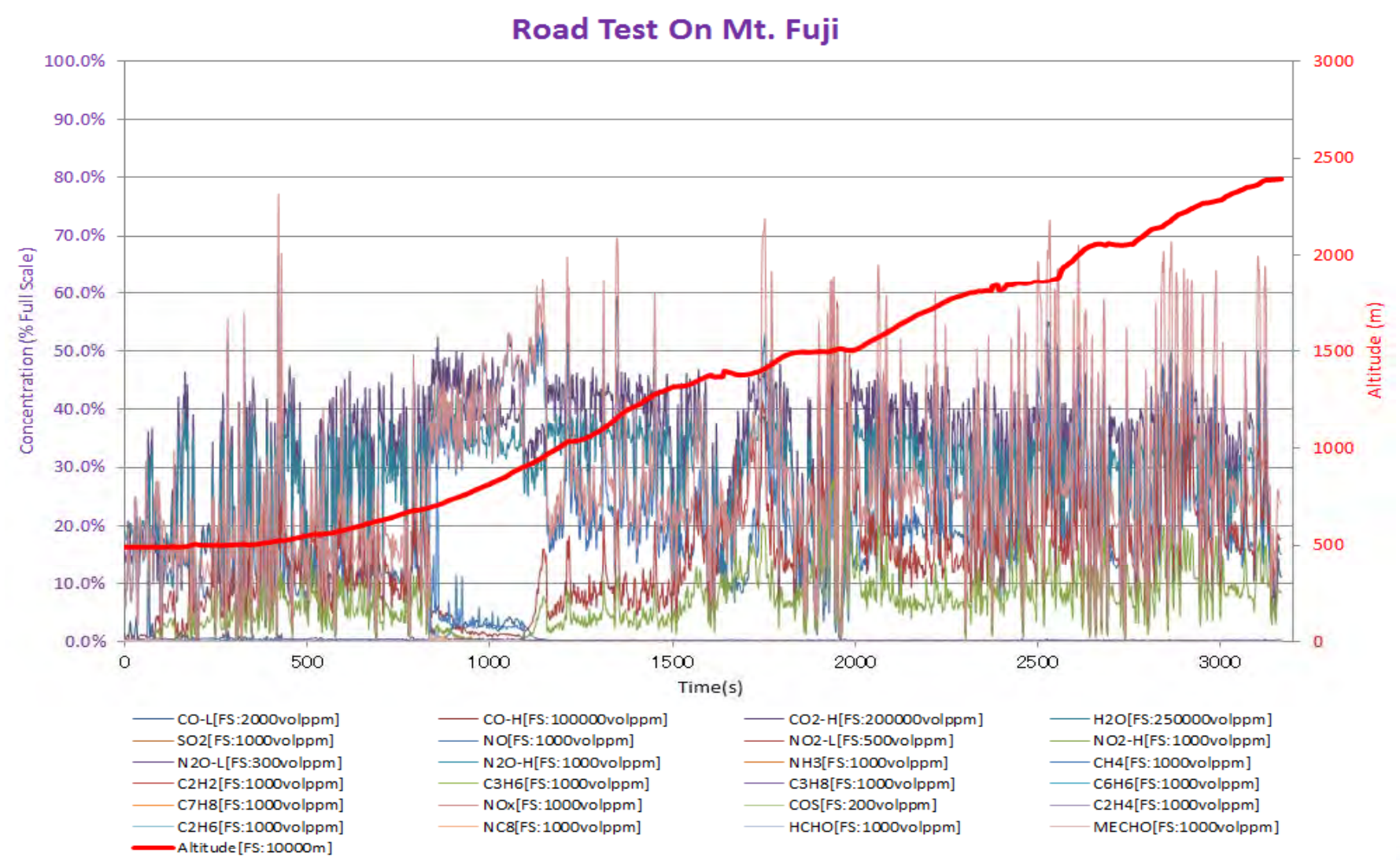
FTIR 25 Gas Graph



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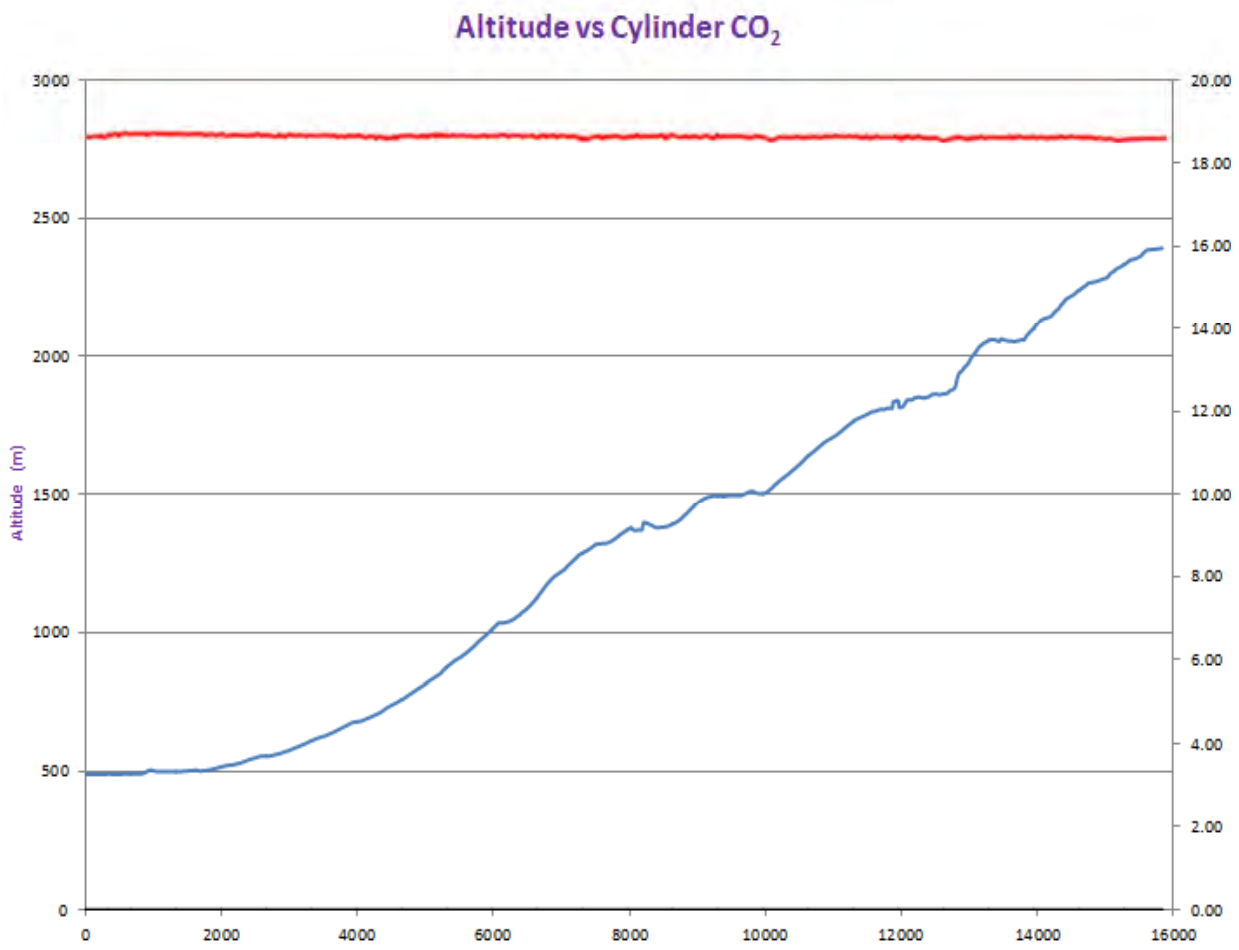
Mount Fuji Cylinder Gas



High Altitude Pressure Option

Maintains required Sample Cell Pressure, regardless of changing barometric pressure conditions.

Stable concentrations have been verified up to 3,200m (11,000 feet)

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Conclusion

- FTIR Technology is a highly accurate method for exhaust gas measurement
- FTIR technology has many advantages over traditional PEMS and conventional analyzers
- FTIR has good correlation to conventional analyzers, for regulated components, while also measuring all gases of interest – with one analyzer
- FTIR as a PEMS instrument will become increasingly important, as we continue to monitor and research additional gases, and more exotic gasses

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Vielen Dank!

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