Non-Dispersive Infrared (NDIR) Gas Measurement: Past, Present & Future

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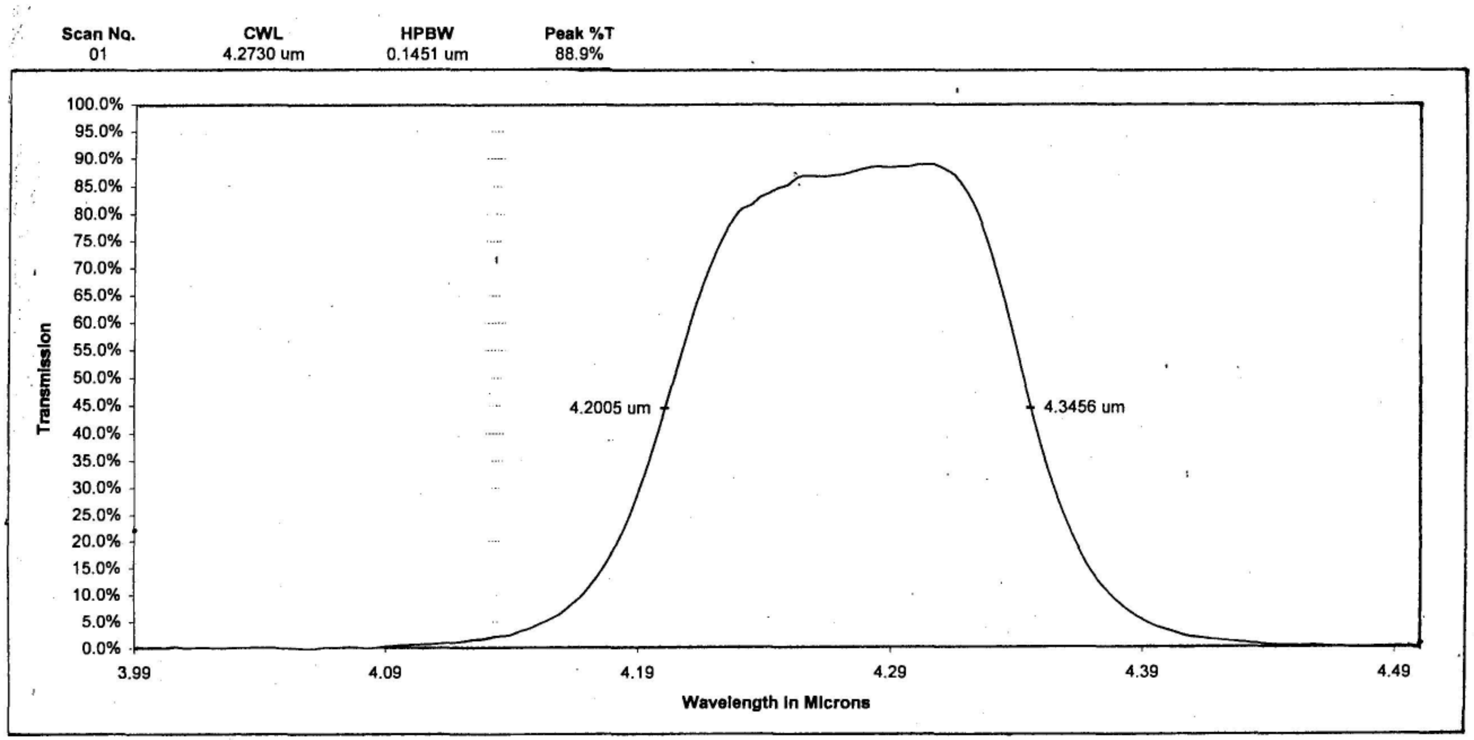
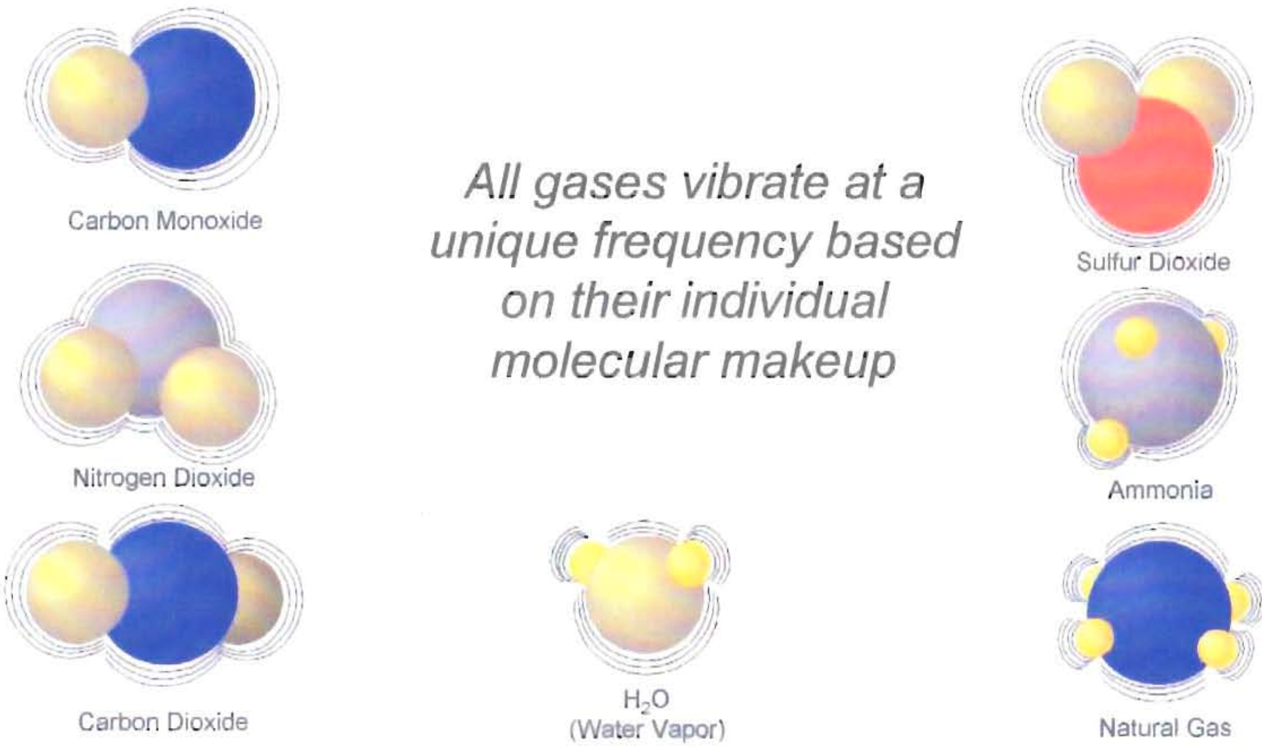
NDIR Gas Measurement: Past

- **The R&D of NDIR gas measurement started around the late 1930's in the U.S. as a classified Defense Department program when the importance of night vision in combat was first noted.**
- **The focus was to develop a small and light-weight non-spatially dispersive device capable of passing infrared radiation at a particular wavelength (CWL) with a very narrow half-power bandwidth (FWHM).**
- **Today this device is called a narrow infrared band-pass filter which is considered to be the brain of NDIR gas measurement.**

Narrow band pass filter for CO2



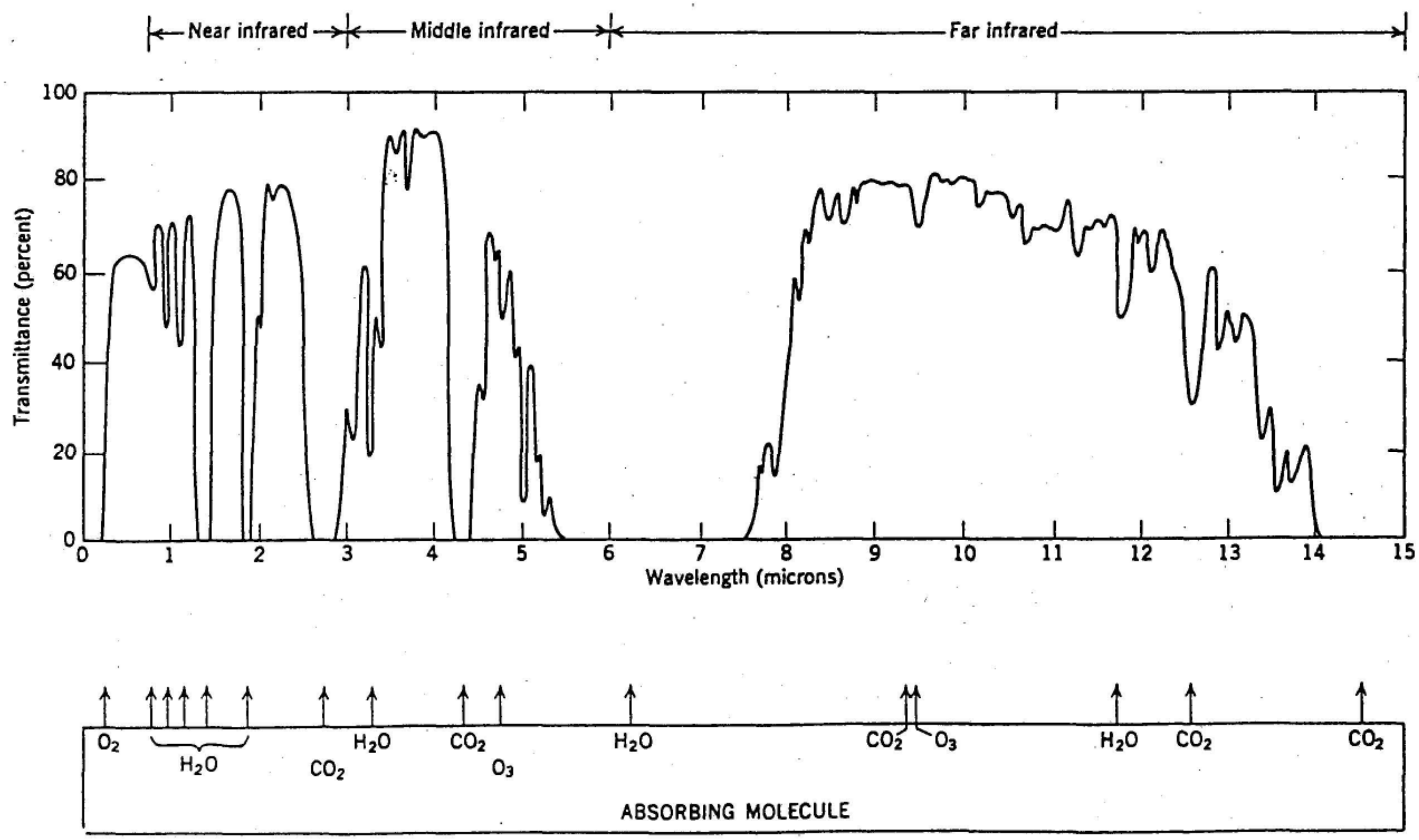
Gas Molecules and Infrared



NDIR Gas Measurement: Past

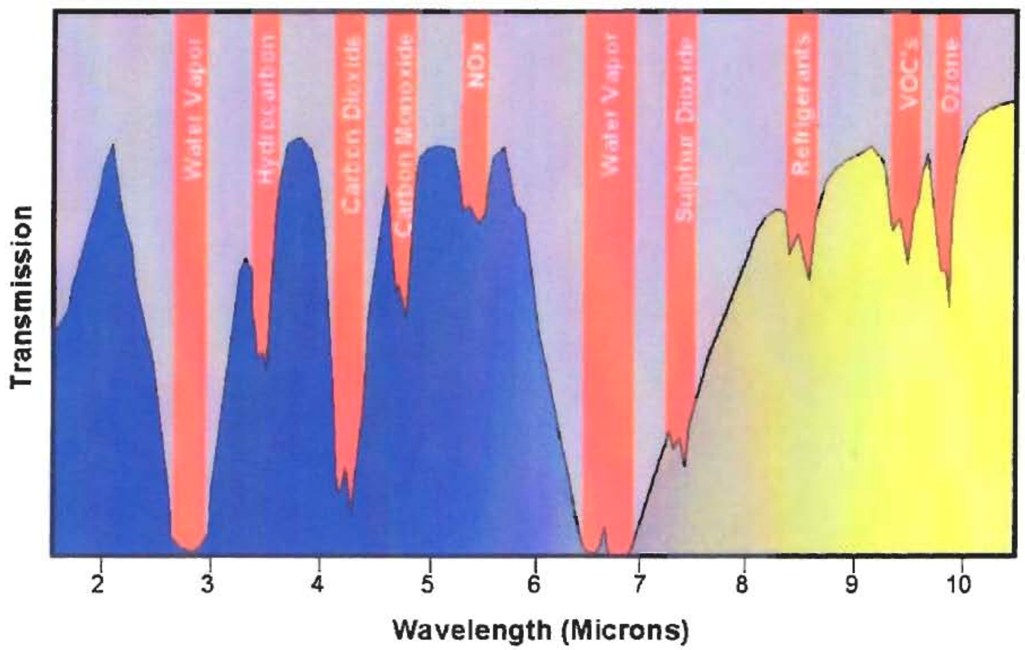
- **All gas molecules vibrate and rotate at particular frequencies. These vibration/rotational frequencies cause asymmetric molecules to absorb light at very specific wavelengths.**

Absorption bands of common gases present in the atmosphere



Infrared Gas absorption

The unique vibration of each type of molecule will absorb gas at very specific and unique wavelengths in the infrared spectrum.



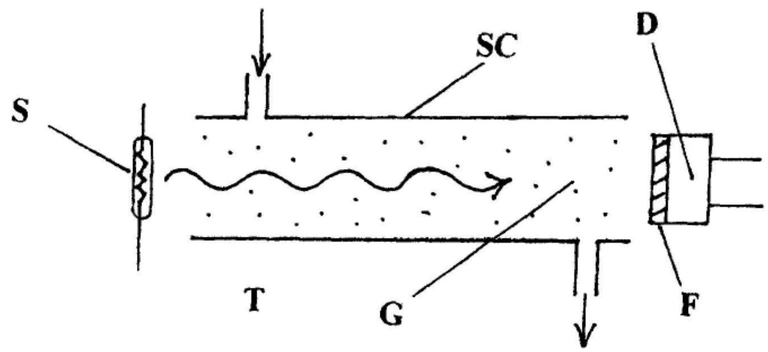
NDIR Gas Measurement: Past

- **The NDIR technique of gas measurement targets these wavelength absorptions in the infrared as a way to identify particular gases.**
- **It is amply clear that if a device were to exist, such as a narrow infrared band-pass filter, which can accurately select and pass infrared radiation at any particular wavelength and be able to discriminate all other unwanted wavelengths against passage, then the unique absorption bands of various gases in the infrared could easily afford their detection and measurement.**

NDIR Gas Measurement: Past

- **The narrow infrared band-pass filter technology was not declassified by the U.S. Defense Department until the late 1940's and commercial devices were not available for utilization in NDIR gas sensors until the late 1950's.**
- **The first ever NDIR gas sensor for sale was the Beckman LB-I medical CO_2 analyzer in the early 1960's for measuring end-tidal CO_2 levels for cardiac patients in hospital ICUs.**
- **The Beckman LB-I was single-beam designed having a DC-operated infrared source chopped at 40 Hz by a small mechanical chopper and a pyroelectric infrared detector. It has a range of 0 – 10% CO_2 and a response time of 100 msec.**
- **Host of problems for the Beckman LB-I including output drifts (needs recalibration every 3 months), temperature dependent and interfered by the presence of water vapor.**

Design Layout for the Single-Beam Methodology



S = Infrared source
D = Detector
F = Spectral filter tuned to gas
SC = Sample chamber
Gas= Gas to be detected
T = Ambient temperature

The technical foundation of NDIR gas sensors is based upon the Beer–Lambert Law:

$$I = I_0 \exp(-k\,C\,L)$$

I_0 = Initial radiation beam intensity
I = Beam intensity after traversing the gas to be detected
k = Absorption coefficient
C = Gas concentration
L = Sample path length

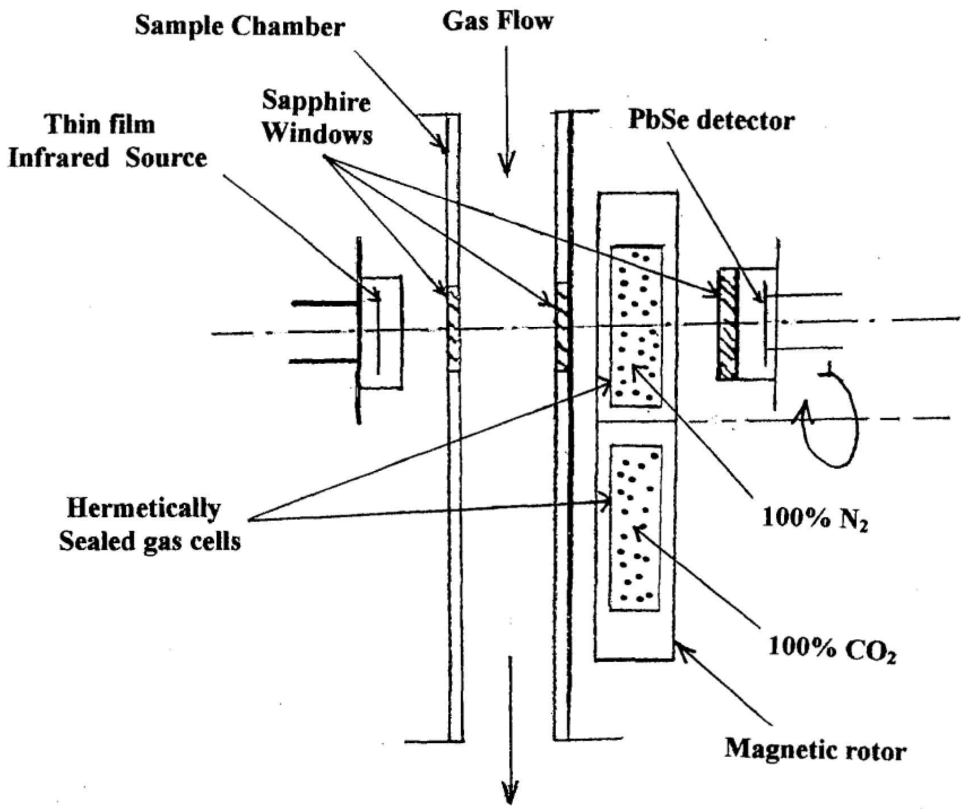
NDIR Gas Measurement: Past

- **Despite its poor performance, the Beckman LB-I and its successor LB-II were widely used in hospital circles throughout the 1960's. The main reason was that users of these analyzers knew that extra care had to be taken to ensure their accuracy, but the non-invasive taking of the end-tidal CO_2 value of a critically ill cardiac patient can replace the dangerous and painful arterial puncture in order to get the same critical arterial blood CO_2 pressure information.**
- **It was not until the mid-1970 that the Beckman analyzers were replaced by the legendary Hewlett-Packard medical CO_2 analyzer called the Capnometer.**

NDIR Gas Measurement: Past

- **The initial version of the Capnometer was the first NDIR gas sensor designed without the use of a narrow infrared band-pass filter which was considered at that time not reliable enough for use in a medical instrument.**
- **The Capnometer was also the first NDIR gas sensor that utilized a unique double-beam signal processing methodology.**
- **This superior methodology rendered the Capnometer unbelievably stable over time and extraordinarily reliable in terms of accuracy and down-time.**
- **The only drawback is that since it remained as the gold standard for medical CO_2 analyzers for almost two decades since its introduction in the mid-1970, it was extremely expensive.**

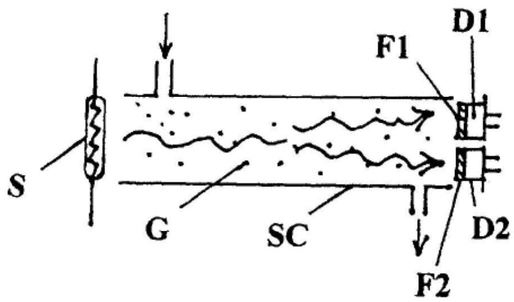
Design Layout for the Capnometer



NDIR Gas Measurement: Past

- **By the early 1970's, reliable narrow infrared band-pass filters were finally available in the marketplace.**
- **A double-beam methodology, first pioneered by the Capnometer, but now with the use of the available non-spatially dispersive infrared filters, was advanced.**
- **Advantages were both in cost and size. The hermetically sealed cells and magnetic rotor used in the Capnometer double-beam methodology were too expensive.**
- **In this new double-beam methodology, the infrared source was either pulsed or a mechanical chopper was used to replace the expensive magnetic rotor of the Capnometer.**

Design Layout for the Double-Beam Methodology



S = Source
D1 = Signal Channel detector, output D1S
D2 = Reference Channel detector; output D2R
SC = Sample Chamber
G = Gas to be detected
F1 = Signal Channel spectral filter with center wavelength (CWL) coincident with gas absorption band
F2 = Reference Channel spectral filter with center Wavelength (CWL) outside of gas absorption band
X = D1S/D2R = Processed sensor signal

As the source S ages, its spectral output shifts leading to an inevitable change in X = D1S/D2R and output drifts over time.

Despite the introduction of the Dual Beam gas measurement methodology decades ago, the output drift over time of NDIR gas sensors remains a serious and unresolved problem.

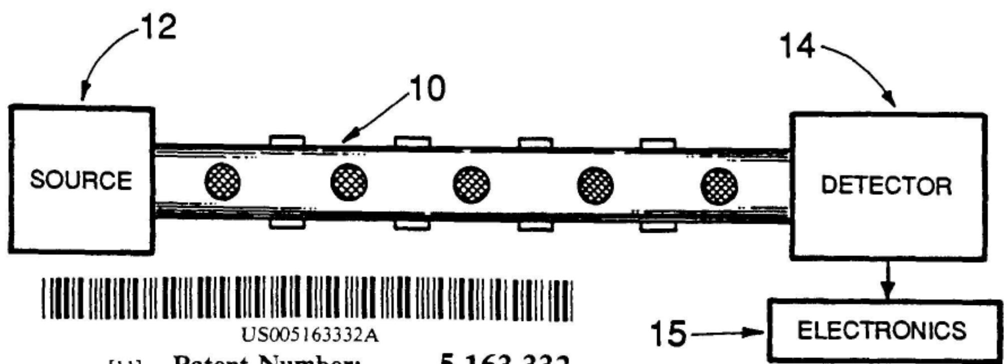
NDIR Gas Measurement: Past

- **Until the 1990's, no dramatic technological breakthroughs were made primarily due to the lack of any urgent or compelling applications for NDIR gas sensors.**
- **It was also during this time period that electrochemical gas sensors started to replace most of the NDIR gas sensor applications due to their small size, excellent detection resolution and much lower unit cost.**
- **Despite the shortcomings of electrochemical gas sensors attributable to their detection non-specificity, output instability over time and rather short life spans, they were able to win out on many applications over NDIR gas sensors whose size and unit cost have not gained any significant ground over the years.**

NDIR Gas Measurement: Past

- **The years 1990 – 1999 were literally a hibernating period for the NDIR gas measurement technique waiting for its awakening.**
- **The marketing pressure from electrochemical sensors plus the opportunity afforded by the energy saving practice of Demand Controlled Ventilation (DCV) for commercial buildings requiring low cost, smaller size and output stable CO_2 sensors finally led to a couple of technological breakthroughs.**
- **The first one was the advance of a so-called “wave-guide” diffusion sample chamber.**
- **The second one was the development of a sensor output correction software known as “Automatic Background Compensation” or “ABC”.**

Waveguide Sample Chamber



US005163332A

[11] Patent Number: 5,163,332

[45] Date of Patent: Nov. 17, 1992

A diffusion-type sample chamber for use in a gas analyzer consists of an elongated hollow tube (e.g. aluminum) having an inwardly-facing specularly-reflective surface that permits the tube to function also as a light pipe for transmitting radiation from a source to a detector through the sample gas.

NDIR Gas Measurement: Past

- **The ABC technique is a self-calibration methodology for NDIR gas sensors.**
- **It is based upon U.S. Pat. No. 5,347,474 issued in 1994.**
- **This invention grew out of prolonged observation of the CO_2 level in an office building.**
- **It has been discovered that the CO_2 level decreases when people leave the building after work, the inside of the building exhibits a prolong quiescent period when the CO_2 level approximates that found outdoors 400 – 500 ppm.**
- **This quiescent CO_2 level is recorded for successive days. The data are fitted to a best-fitting straight line. The slope of which will reflect the long-term drift rate for the sensor which can then be appropriately corrected.**

NDIR Gas Measurement: Past

- The “Past” period for NDIR gas measurement has been arbitrarily defined to end in 2010 about three years ago.
- During this time period, the mechanical chopper approach has been completely eliminated and replaced by infrared source pulsing.
- Sensors were still being made using both the single-beam and double-beam methodology with appropriate infrared narrow band-pass filters.
- The CO_2 sensor module size has gone down from several inches in extent to just a couple of inches.
- The CO_2 sensor module price has gone down to under US$50.00.
- But most NDIR gas sensors still exhibit significant output drifts over time.
- Also the output of most NDIR gas sensors are still ambient temperature dependent and has to be appropriately corrected.

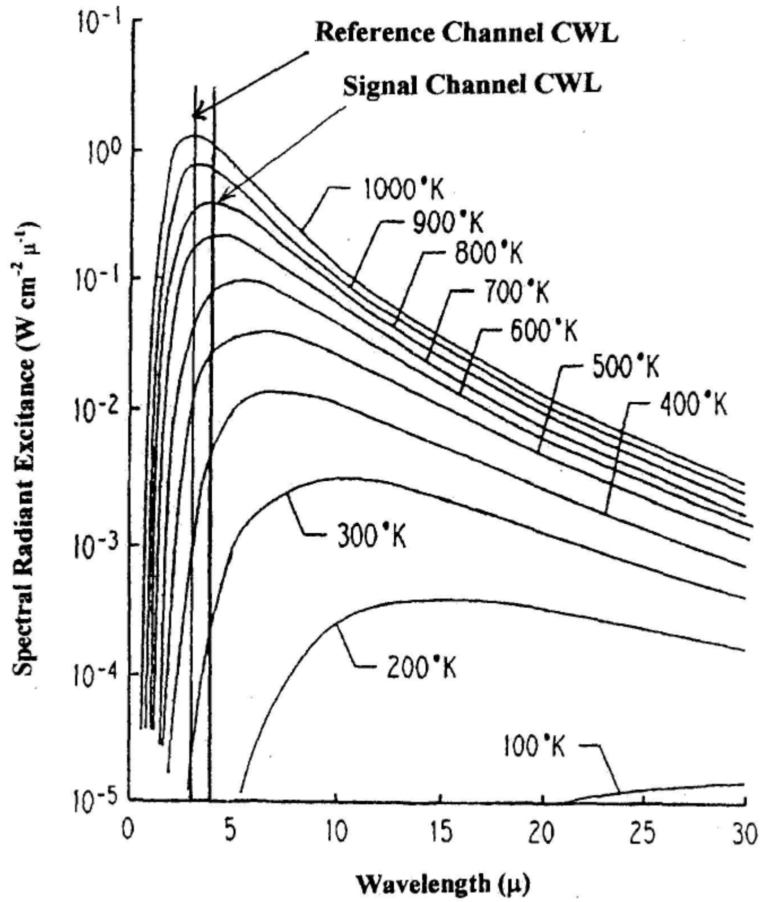
NDIR Gas Measurement: Present

- The “Present” period started about three years ago.
- During this period the output drifts over time problem for NDIR gas sensors has finally been overcome via the advent of the Absorption Biased (AB) methodology [U.S. Pat. No. 8,143,581 (2012)].
- The Synchronization Calibration (SynCal^{TM}) technique to recalibrate already installed sensors without the use of standard gases [U.S. Pat. No. 8,178,832 (20120] was advanced.
- The first NDIR Dew Point sensor which measures directly water vapor pressure in mmHg was also successfully developed.

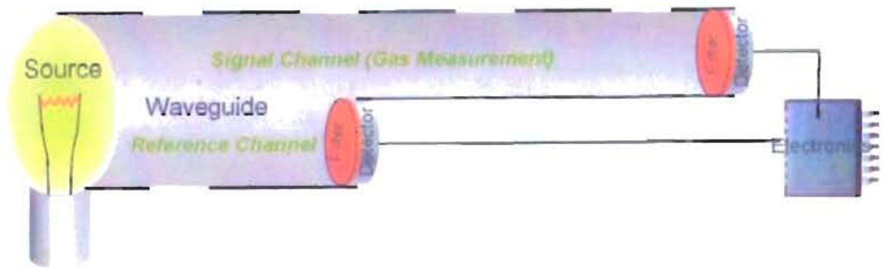
Understanding the Physics of NDIR gas measurement

- **Finally starting from about three years ago and up until today, the technology for significantly reducing the output drift of NDIR gas sensors over time has finally been developed and successfully demonstrated.**
- **As it turned out, there had been a technical flaw never recognized by engineers for decades in the design of the conventional double-beam NDIR gas sensors that causes the problem of the inevitable sensor output drift over time.**
- **The aging of the Blackbody source for NDIR gas sensors spectrally shifts its output over time causing unavoidably the ratio of the Signal channel output over that of the Reference channel to change. When that happens, the sensor output will also inevitably change.**

Spectral Radiation Excitance Curves of a Blackbody at various Temperatures



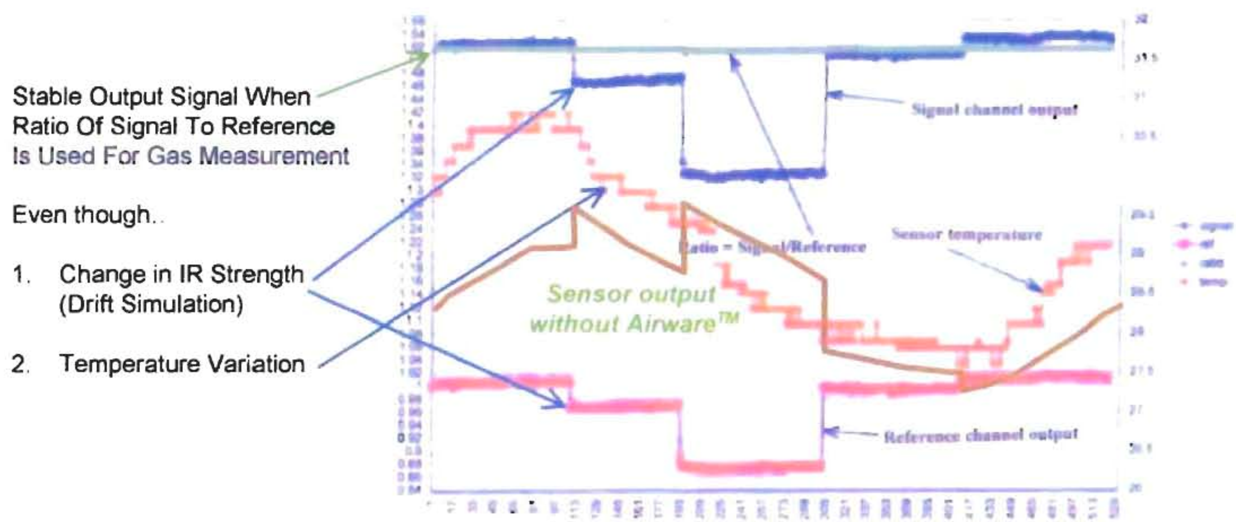
NDIR Absorption Biased (AB) Gas Sensing Methodology



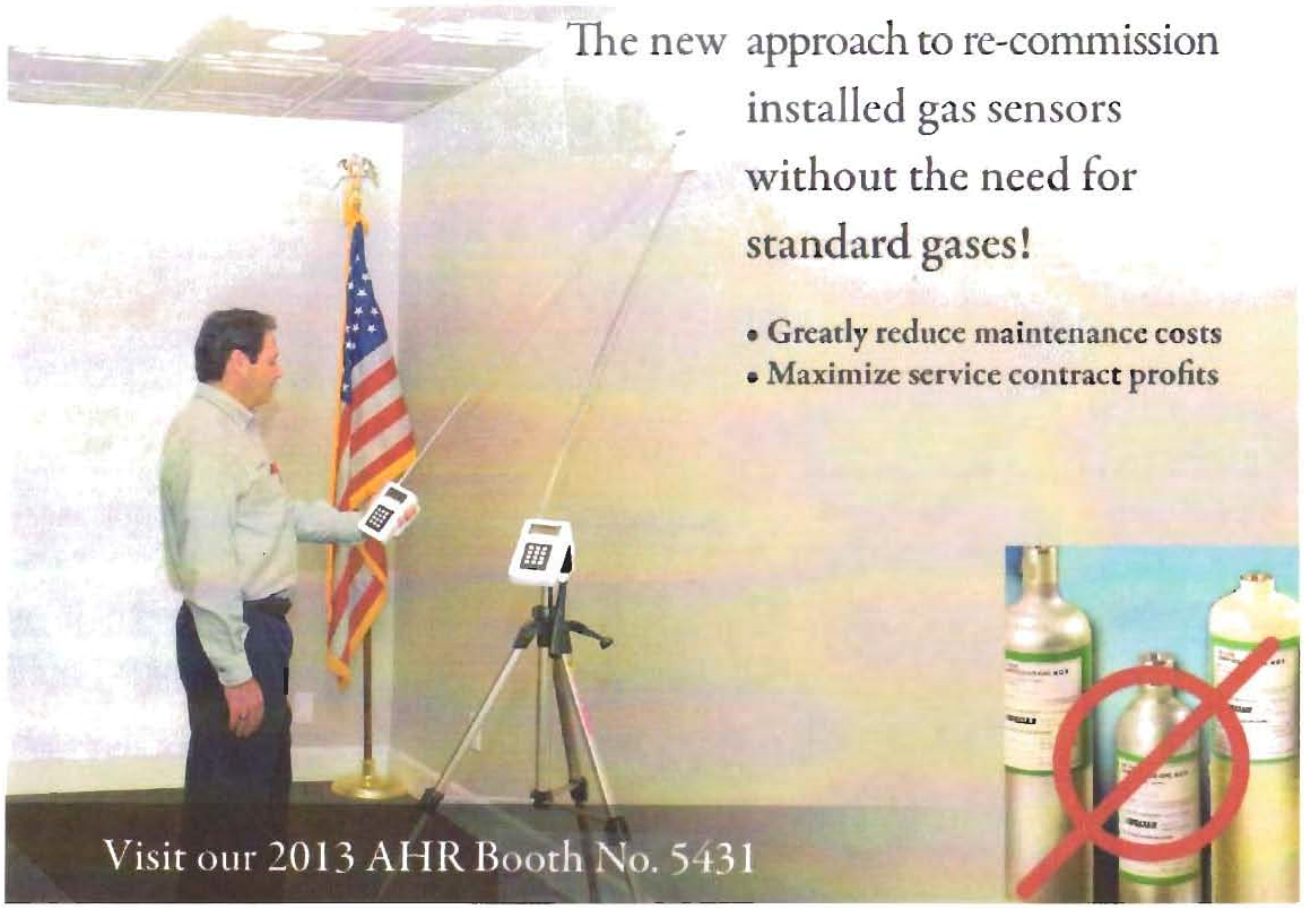
- Use identical spectral filters (CWL, FWHM and η) for both Signal and Reference Channels
- Use "waveguide" (aluminum tubing with reflective inner walls) sample chambers
- Path length of sample chamber for Reference Channel shorter than that for Signal Channel
- All sensor components share the same thermal platform whose temperature is constantly monitored

Absorption Biased (AB) Methodology Experimental Results

Figure 3   072100 HPK 4V7 4V5 4V2 4V5 4V7



SynCal^{TM} Recalibration Methodology



NDIR Gas Measurement: Present

- **Besides the advent of the Absorption Biased (AB) methodology for designing NDIR gas sensors and the SynCal™ recalibration technique to keep such sensors stay accurate over time without the need for standard gases, several noteworthy improvements were made.**
- **Further sensor module size reduction to 2” x 1” x 0.375”.**
- **Further sensor unit cost reduction to <US$50.00 for large quantities**
- **Although the double-beam methodology has been steadfastly maintained, more attention has been paid to the burn-in period for infrared sources especially miniature incandescent light bulbs. The adoption of this pre-production source selection procedure similar to wine-aging practices has led to more output stable sensors even for some single-beam designed sensors.**

NDIR Gas Measurement: Future

- **Before we take a look into the crystal ball to find out what could possibly lie ahead in the world of NDIR gas measurement, we must try to understand the shortcomings of this technology.**
- **The reason is that the only way one can extend the performance limit for NDIR gas sensors is to circumvent its fundamental weaknesses taking full advantage of the advancement of other technologies like in the world of micro and integrated electronics, MEMS, nanotechnology, superfast processors, intelligent software, wireless communications including the Internet and smart phones.**

Basic weaknesses of NDIR gas measurement

- **The absorption strength of the infrared signatures or absorption bands for gases detectable using this technique varies a great deal from one another.**
- **The spectral locations of these infrared signatures also vary widely from 2 - 20μ.**
- **The line shape of these infrared signatures also are distinctly different from one another and some are very difficult to handle.**
- **The detection range and sensitivity required for detecting most gases using this technique also vary a great deal, detection range from tens of thousands of ppm to just a few ppm; detection sensitivity from +/- 50ppm to sub-ppm or ppbs.**
- **Measurement of gas concentration using this technique actually is measuring the gas density inside the sample chamber. Thus the measurement always depends upon ambient temperature and atmospheric pressure. They must be appropriately accounted for in the measurement in order to obtain accurate results.**

NDIR Gas Measurement: Future

- **Looking briefly into the crystal ball today, one can already see the performance limit for NDIR gas sensors being continually extended both in the technology front and also in applications.**

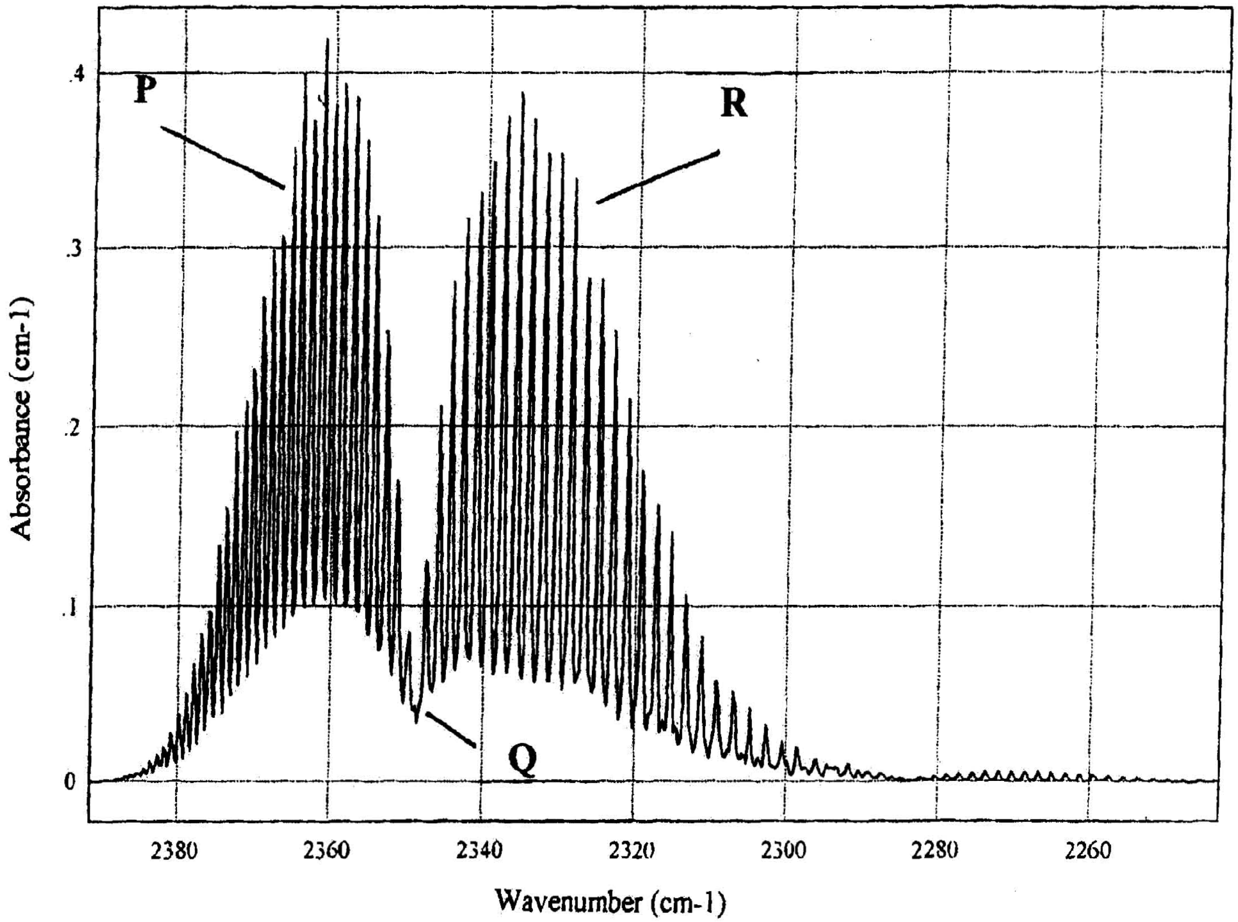
NDIR Gas Measurement: Future Technology Front

- A design for an intrinsically safe NDIR gas sensor based upon the Absorption Biased (AB) design methodology was advanced in U.S. Pat. No. 8,158,946 B1 (2012).
- A methodology for implementing self-commissioning NDIR gas sensors based upon the Absorption biased (AB) sensor design was put forward in U.S. Pat. No. 8,217,355 B1 (2012).
- In U.S. Pat No. 8,415,626 B1 (2103) an approach to further reduce the size for NDIR gas sensors was disclosed by designing the entire NDIR gas sensor onto a TO-5 header can.
- But the most encouraging sign to observe is the continual overcoming of the weakness of this technology in extending applications that hitherto unachievable as exemplified in the applications to follow.

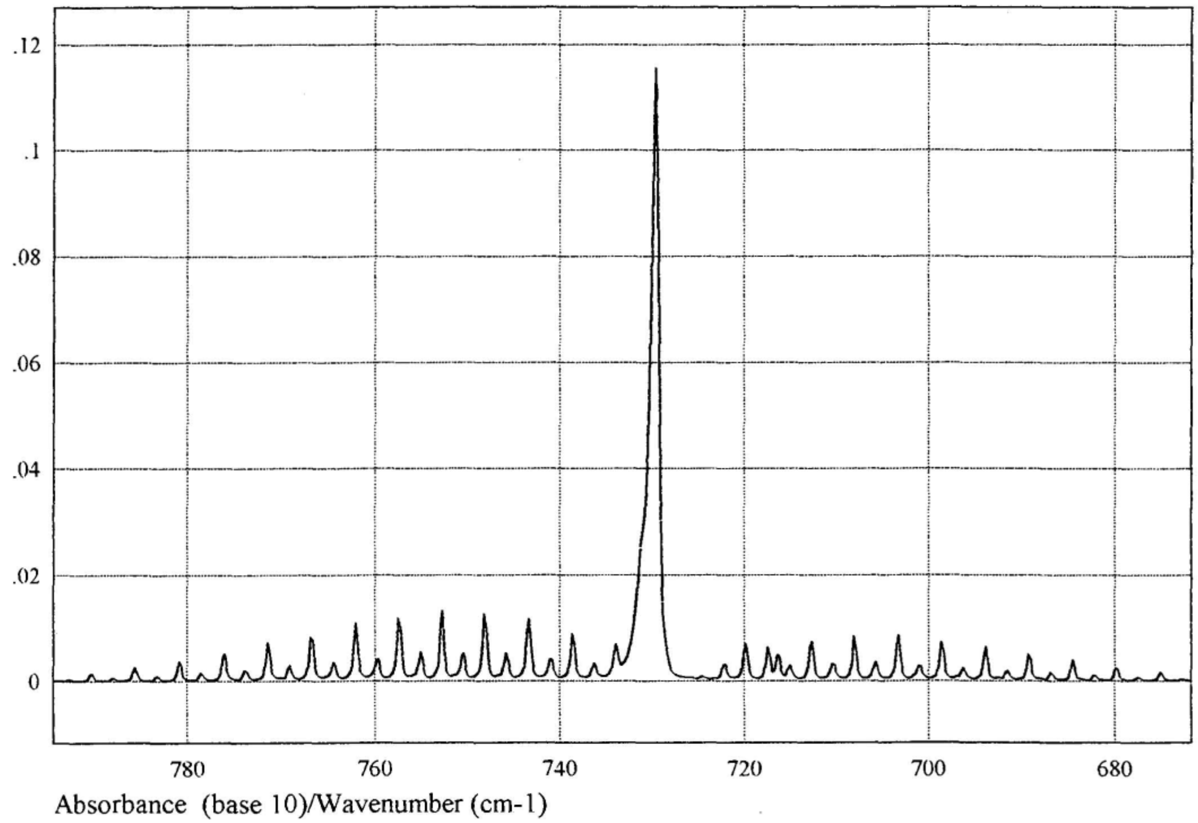
NDIR Gas Measurement: Future Coming Applications

- **Acetylene (C_2H_2) sensor; Location: 13.7µ; absorbance = 0.01; absorption bandwidth: 0.01µ; Range: 0 – 10 ppm; Accuracy: 0.1 ppm; Continuous transformer oil breakdown monitoring**
- **Tetrahydrothiophene (THT) sensor; Location: 7.92µ; absorbance = 0.007; absorption bandwidth: 0.04µ; Range: 0 – 15 ppm; Accuracy: 0.1 ppm; Detection of this poisonous sulfur compound amid ~100% natural gas**
- **Formaldehyde (HF) sensor; Location: 3.56µ; absorbance = 0.008; absorption bandwidth: 0.04µ; Range: 0 – 2 ppm; Accuracy: 0.05 ppm; Indoor air quality monitoring in school classrooms**
- **Underground Garage Monitor (UGGMON); Detection of CO, NO_2, H_2O and CO_2; Accurate, output stable, easily check and recalibrationable with long life.**

Absorption Band of CO_2



Absorption Band of C_2H_2



NDIR Gas Measurement: Future Coming Applications (Cont'd)

- **ATMOS-6 Six-Point Environmental Monitoring Station; The ATMOS-6 is a cost effective, multi-parameter climatic monitoring platform intended for air monitoring systems tied into existing street lighting or power distribution networks. Monitoring parameters include CO_2, CO, NO_2, Dew Point, barometric pressure and temperature.**
- **Multi-criteria fire alarm (Mcfa) – A new and improved fire detector which detects CO and CO_2 gases along with smoke at fire initiation. This Mcfa fire detector is designed so that the detection of a routine level of smoke obscuration must be accompanied by a well-defined rate of rise of a gas level for either CO or CO_2 before the fire alarm could be sounded.**
- **All manners of NDIR gas sensors directly communicable with smart phones via WiFi and Access Points of Internet or directly using smart phone cell network.**

Conclusions

- **There is very little doubt that the technique of NDIR gas measurement is one of the best among a dozen or so of others in terms of accuracy, speed of response, output stability, long operating life, ease of use and to maintain. But it has taken almost seven decades until about three years ago before this technology finally reaches its full potential. It is expected that NDIR gas sensors will play an even more important role in our daily lives and activities as we enter into the Twenty-first century!**