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Preliminary Evaluation of Commercial Indoor Air Quality Sensors for Application to Aircraft Cabin Air Measurements

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Outline

- Introduce the overall program objectives
- Highlight relevant aircraft system information
- Provide brief overview of experimental setup
- Discuss Fourier Transform Infrared Spectroscopy (FTIR)
- Report initial commercial CO_2 sensor data
- Conclude with recommendations & proposed future work

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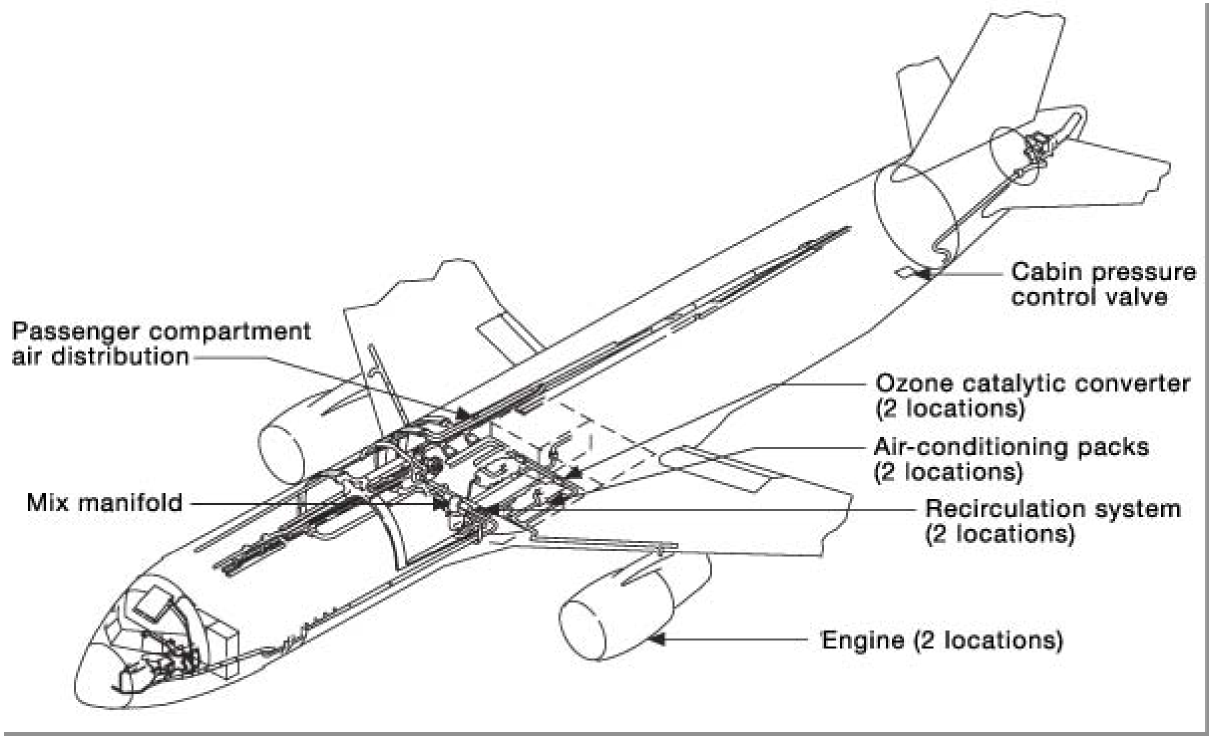
Overall Program Objectives

- Identify commercial sensors that have potential for aircraft cabin air quality sensing for multiple gases
- Determine reliability and operation characteristics of commercial sensors in different pressure and background gas operating environments
- Investigate current sensor technologies to determine areas where improvements can be made

Ref. 1, 2

Aircraft System Overview



Environmental Control Systems

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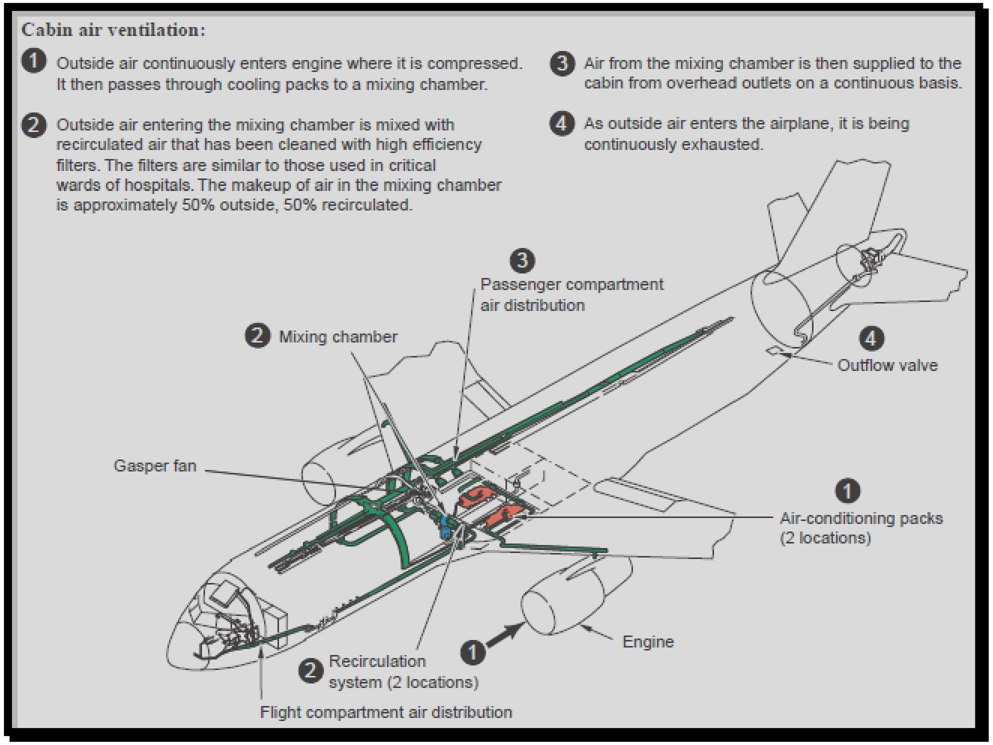
Ref. 1,2,3

- Bleed Air System
- Mix Manifold System
- Recirculation System
- Cabin Ventilation System



Bleed Air System

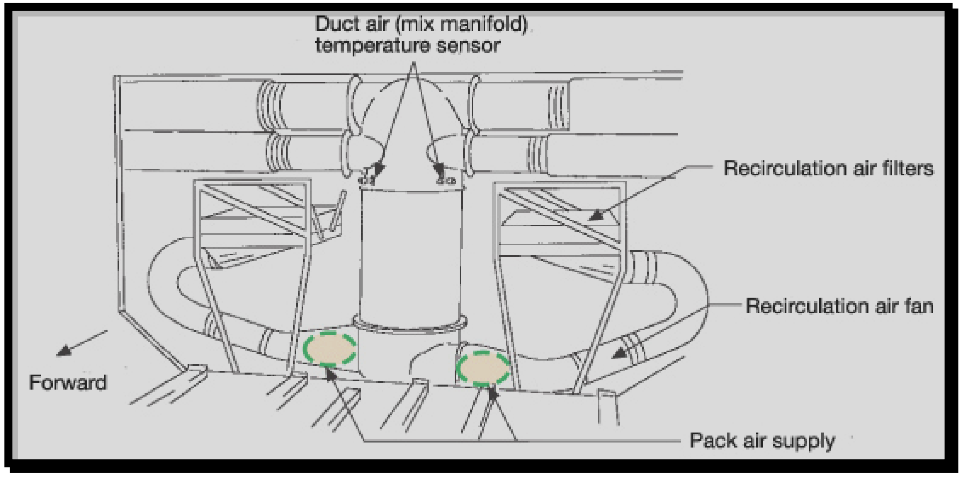
Ref. 1

- Totally automatic system, except for an emergency shutoff available to pilots
- Outside air entering the airplane is compressed to 220 kPa (2.2 atm) and rises to a temperature near 160 °C (320 °F)
- Number of valves and heat exchanger provides air at proper temperature and pressure to numerous flight system
  - Air conditioning packs
  - Cabin ventilation and pressure system
  - Potable water pressurization
  - Wing and engine anti-ice protection

Mix Manifold System

Ref. 1

- Air entering cooled by air conditioning system and decompressed
  - Temperature = 15 °C (59 °F)
  - Relative Humidity = 5%
  - Pressure = 82 - 78 kPa (6,000-7,000 ft altitude) (0.81-0.77 atm)



- CO_2 / CO unchanged from outside

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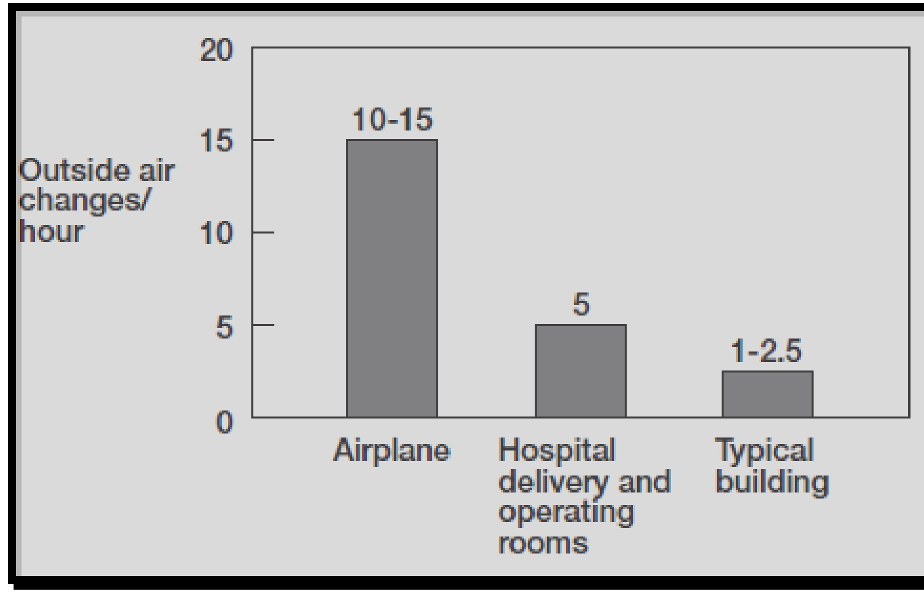
Recirculation System

Ref. 1,3,6

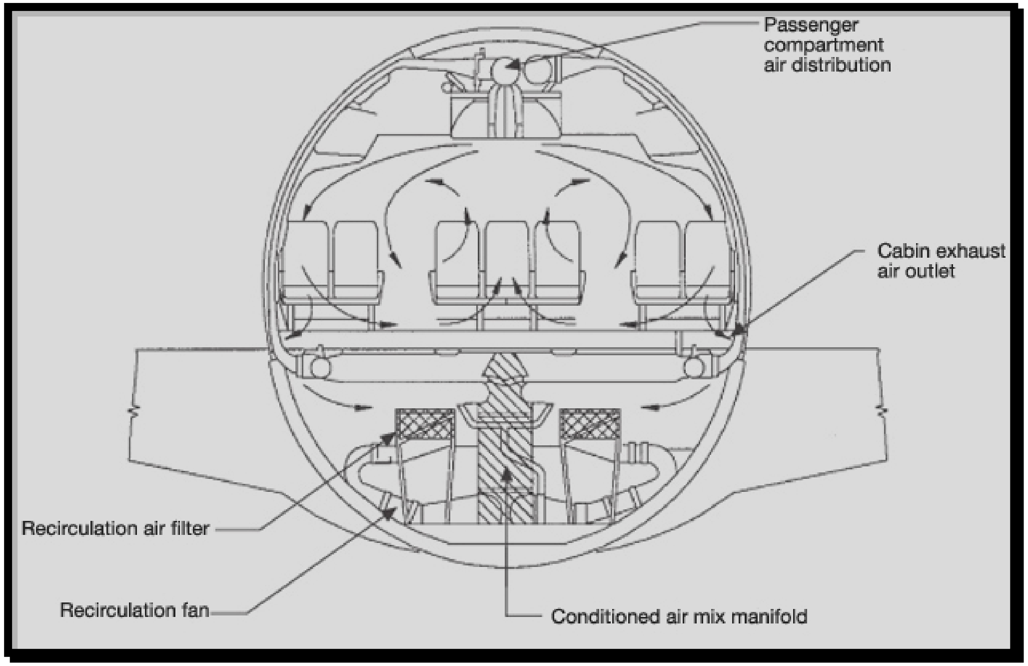
- Re-circulated air is essentially sterile
- HEPA filters remove 99.9+% of bacteria and viruses produced by passengers
  - Filters similar to those used in critical wards of hospitals
  - Harmful gases are NOT removed by filters
- Attempted control of gases to low levels in the cabin through dilution with high quantities of outside air



Cabin Ventilation System

Ref. 1,7

- Air flow is directed from below floor to overhead cabin
  - Temperature = 18-30 °C (64-86 °F)
  - Relative Humidity = 10-20%
- Provides approximately 1.9 L/s of oxygen
  - Human at rest consumes 0.007 L/s
- No sensors or monitoring of potentially harmful gases
  - Assumed below harmful levels through dilution



Experimental Setup

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Experimental Setup – Control Module

Controls system settings for pressure and gas environment

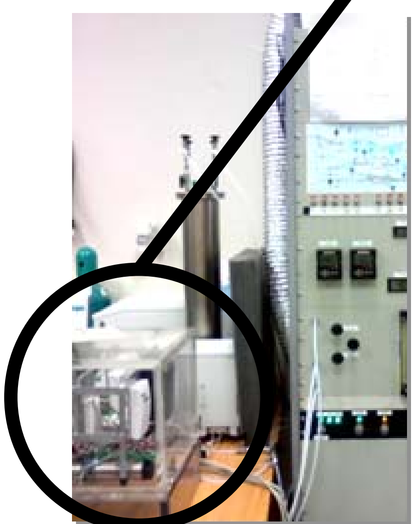
Gas lines rated for pressures up to 12,000 feet (50.5 kPa, 0.5 atm)

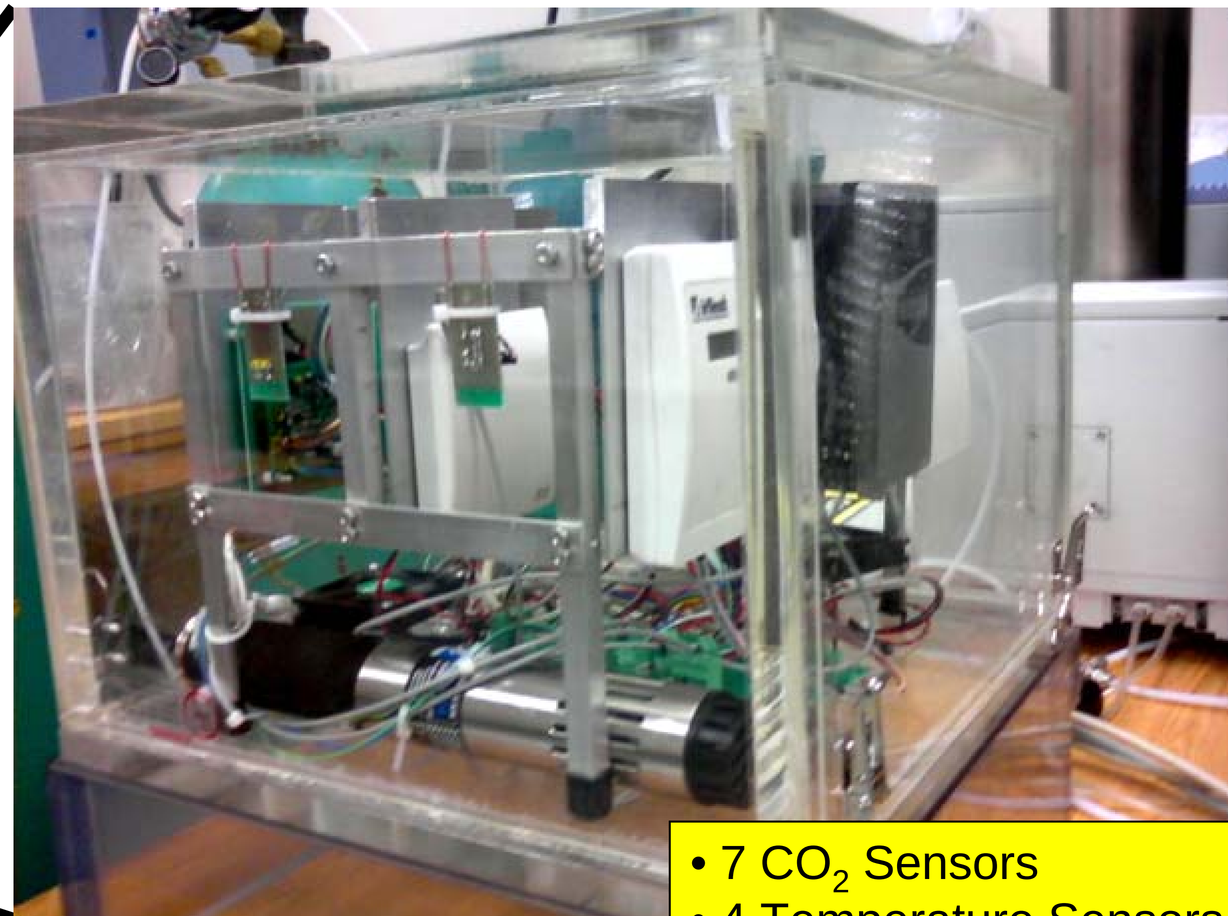
Test & Inert Gas Flow Meters

Altitude Readouts

inHg Vac
&
ft above sea level

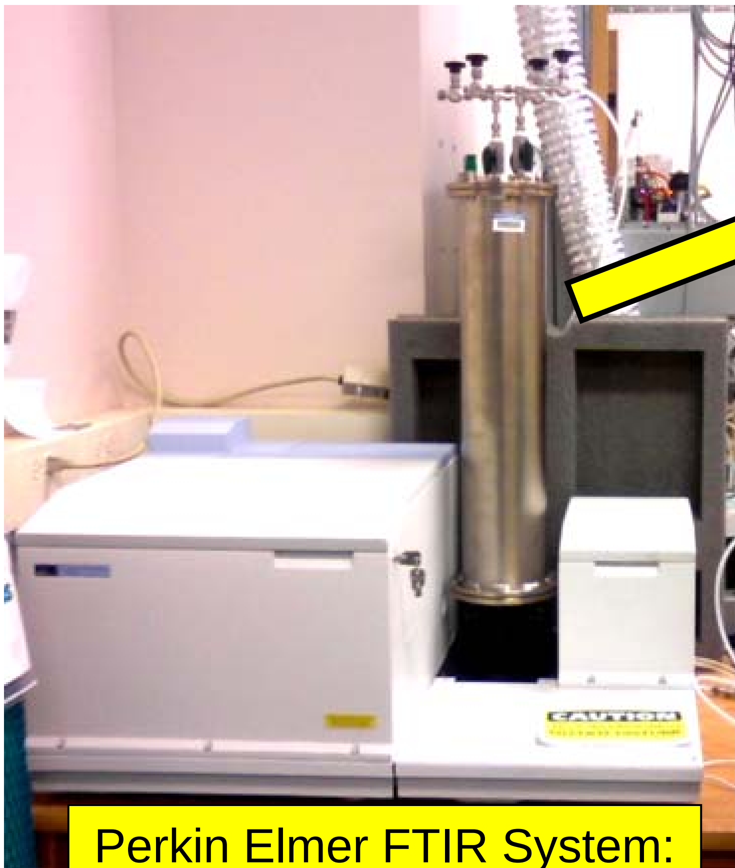
Experimental Setup – Commercial Sensor Module





- 7 CO_2 Sensors
- 4 Temperature Sensors
- 2 Relative Humidity Sensors

Experimental Setup – FTIR Module



Perkin Elmer FTIR System: Spectrum GX

- Variable path length gas chamber cell
  - Model M-5-22-V
- Optical path folded in a volume of 8.5 L
- Cell path length = # of passes * length of base path
  - Length of base path = 56 cm
  - Min # of passes = 4
  - Min cell path length = 2.24 m

FTIR Analysis

FTIR – Pressure Effects

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- Airplane cabin pressure is approximately that of air pressure at 6,000 to 8,000 feet above sea level
  - ~ 81-75% of sea level pressure

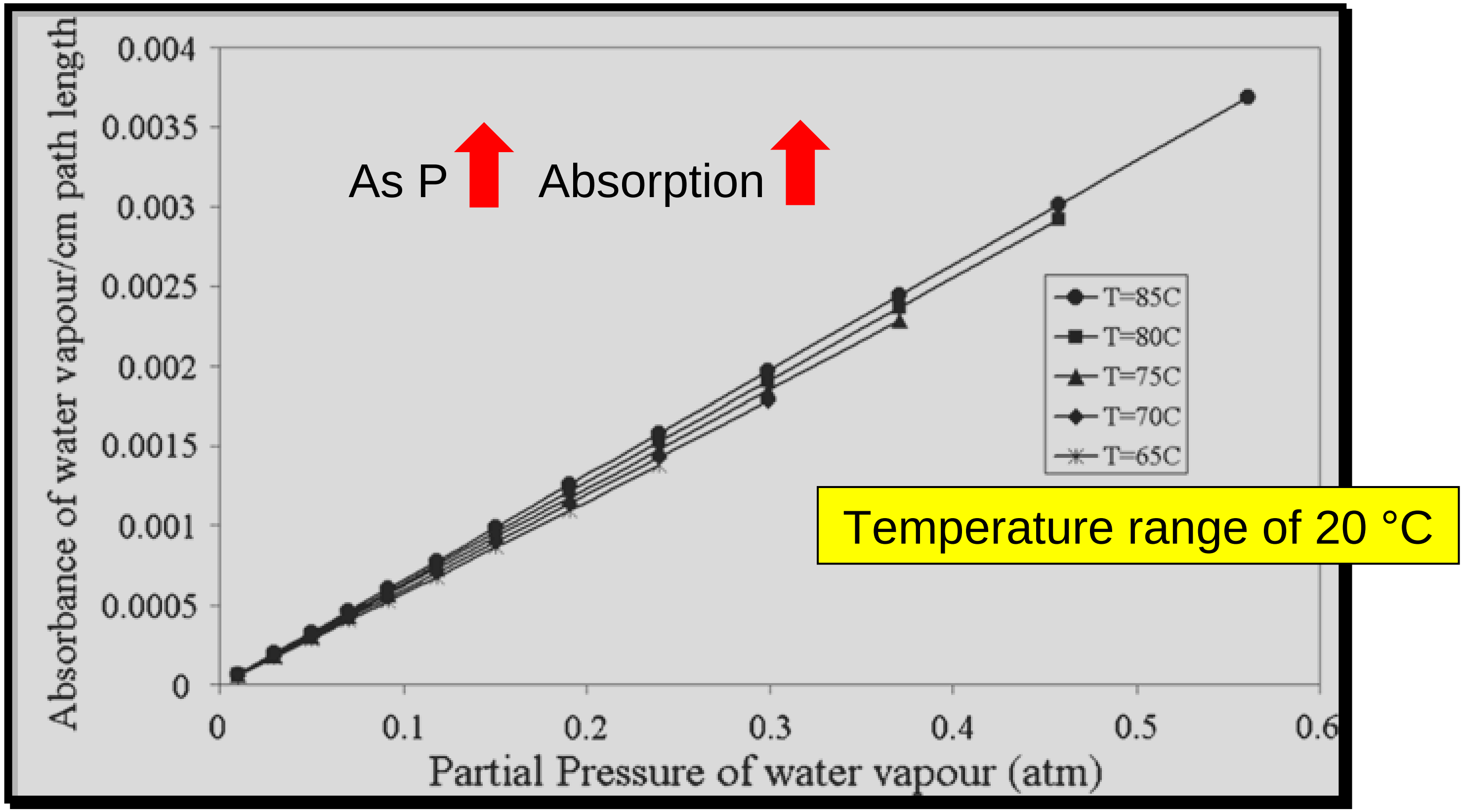
Altitude		Pressure		
[feet]	[m]	[kPa]	[atm]	[in Hg]
0	0.0	101.3	1.00	29.9
500	152.4	99.5	0.98	29.4
1000	304.8	97.7	0.96	28.9
1500	457.2	96.0	0.95	28.3
2000	609.6	94.2	0.93	27.8
2500	762.0	92.5	0.91	27.3
3000	914.4	90.8	0.90	26.8
3500	1066.8	89.1	0.88	26.3
4000	1219.2	87.5	0.86	25.8
4500	1371.6	85.9	0.85	25.4
5000	1524.0	84.3	0.83	24.9
6000	**1828.8**	**81.2**	**0.80**	**24.0**
7000	**2133.6**	**78.2**	**0.77**	**23.1**
8000	**2438.4**	**75.3**	**0.74**	**22.2**
9000	2743.2	72.4	0.71	21.4
10000	3048.0	69.7	0.69	20.6

Pressure [kPa] = 101.325 * (1-2.25577*10^{-5} * altitude in meters)$^{5.2558}$
http://www.engineeringtoolbox.com/air-altitude-pressure-d_462.html

FTIR – Pressure Effect cont.

www.acer-coe.org

Ref. 10



FTIR – Pressure Effect cont.

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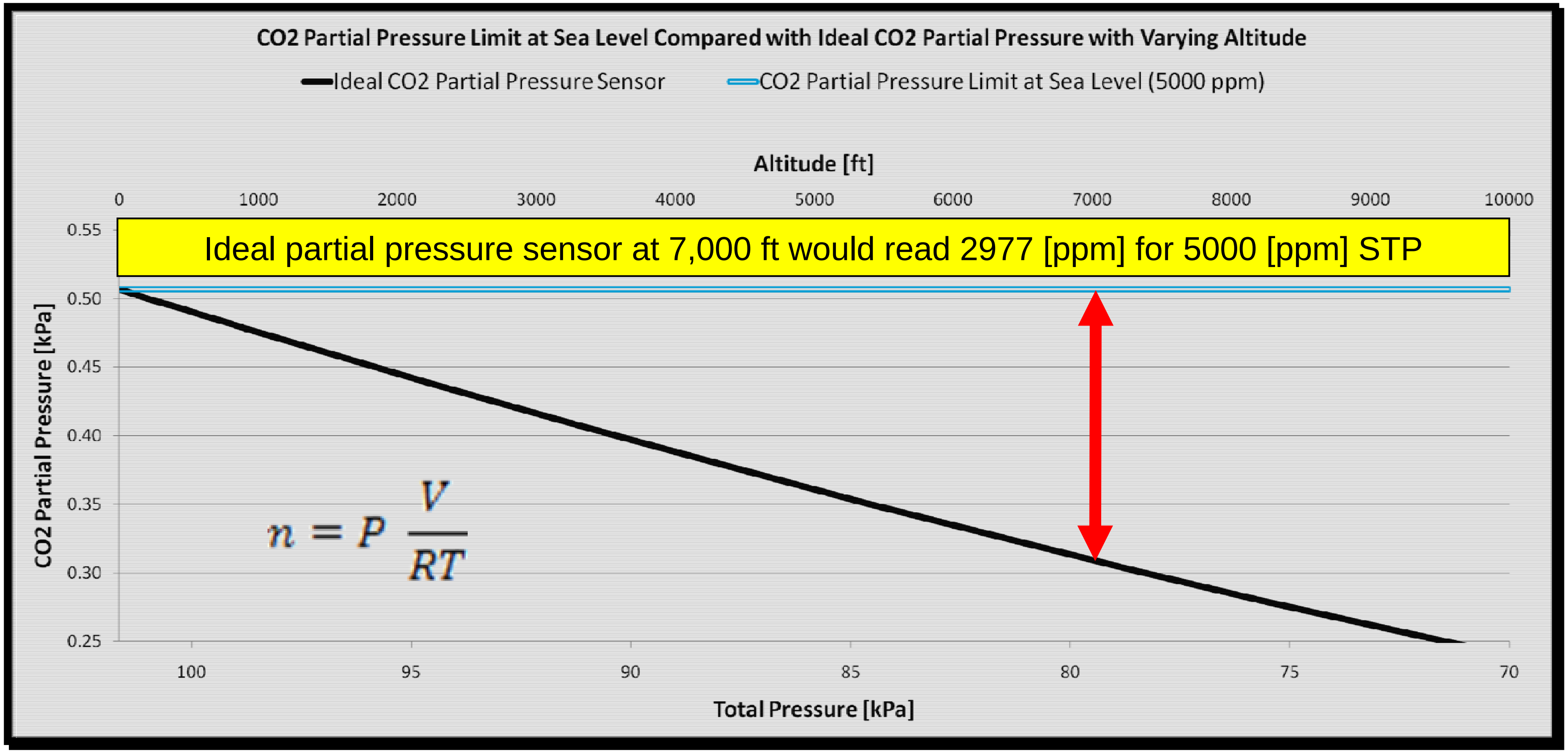

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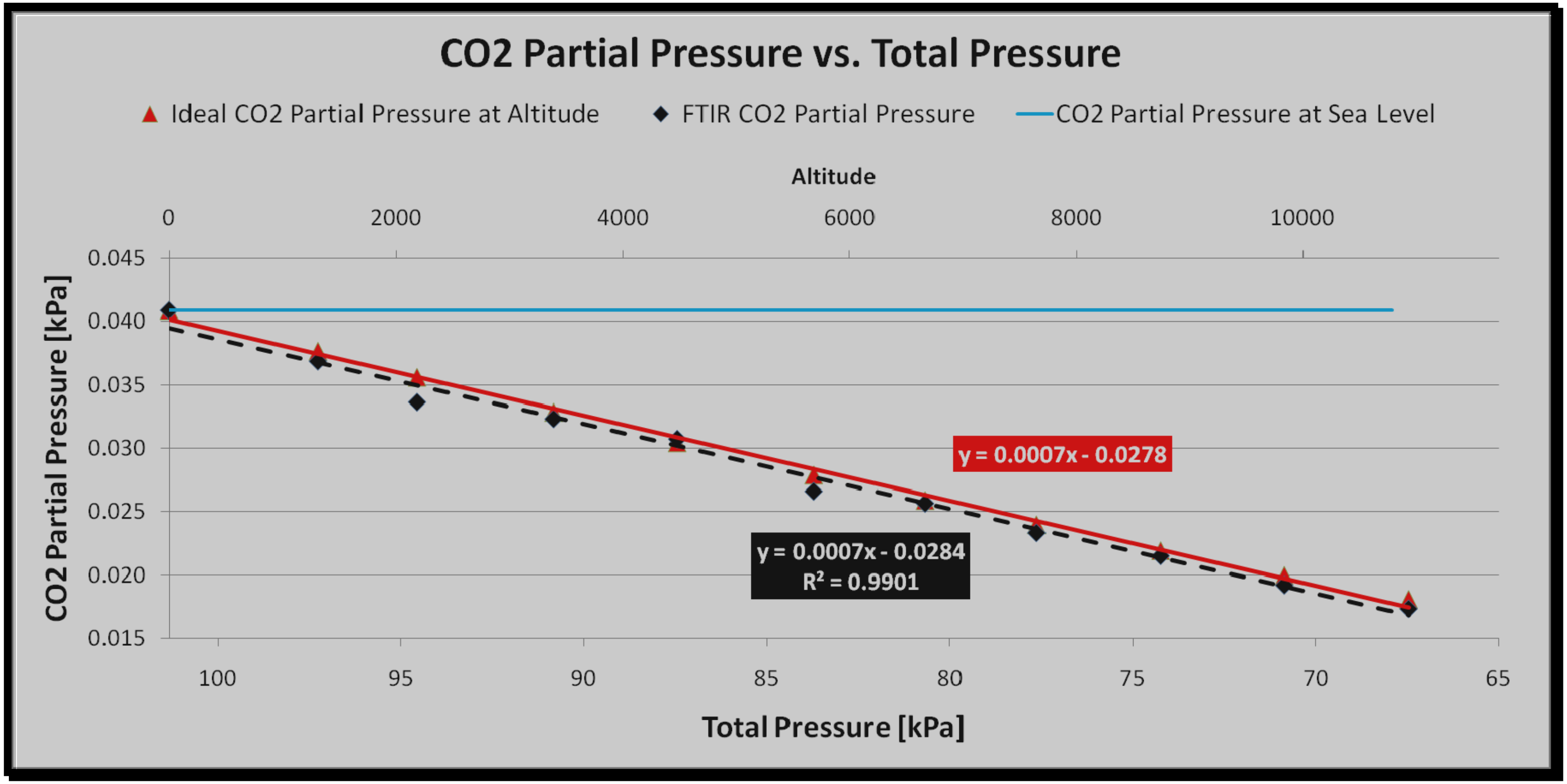
Number of Scans = 1
Range = 4000 – 600 cm-1
Resolution = 0.5 cm-1
Interval = 0.1 cm-1

FTIR Analysis



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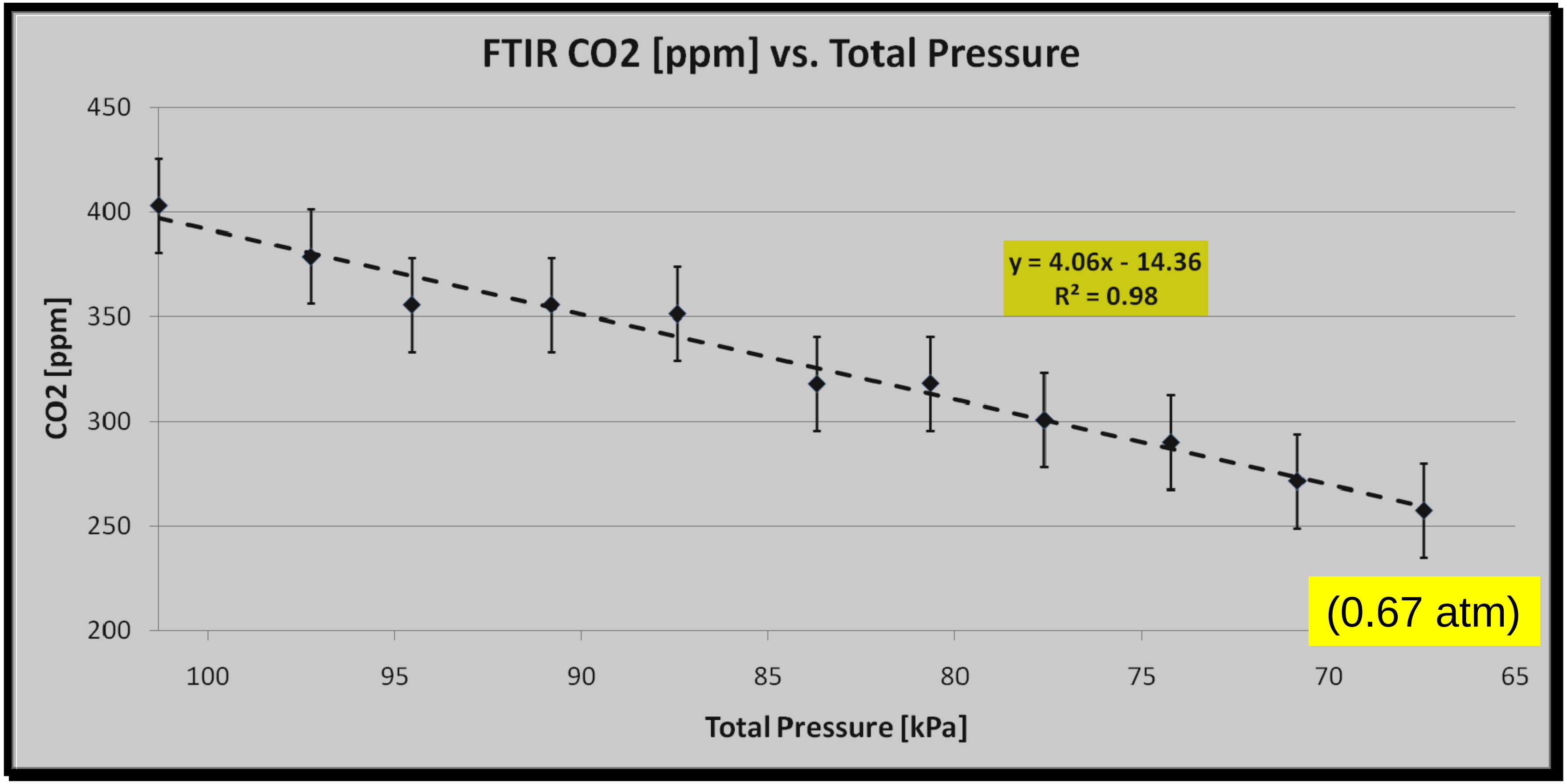


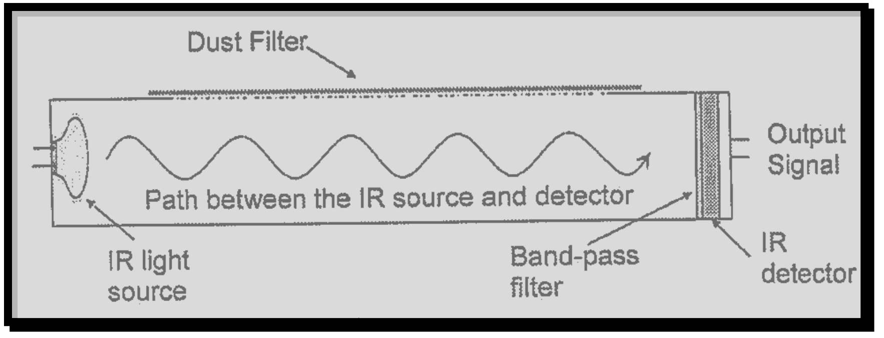
CO_2 Commercial Sensor Initial Testing Results

- K-22 LO Sensor
- Siemens QPA2000
- Airtest EE80
- Airtest TR9294
- Johnson Controls CD-WAO
- SenseAir aSense mIII

NDIR CO_2 Sensor – General Operation

Ref. 15

- CO2 has several absorption bands with the 4.26 μm (2349 cm^{-1}) band being the most widely used
  - Wavelength provides the least interference by other common components in air
- Typical systems utilize 2-step drying system to remove water vapor in sample air
- Degradation of IR light source over time



(A1,A2) K-22 LO Sensor

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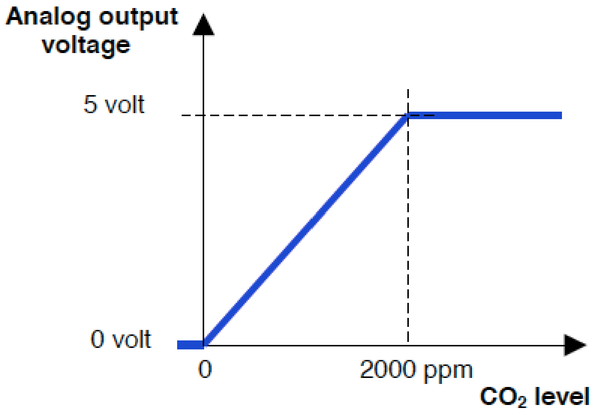
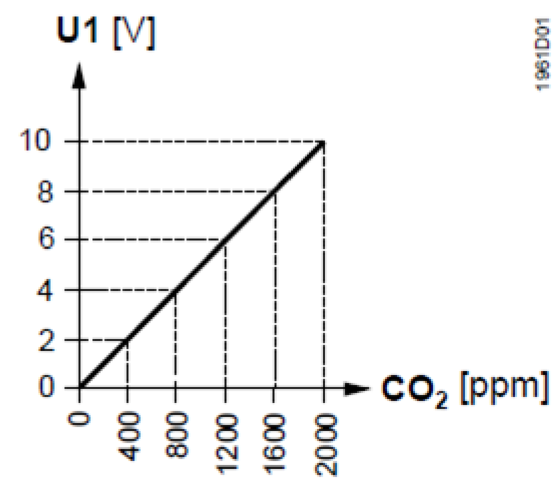
- NDIR CO2 Sensor
  - Automatic Baseline Correction (ABC) of ~400 ppm as set point
  - Range: 0 – 2,000 ppm
  - Accuracy: ± 75 ppm ± 5% of measured value
- Single IR lamp source with monitoring of a single wavelength



(A3) Siemens QPA2000

- NDIR CO2 Sensor
  - Range: 0 – 2,000 ppm
  - Accuracy: ± 50 ppm ± 2% of measured value
  - Temp Dependence: 2 ppm/°C

- Dual IR lamp source with monitoring of a single wavelength



(A4) AirTest EE80

- NDIR CO2 Sensor
  - Range: 0 – 2,000 ppm
  - Accuracy: ± 50 ppm ± 2% of measured value
  - Temp Dependence: 5 ppm/°C

- Dual IR lamp source with monitoring of a single wavelength

- Auto-calibration procedure compensates for aging of the IR source

(A5) AirTest TR9294

- NDIR CO2 Sensor
  - Automatic Baseline Correction (ABC)
  - Range: 0 – 2,000 ppm
  - Accuracy: ± 20 ppm ± 3% of measured value
- Single IR lamp source with monitoring of a single wavelength

- Use of “oval sensor element” to create longer path-length to measure CO2
  - Increased IR path-length allows higher signal-to-noise ratio

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(A6) Johnson Controls CD-WAO

- NDIR CO2 Sensor
  - Range: 0 – 2,000 ppm
  - Accuracy: ± 30 ppm ± 2% of measured value
- IR lamp source with monitoring of a dual wavelengths
  - Tunable filter allows for measurement at two wavelengths

- Auto-calibration procedure compensates for aging of the IR source

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(A7) SenseAir aSense mIII

- NDIR CO2 Sensor
  - Automatic Baseline Correction (ABC)
  - Range: 0 – 2,000 ppm
  - Accuracy: ± 20 ppm ± 5% of measured value

- Single IR lamp source with monitoring of a single wavelength

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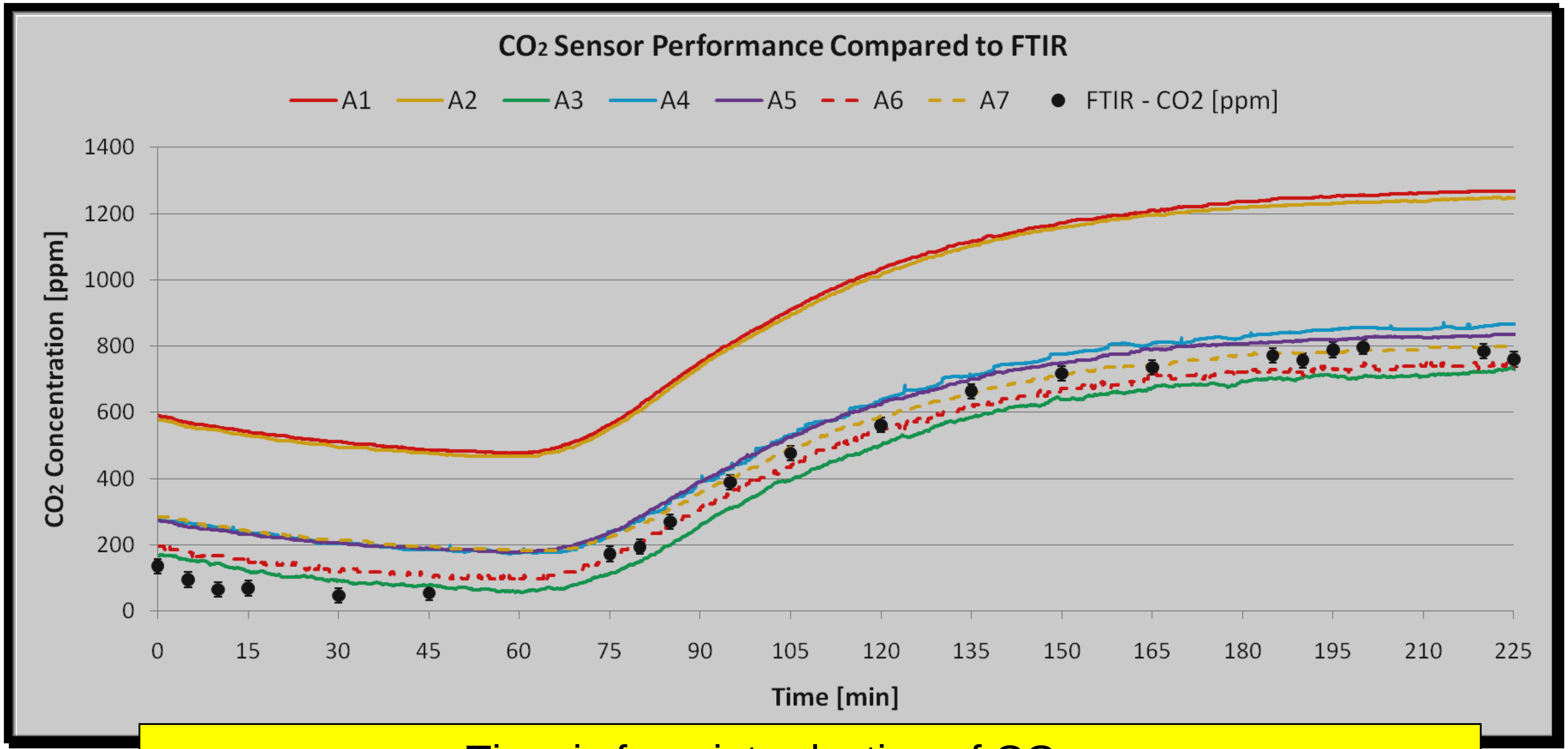
Test Date: 8-23-2010
Start Time: 11:15 AM
End Time: 3:05 PM
Flow Rates: 1.0 sccm CO_2; 499.0 sccm N_2
Altitude (Pressure): 10,780 ft (67.5 kPa, 0.67 atm)
Expected Final CO_2 Concentration: 1332 [ppm]

Commercial CO_2 Performance



Time is from introduction of CO_2 gas

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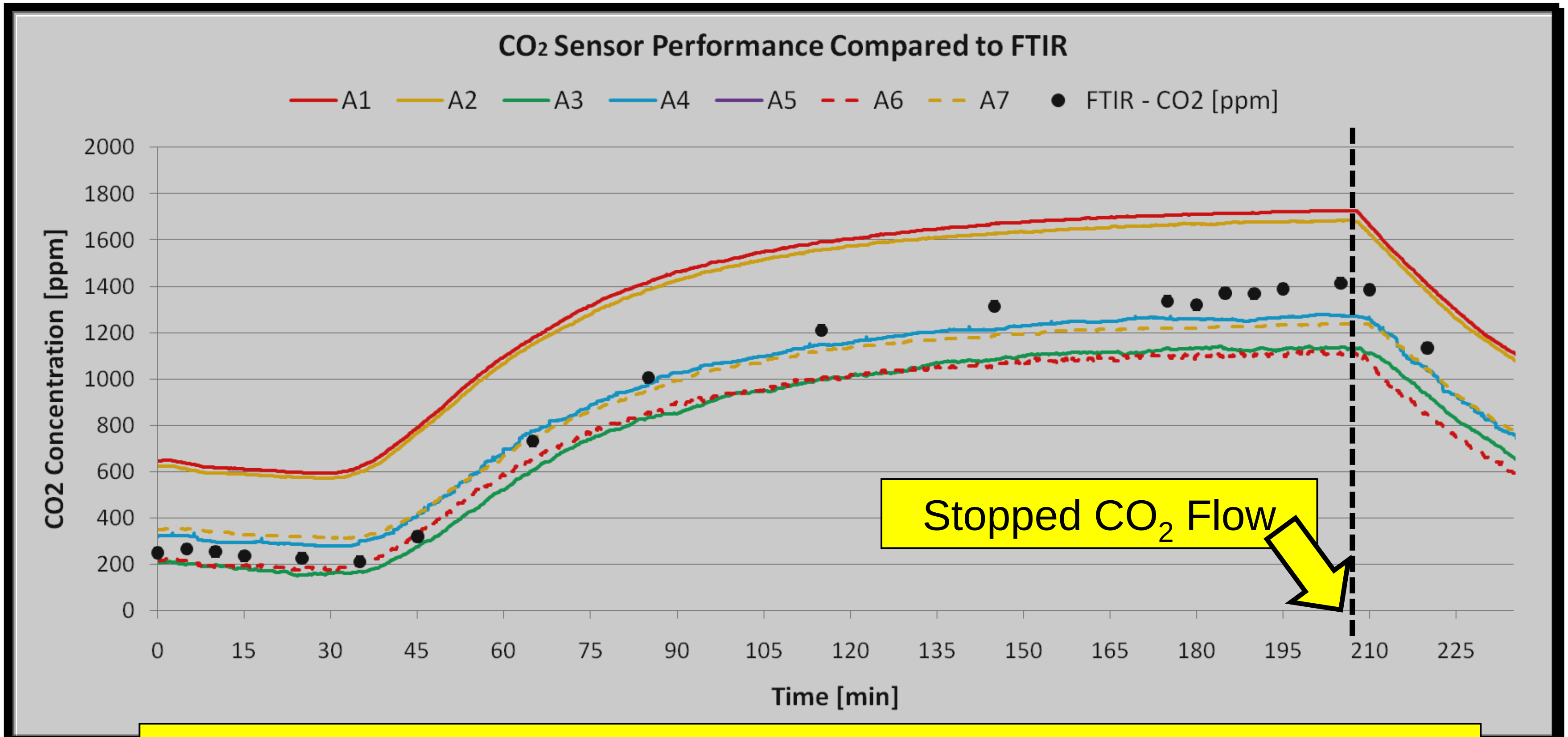
Test Date: 8-27-2010
Start Time: 8:35 AM
End Time: 12:30 PM
Flow Rates: 1.5 sccm CO_2; 498.5 sccm N_2
Altitude (Pressure): 10,780 ft (67.5 kPa, 0.67 atm)
Expected Final CO_2 Concentration: 1997 [ppm]

Commercial CO_2 Performance



Time is from introduction of CO_2 gas

Commercial CO_2 Performance cont.

- Sensor drift due to automatic baseline correction (ABC) algorithms
  - Algorithms typically use a set time period to calculate the baseline reference value
- ABC algorithms used to compensate for difficult to decouple effects of IR sensing technology
  - Long-term degradation in IR lamp source(s)
  - Collection of dust & water vapor condensation on IR beam window

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Recommendations

- As-is commercial CO_2 sensors may need to be modified to overcome the issues associated with the automatic baseline correction algorithms
- Long-term ABC algorithms may not be appropriate for sensor operation in an aircraft cabin environment
  - Sensors that monitor a known reference sample and quickly reset their baseline value may be more applicable
- Sensors without baseline correction that are replaced at regular intervals to reduce the effects of IR source aging may be an alternative

Future Work

- Additional testing with CO_2 sensors to determine exact effects of automatic baseline correction (ABC)
- Attempt to bypass ABC within commercial sensors to directly test the IR sensor performance
- Explore other CO_2 sensing technologies as potential replacement for IR based devices
- Perform similar testing on commercial CO and O_3 sensors

Conclusions

- Experimental setup allows for accurate reproduction of aircraft cabin pressure environment to study commercial sensors
- FTIR module allows for accurate determination of gas concentration for use as standard comparison for all commercial sensors
- Commercial CO2 sensors produced for building environments may need modifications to accurately work in an aircraft cabin
- Multiple approaches within CO_2 IR sensor technology experience similar operational issues when studied in an aircraft cabin environment

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- Technical Support
  - L. C. Mathison
  - Michael Friedman

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QUESTIONS?

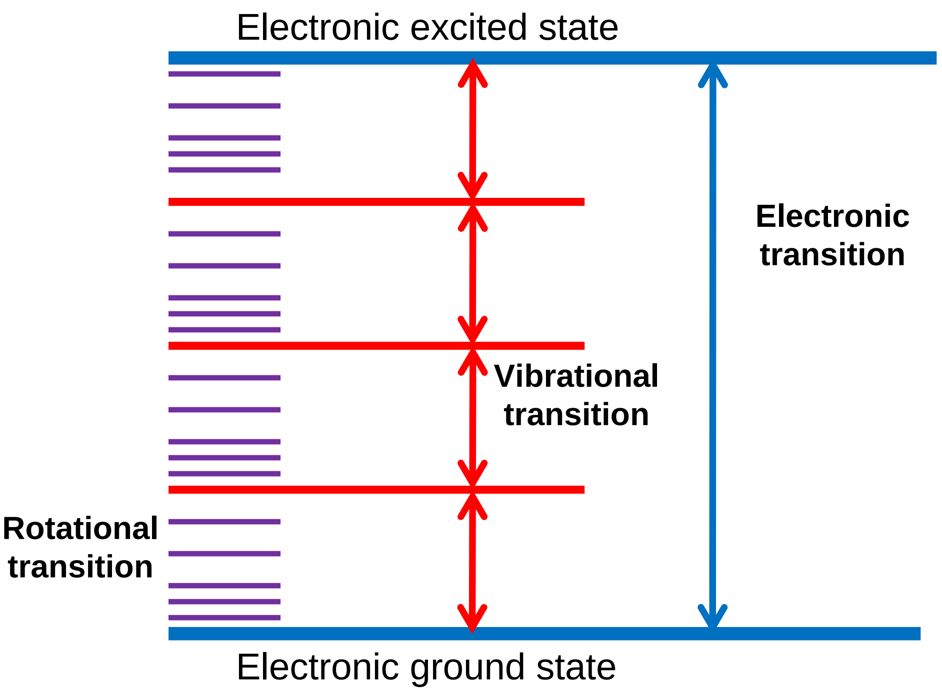
Additional Information

FTIR Analysis Background

FTIR – Principles of Operation

Ref. 8,9

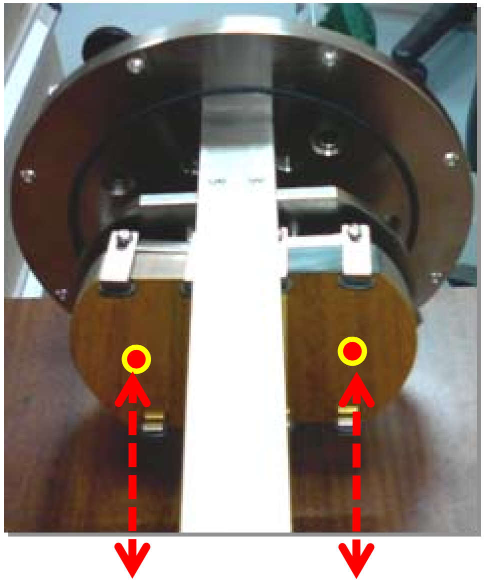
- Energy of molecule comprised of three additive components
  - Rotation of molecule as whole (1 cm^{-1} to 10^2 cm^{-1})
  - Vibration of constituent atoms (10^2 cm^{-1} to 10^4 cm^{-1})
  - Motion of electrons (10^4 cm^{-1} to 10^5 cm^{-1})
- IR absorption originates in photons that are absorbed by transitions between two vibrational levels

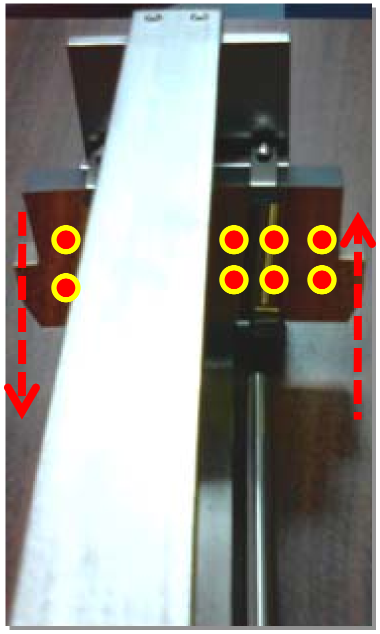


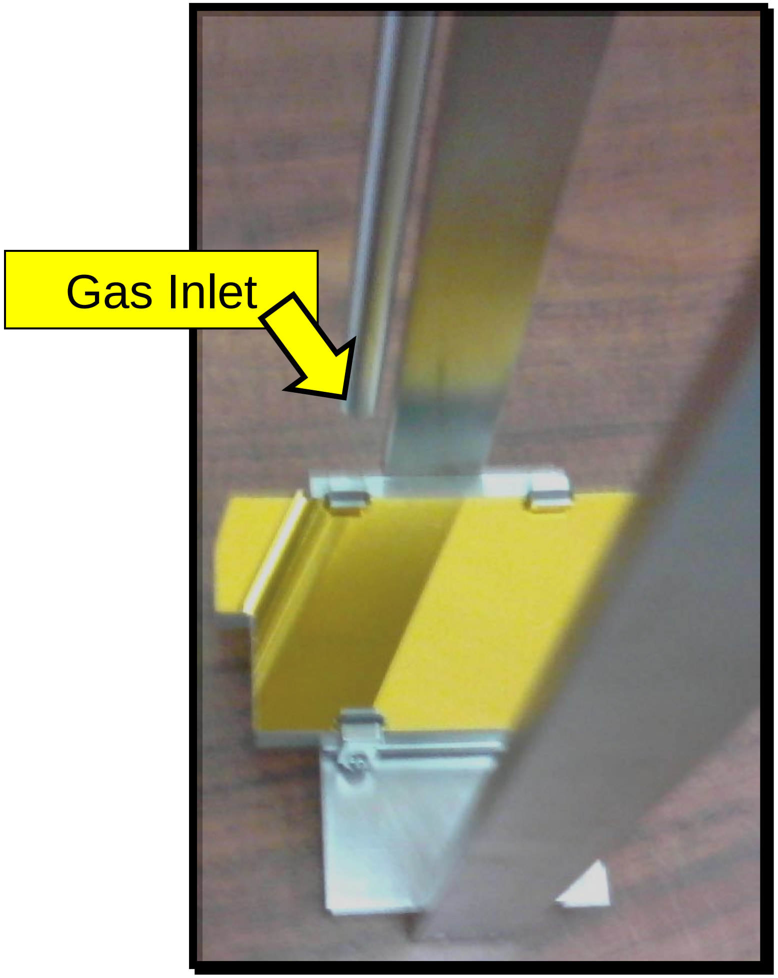
FTIR – Principles of Operation cont.

- All polyatomic molecules and hetero-nuclear diatomic molecules absorb IR radiation
- Pattern of absorption determined by physical properties of molecule
  - Number of atoms, bond angles, bond strengths
- Interpretation of spectra involves correlation of absorption bands of an unknown gas with known absorption frequencies for bond types
- Each spectrum differs from all others and is considered a molecular signature

Experimental Setup – FTIR Module







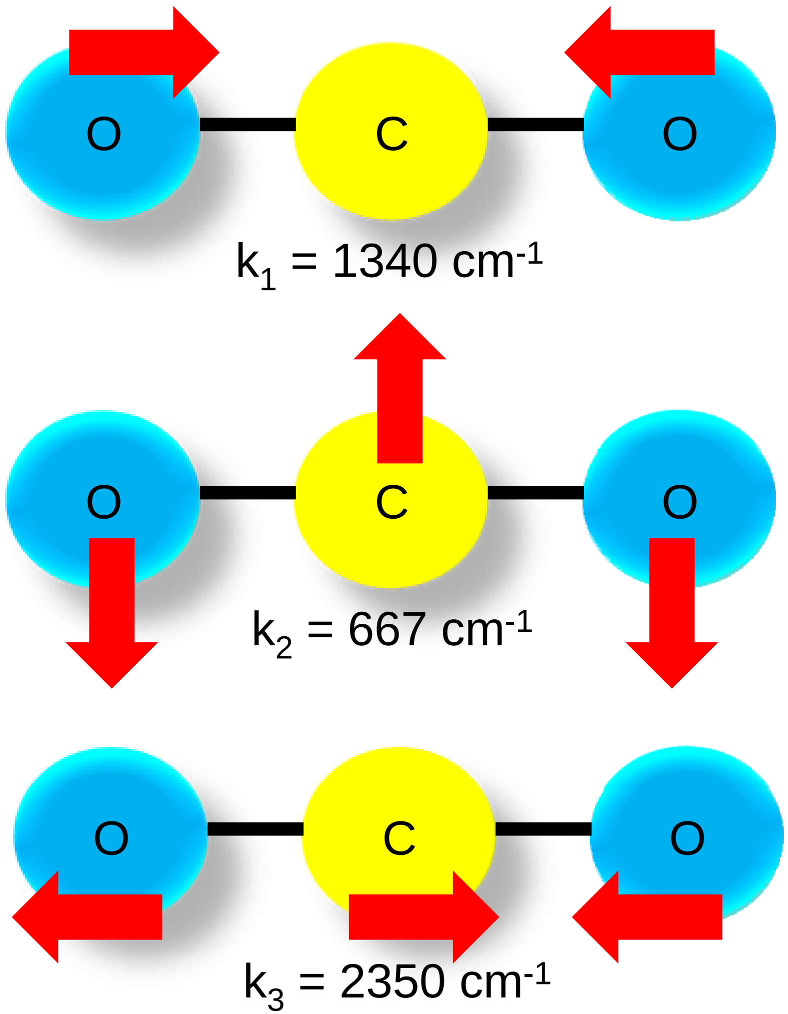
FTIR – Principles of Operation cont.

- Current QASoft database covers 386 gases
  - Compounds that have a vapor pressure 1 atm at room temperature (standard conditions)
- IR spectra of database covers 3700 cm-1 to 500 cm-1
  - Fundamental IR region where rotation and vibrations of molecules give rise to IR absorption
- Strongest spectral features most often used in measurements
  - Regions where absorbance is proportional to concentration-path length product
- Intensity of absorption depends on total number of molecules present in path of radiation

IR Spectrum of CO_2

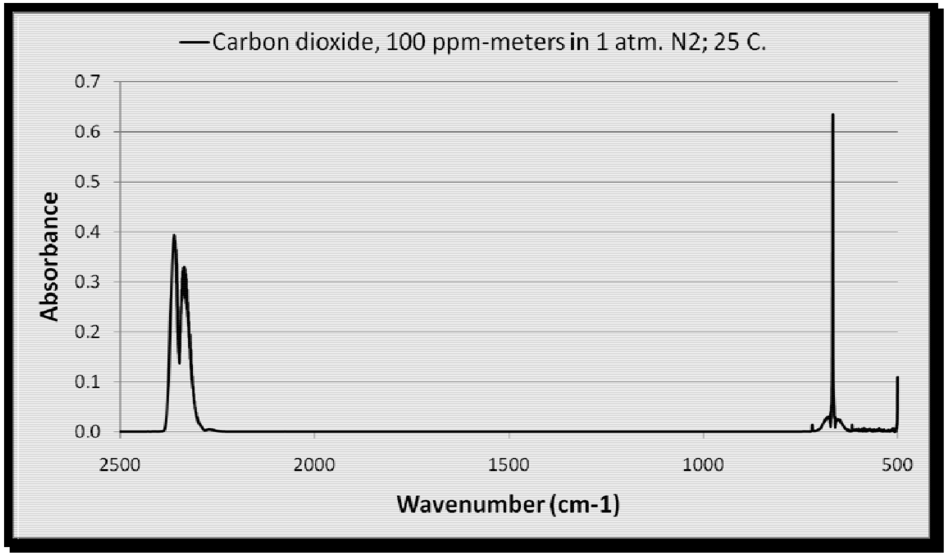
Ref. 8

- 3 distinct modes of vibration
- Symmetrical motion of O atoms, C atom fixed
  - $\omega 1 = 7.5\ \mu$ (k1 = 1337 cm^{-1})
  - Inactive in IR (lack of dipole moment)
- C oscillates perpendicular to O atoms, β(OCO)
  - $\omega 2 = 15\ \mu$ (k2 = 667 cm^{-1})
- Asymmetrical vibration , C moves relative to center of mass of O atoms
  - $\omega 3 = 4.3\ \mu$ (k3 = 2349 cm^{-1})



IR Spectrum of CO_2

- Theoretical: k2 = 667 cm^{-1}
  - Database: k2 = 667.2 cm^{-1}
  - Absorbance = 0.63
- Theoretical: k3 = 2349 cm^{-1}
  - Database: k3 = 2339.9 cm^{-1}
  - Absorbance = 0.31
  - Database: k3 = 2364.3 cm^{-1}
  - Absorbance = 0.37
- Absorbance scale adjusted to 100 ppm-meters



From QASoft Database

Vacuum Chamber Temperature Monitoring During Sensor Testing

Temperature Monitoring

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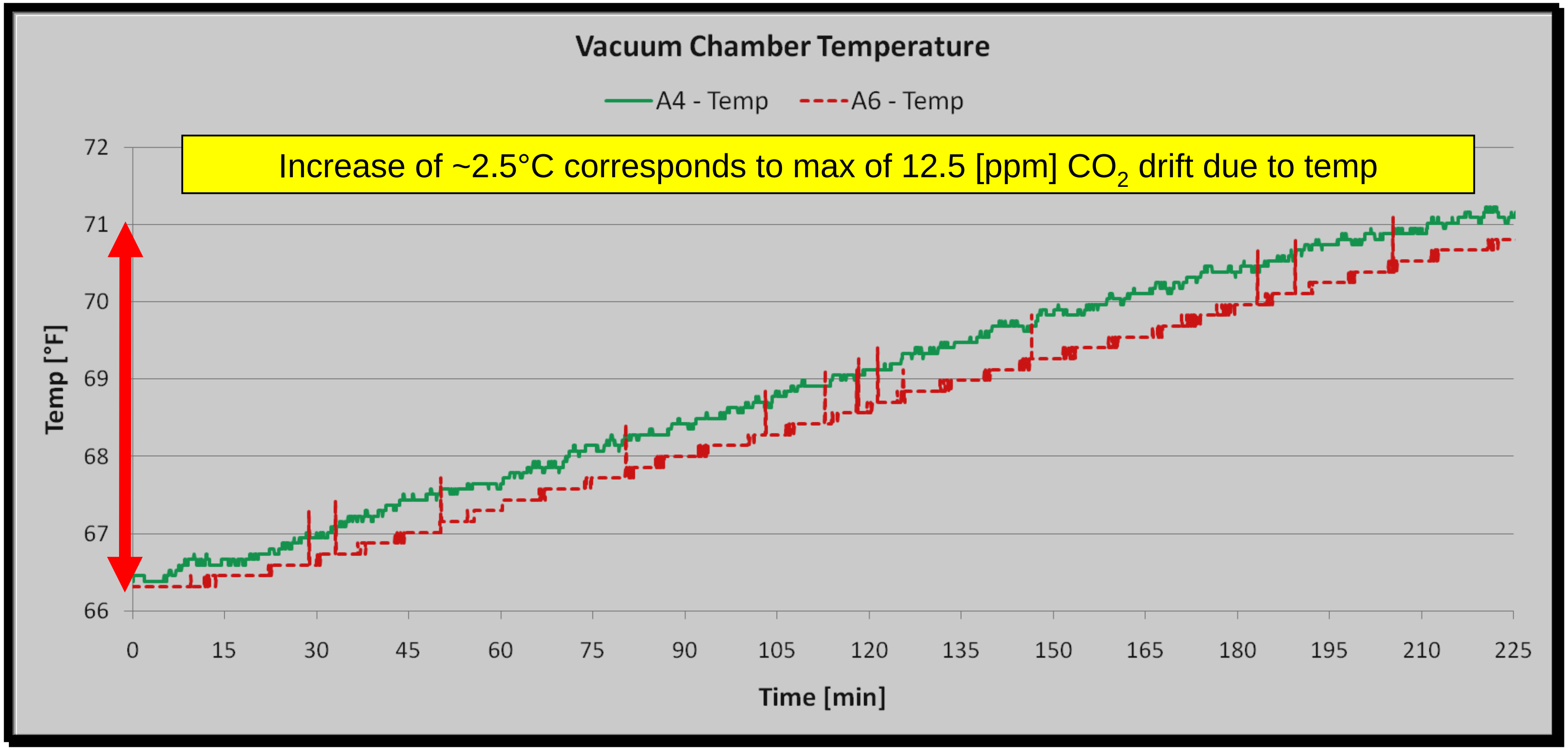
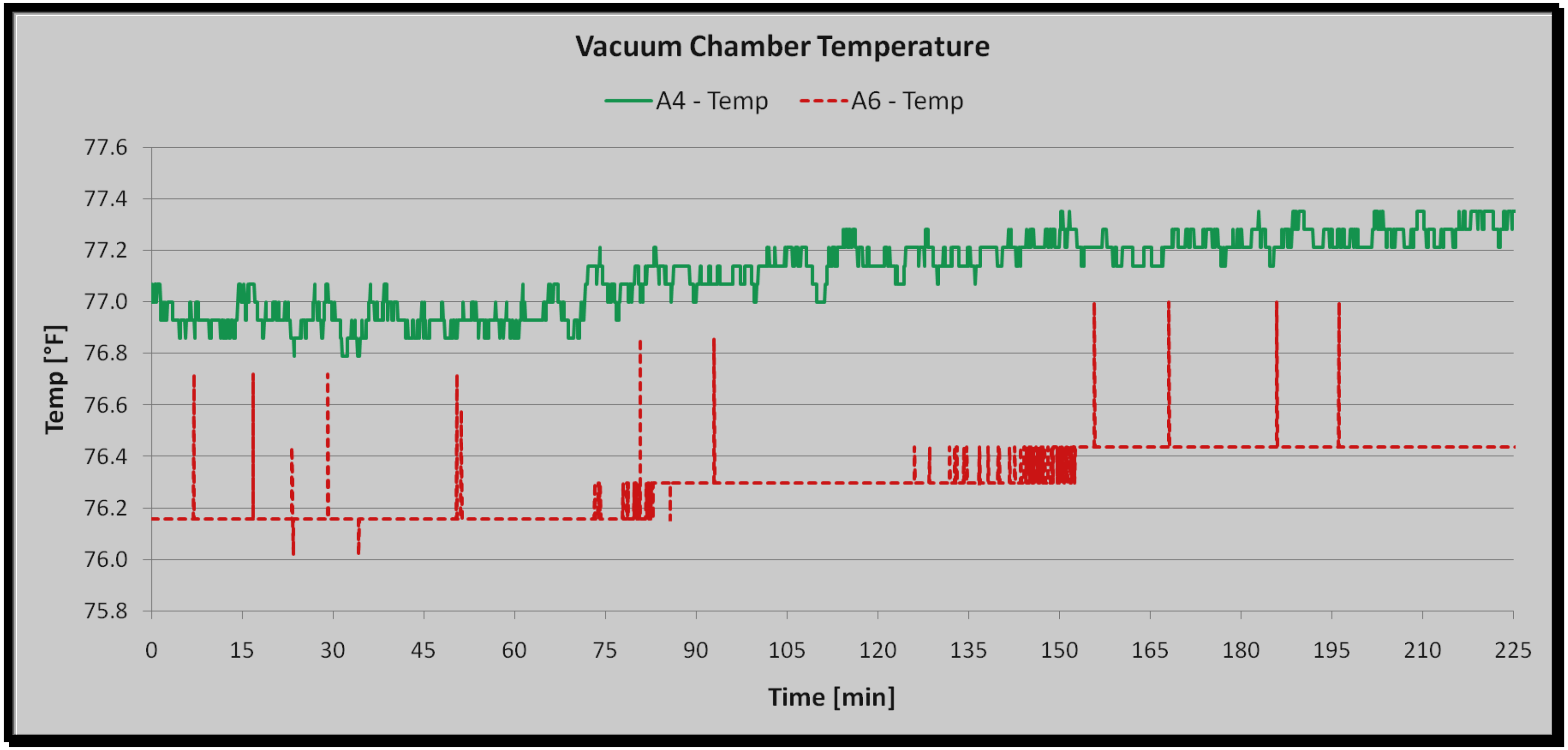
Test Date: 8-23-2010
Start Time: 11:15 AM
End Time: 3:05 PM



Temperature Monitoring

www.acer-coe.org

Test Date: 8-27-2010
Start Time: 8:35 AM
End Time: 12:30 PM



Vacuum Chamber
Relative Humidity Monitoring During Sensor Testing

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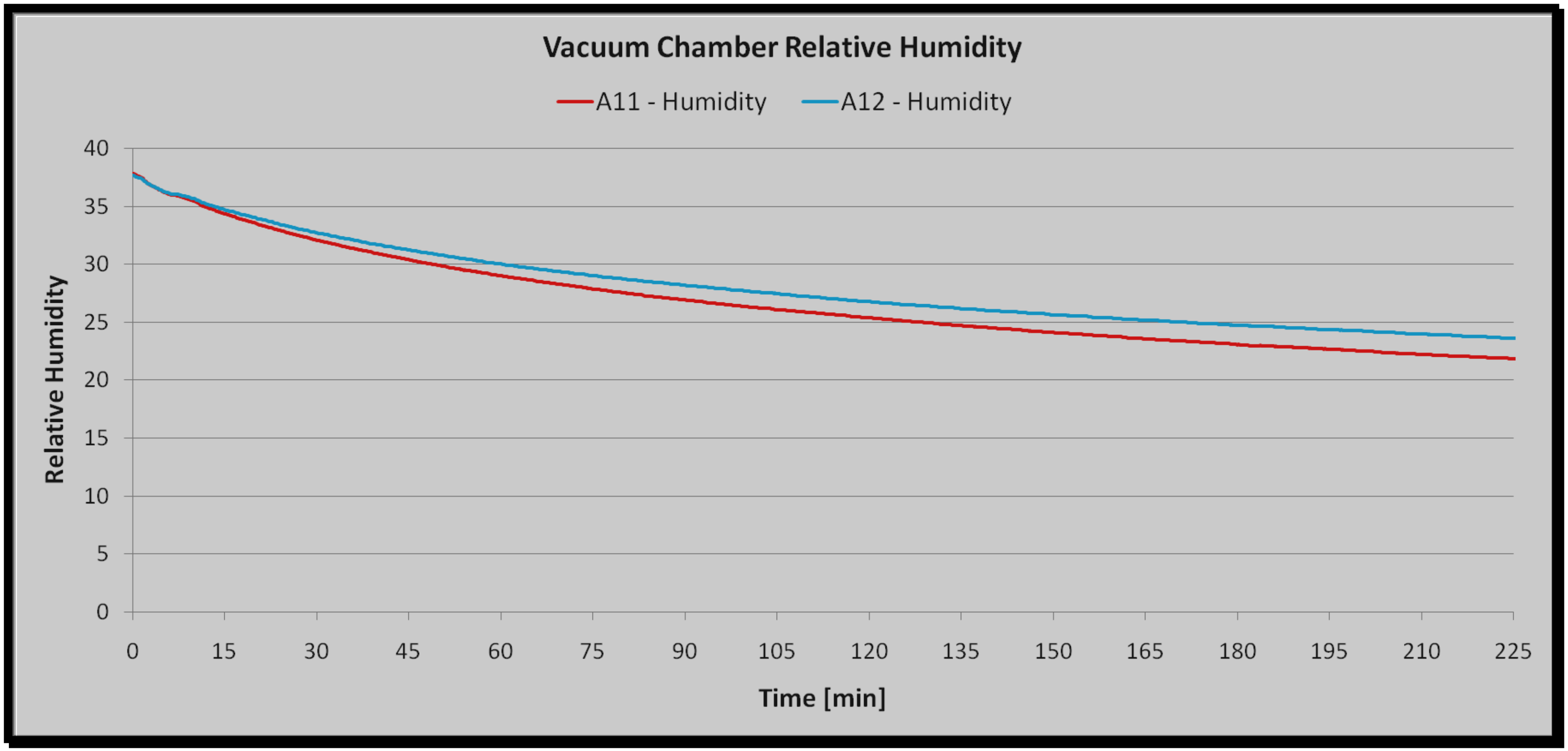
Relative Humidity Monitoring

Test Date: 8-23-2010
Start Time: 11:15 AM
End Time: 3:05 PM



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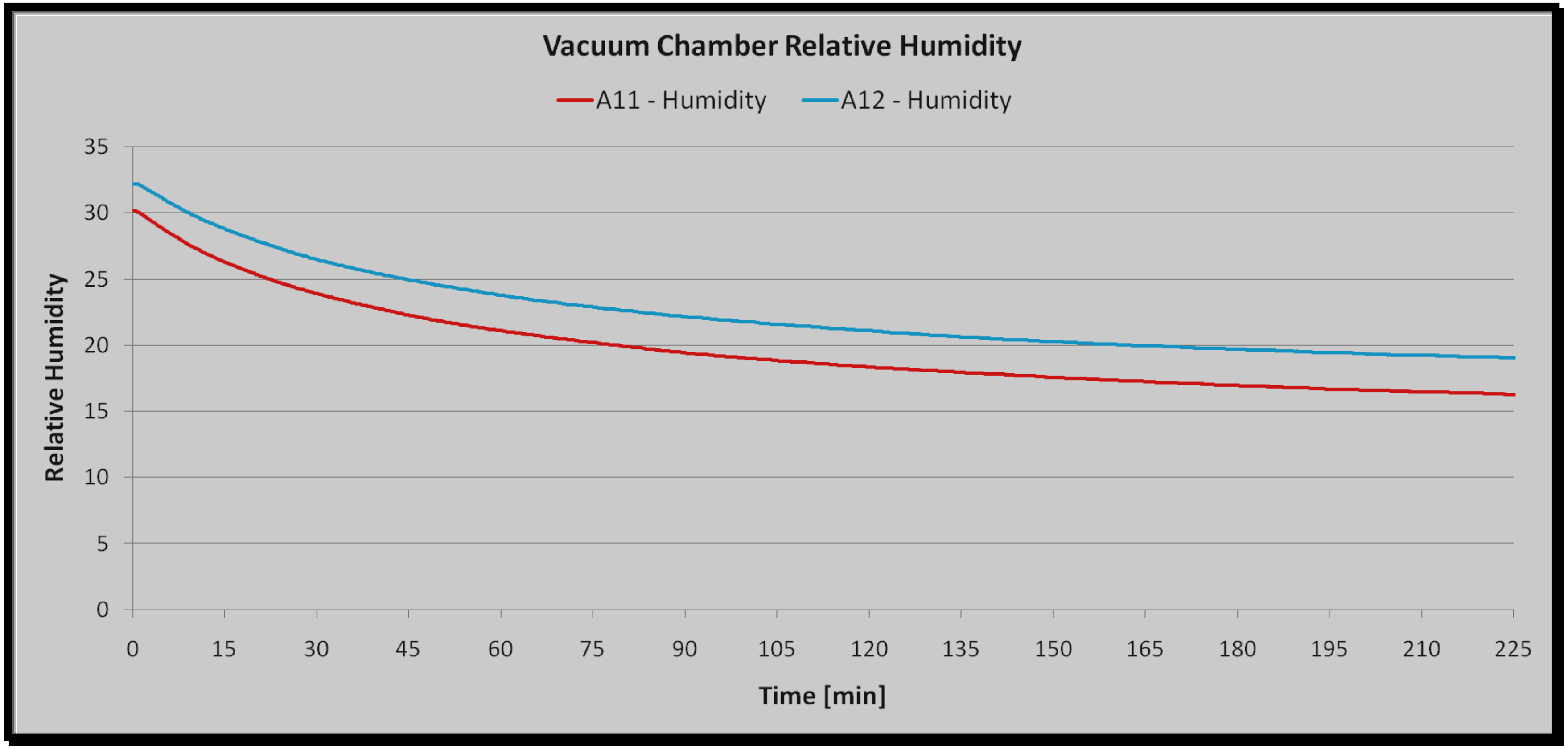
Relative Humidity Monitoring

Test Date: 8-27-2010
Start Time: 8:35 AM
End Time: 12:30 PM



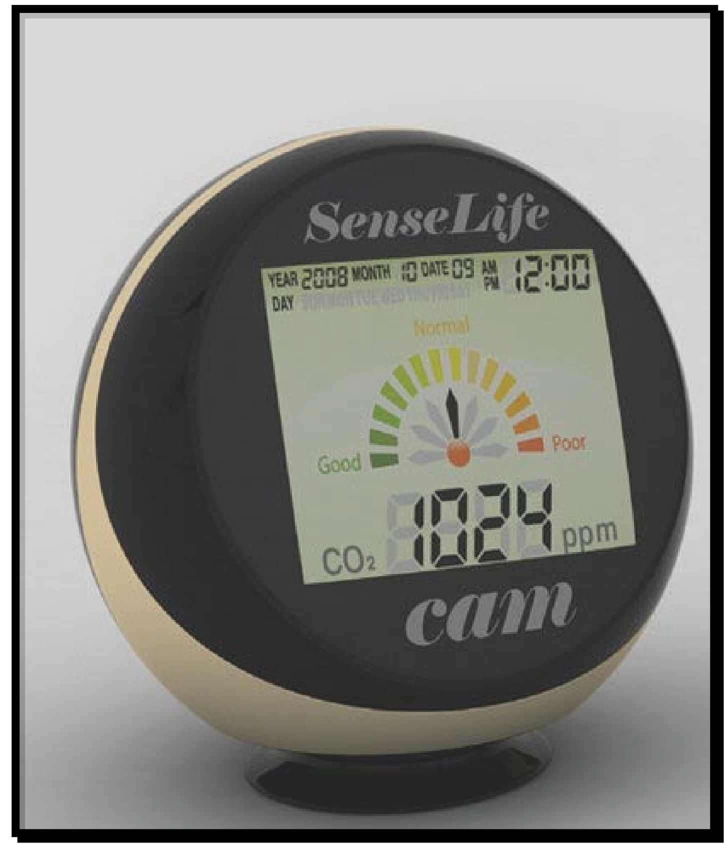
CO_2 Commercial Sensor Previous Results

- SenseLife CAM CO_2 Meter
- Gray Wolf Multi-gas Sensor IQ-604

SenseLife CAM CO2 Meter

- NDIR CO_2 Sensor
  - Automatic background calibration
  - Range: 0 – 9,999 ppm
  - Accuracy: ± 75 ppm + 5% of measured value

- Sensor automatically resets baseline value according to minimum CO_2 concentration observed over a given time period



Gray Wolf Multi-gas Sensor IQ-604

- NDIR CO_2 Sensor
  - Range: 0 – 10,000 ppm
  - Accuracy: ± 50 ppm + 3% measured value
- Electrochemical CO Sensor
  - Range: 0 – 500 ppm
  - Accuracy: ± 2 ppm < 50 ppm
    ± 3% measured value > 50 ppm
- PID O_3 Sensor
  - Range: 5 – 20,000 ppb
  - Accuracy: Not provided

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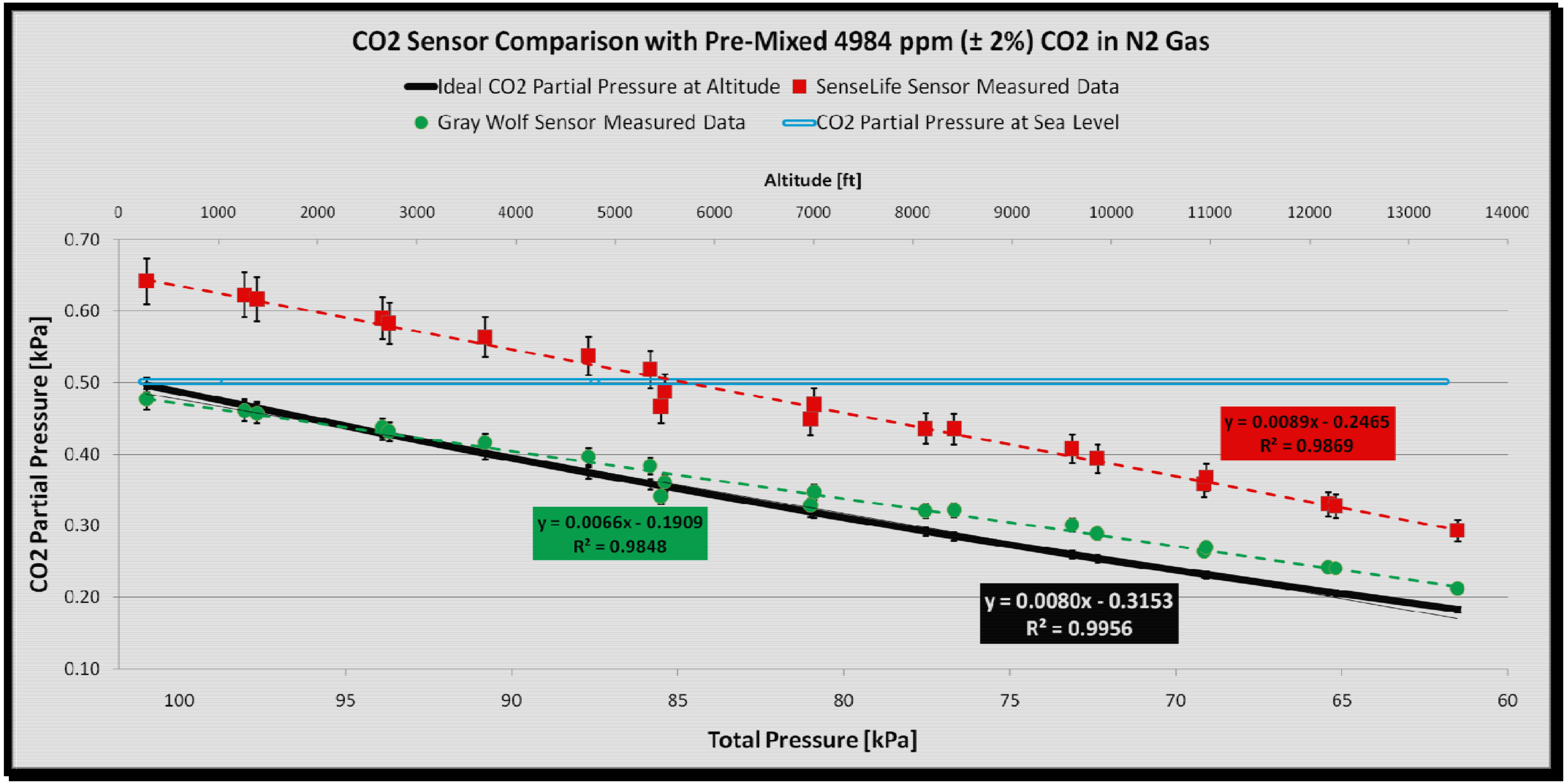
Sensor Comparison Pre-mixed CO_2/N_2 Gas



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