Paper presented at the Annual AWMA Technical Conference
Indianapolis, IN, June 22-25, 2004

Spanning Two Decades of Experience Using Hot-Wet Multi-component IR Gas Analyzers for Continuous Emissions Monitoring Systems (CEMS)

Control # 146

Ronald L. Baker
EcoChem Analytics, 8 Paret Lane, Hartsdale, NY 10530

Robert J. Peters
EcoChem Analytics, 202 Reynolds, League City, TX 77573

Edul D. Chikhliwala
EcoChem Analytics, 24386 Silver Bullet, Murrieta, CA 92562

Timothy J. Porter
Wheelabrator Technologies, 4 Liberty Lane West, Hampton, NH 03842

ABSTRACT

Over the past two decades, Hot-Wet Multi-component Infrared Gas Analyzers have been increasingly used as the analyzer component within Continuous Emissions Monitoring Systems (CEMS). As compared to a system of discrete analyzers, multi-component gas analyzers offer distinct advantages including real-time correction for interfering variables, direct measurement of all gases, reduced maintenance effort and significantly lower purchase price. Multi-component gas analyzers have evolved over time and currently the third generation of instruments is being installed. The first generation consisted of large, bulky instruments that used proprietary communication interfaces. The second-generation instruments were more compact and used more advanced electronics. The third generation instruments are extremely compact and use industry-standard protocols like Modbus to communicate with the Programmable Logic Controllers (PLC). Currently using one compact third-generation multi-component infrared gas analyzer instrument it is possible to measure up to 8 compounds (for example, HCl, NH_3, SO_2, NO_x, CO, CO_2, H_2O) and O_2 using an integrated Zirconium Oxide analyzer.

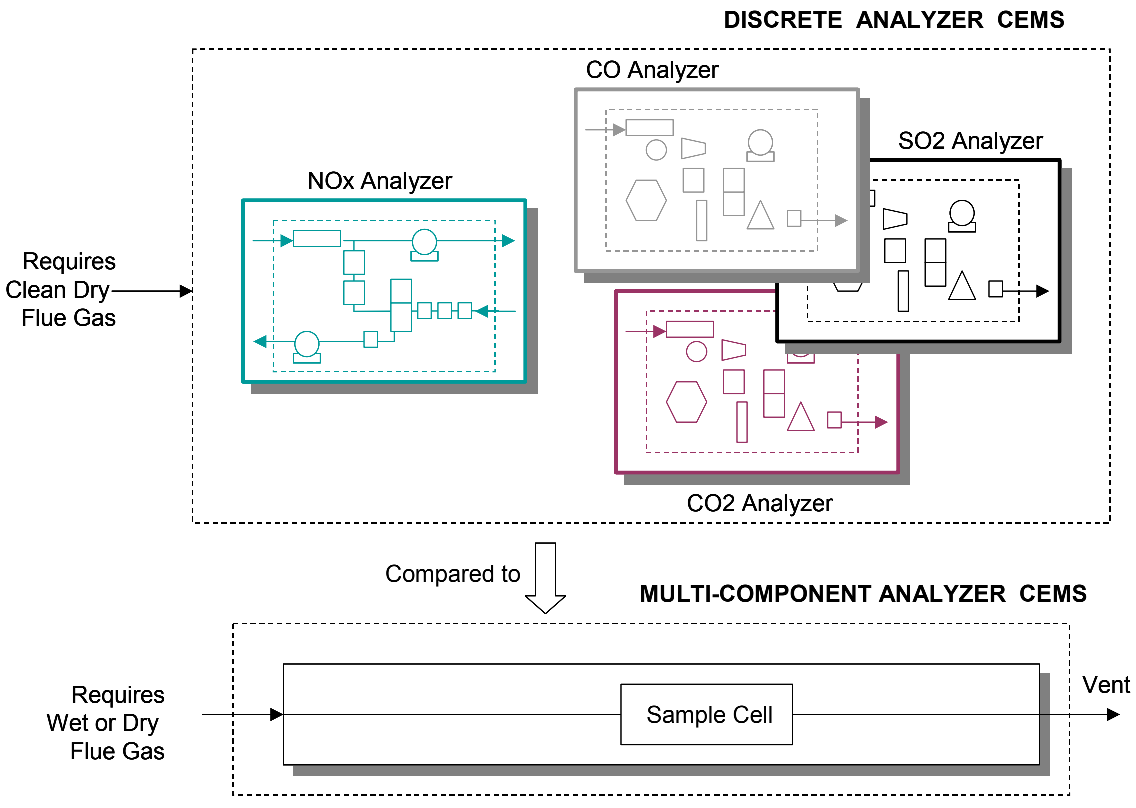
After discussing the construction and working principle of the multi-component infrared gas analyzers we will present information about the use and real-life application for regulatory monitoring and process applications. Integrated with appropriate Data Acquisition Systems (DAS), these CEMS have been successfully used to meet the Maximum Available Control Technology (MACT) and Best Available Control Technology (BACT) requirements at installations in waste-to-energy facilities, gas turbine utilities, cement kilns and pharmaceutical plants. The paper will also provide information regarding results from Relative Accuracy test audit (RATA) and CEMS availability.

INTRODUCTION

Continuous Emission Monitoring Systems (CEMS) were introduced in the late 1970s and have been used for a wide variety of applications (coal-fired utility boilers, gas turbines, cement kilns, hazardous waste incinerators, municipal waste-to-energy facilities etc.). Different design configurations of the CEMS have been proposed to meet the challenges posed by the various applications. Jahnke[1] provides an excellent discussion and overview of the various techniques used by various CEMS.

In this paper we will focus our attention on a very specific CEMS configuration called "Hot-Wet Multi-component IR Gas Analyzer based CEMS". In 1989, the first multi-component infrared analyzer was introduced for both CEMS and process control monitoring. The underlying advantages were as obvious then as they are today. If just a single instrument could measure all of the gases, using just one source lamp, sample cell and detector, then it could replace several analyzers and inherent complexity. Indeed, if one has four gas analyzers, each must have its own sample cell, sources, detectors, electronics, and ancillary equipment. Then, if it could be an infrared photometer, it could greatly reduce the components in contact with flue gas, perhaps to less complexity than any one of the four it replaced.

Figure 1: Comparison in complexity between discrete and multi-component analyzer based CEMS



Summarizing the advantages of an integrated multi-component gas analyzer over a collection of discrete analyzers include:

- Real-time correction for quantifiable interfering compounds using computerized algorithms – this is absolutely necessary for a multi-component IR analyzer where water interference was traditionally a recognized drawback
- Direct measurement of all gases (no converters like those in chemiluminescence NO_x analyzers)
- Elimination of multiple discrete analyzers and replacement by a single integrated "box" leads to reduced maintenance efforts and lower training costs
- Significantly lower purchase costs due to common use of components and reduced parts count

DESCRIPTION OF A HOT-WET MULTI-COMPONENT CEMS

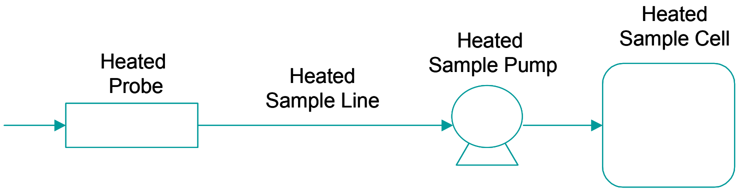
Sampling System

In order for a CEMS to function as desired, it must be configured to deal with the environment and source type it will operate in. Application engineering aspect of CEMS may be one of the most important part and it is in sampling systems where that is most critical. Each system should be custom engineered for the job it is intended for, and a "*template – cookie cutter*" should never be widely used.

The sampling system may be the least understood part of a CEMS. It is often very difficult to extract a sample of gas from the exhaust stream of a combustion source and transport it for analysis without affecting the gases to be measured. There is the problem of particulate deposition, moisture, corrosive acid condensates--and the gases to be measured may themselves be highly reactive, perhaps even with the sample system itself. However, through proper consideration of the source conditions, required measurements and site geography, it is possible to produce very reliable, low maintenance CEMS sampling systems.

The primary key is to keep the system as simple as possible while dealing with four primary concerns: Particulates, Corrosion, Condensates and Reactive Gases. This is accomplished in the Hot-Wet (HW) sampling systems using specially designed components. The HW sampling system maintains high temperature throughout the sampling and analysis process. In the HW system only four parts are in contact with the flue gas.

Figure 2: Typical sampling system used by a Hot-Wet Multi-component CEMS



1. Probe Assembly

The probe assembly provides specific functions needed for reliable sampling of flue gases while closely maintaining temperatures at elevated levels. Those functions are probe-back purge with instrument air, calibration gas injection, and failsafe inert gas protection of the system from corrosion if loss of temperature control should occur.

A probe tube heater for stacks with condensing conditions is often provided. Filtration is provided in two stages using sintered filters. The coarse filter is purged by the use of a one-way valve for high-pressure injection and operation of a special bellows valve for isolation. Instrument air purging of the probe tip coarse filter is accomplished through a fine filter assembly by use of a one-way valve for injection and operation of a special bellows valve for isolation housed outside of the duct. Calibration gas is injected into the probe by a check valve, using the same bellows valve for isolation. The isolation function is of critical importance while calibrating and the probe uses an air-operated bellows valve and seat to provide positive sealing at temperatures as high as 480 °F (~250 °C).

2. Heat Traced Sample Line

The heat traced sample umbilical will maintain the gases at an appropriate temperature all the way from the probe assembly to the analyzer enclosure. Good engineering practice dictates that this must be short as possible but it is of more importance to place the analyzer in a convenient location. Lengths up to 400 feet are possible. The sample umbilical bundle will contain one or more tubes for the sample gas and may contain additional tubes for instrument air and calibration gas. It may also have conductors and control wires for other functions needed at the probe assembly. The materials of the sample tube may be either Teflon or stainless steel depending on the temperature requirement. Normally the measurement of ammonia will require the highest sample line temperatures, at about 450 ºF (~230 °C).

3. Heated Sample Pump

The driving force for sample system flow is a special high capacity heated pump. A key in reactive gas sampling is that it is important to minimize residence time in the sampling system and that means the pump must have high capacity. A three-layered Teflon diaphragm is used. The heated sample pump has been specially designed for this service and has proven to be very reliable.

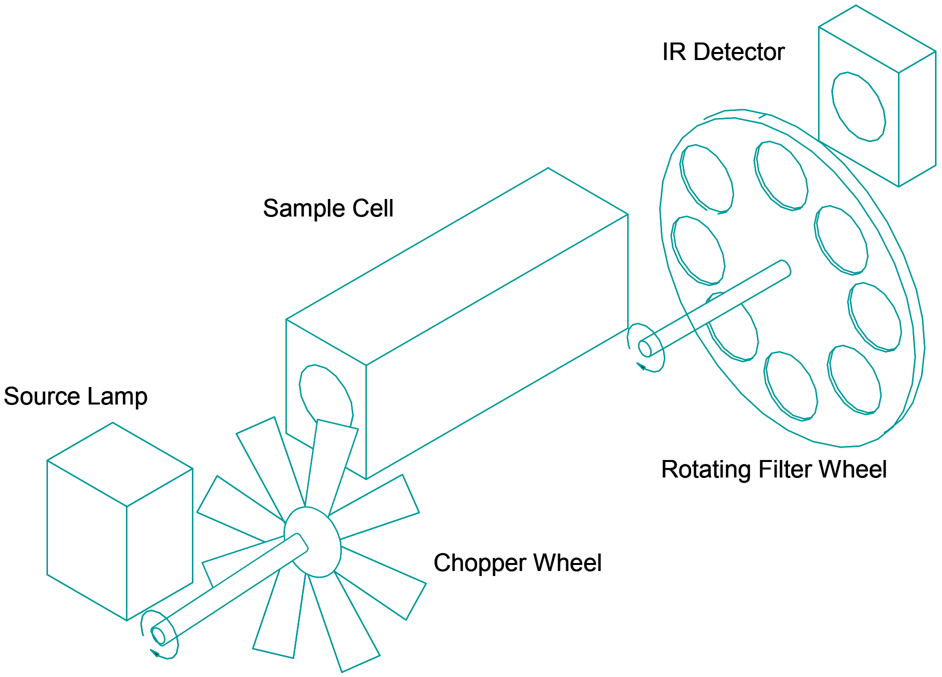
4. Analyzer Sample Cell

The analyzer sample cell may be of straight or folded path construction depending on the gases to be measured and range of analysis. Starting with the second generation Hot-Wet multi-component analyzers, an integral Zirconium Oxide oxygen sensor is also being included. The entire sample cell along with the oxygen sensor is temperature controlled and the sample exhaust is vented to the atmosphere.

Multi-component Infra-Red Gas Analyzer

The infrared optical bench consists primarily of an infrared source with chopper, a sample cell that the infrared light pulses travel through, a motor driven filter disk with different optical filters or gas filled cells in the infrared light beam, and a solid state detector to measure energy of the infrared light pulses [2].

Figure 3: Optical workbench associated with a multi-component IR gas analyzer



In order to understand the operation of the multi-component analyzer, we have summarized some of the important aspects of its functioning:

Analysis Techniques

The multi-component IR gas analyzer can measure different gases using the Gas Filter Correlation (GFC) or the Single Beam Dual Wavelength (SBDW) techniques[1].

GFC is a well-established method to reduce cross sensitivities to gases that cause interference in infrared measurements. In the technique an optical band pass filter is used to select an infrared band and then a cell filled with 100% concentration of the gas of interest is placed in the beam, effectively blocking the spectral lines that the gas absorbs at. It is important to note that variations in optical clarity like dirt on cell windows, source strength, and other causes not related to the spectral lines selected, will have no effect on the ratio of two pulses, making GFC an extremely sensitive and selective analytical technique. Typically CO, NO, NH_3 and HCl are measured using the GFC technique.

In the SBDW technique ultra narrow band optical filters are used to select infrared wavelengths. One wavelength is at a spectral line that the gas of interest absorbs (measuring) at, and the other is one at which it does not (reference). Typically SO_2, NO_2, CO_2, H_2O are measured using the SBDW technique.

Folded Path Sample Cell

Most multi-component IR gas analyzers use a folded path sample cell that is achieved by a specialized mirror configuration. These simple and robust sample cells have allowed IR photometers to routinely have extremely long path lengths (up to 20 meters) yet occupy small volumes. The sample cell path length is fully adjustable for optimization of each application and has reduced volume to save on maintenance and calibration gases.

Construction

The gas analyzer is specifically designed for Continuous Emission Monitoring service and the optical bench, sample cell and control components are all integrated into one convenient, and easily serviced enclosure. In particular, the integrated design allows the photometer source and detector to be housed in the same temperature controlled housing which significantly improves stability. A stepper motor controls the filter disk. The geometry and size of the filters is such that alignment of the filters is not critical. The solid-state detector is located on its own subassembly but in the temperature controlled housing.

System PLC

A Programmable Logic Controller (henceforth referred to as the system PLC) controls the entire CEMS (sampling system and multi-component analyzer). A commonly used industry standard PLC is deployed. The system PLC is flexible, configurable and has to capability to accommodate various configurations. Depending upon the application, separate modules can be added for input/output purposes, temperature controllers, networking or serial communication etc. The system PLC can be re-programmed in the field using a touch-screen display. Using the system PLC the set points (e.g. sampling line temperature) and other crucial parameters (e.g. time values associated with a calibration sequence) can be defined.

Inputs and Outputs

The IR analyzer communicates with the system PLC using a serial link and Modbus communications protocol. The system PLC unit can be connected to the plant's network and standard Ethernet TCP/IP can be used for communications. This is especially useful when a remote data acquisition system is employed. Additional system PLC units can be located anywhere within the plant and the only connection needed to communicate all system analog and digital signals is the plant's existing network. In addition, the analyzer can be controlled via modem, Ethernet or TCP/IP.

EVOLUTION OF THE MULTI-COMPONENT GAS ANALYZER TECHNOLOGY

The current generation of multi-component gas analyzers has arrived at the present state through an evolutionary process. Following is a summary of some important advances that have occurred:

First Generation to Second Generation

A considerable advance made in evolving from the first generation to the second was the incorporation of the oxygen sensor into the chassis of the multi-component analyzer. This eliminated a troublesome interconnection because of the size of both the first generation analyzer and the oven used to maintain the zirconium oxide sensor used to measure oxygen concentration. Unavoidable temperature transitions resulted in flow-path plugging caused by various compounds, typically sulfur-based. The clumsy and expensive method of sample gas flow (heated rotometer) was also improved by going to a "solid-state" dual temperature loss detector. This allowed for further system streamlining and cost reduction. This advance also eliminated discrete oxygen sensor electronics (power supply, linearizer boards, display panels) by utilizing pre-existing components within the second-generation gas analyzer.

A second advance was a more advanced communication capability to upload and backup site-specific configurations (linearity and interference tables, ranges, and sequence of component being measured). Although still limited, the ability to document and remotely store these configuration files were clearly superior to the often-inconsistent serial port on the first generation systems controlled by an 8086-type processor. The second-generation multi-component analyzers were upgraded to an 80386-equivalent processor.

Finally, the second generation incorporated markedly improved accuracy over the first generation with improved IR source and detector. Additionally, the overall size was reduced as a result of improvement in optics/sample cell folded path design.

Second Generation to Third Generation

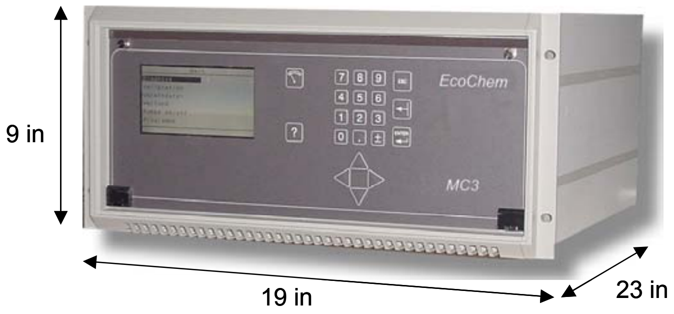
With the benefit of hundreds of installations in many industries, some for over 5 years, the advances and enhancements built into the third generation analyzer focused on accuracy and sensitivity. The accelerating electronics evolution of the 90's throughout the industry also allowed many enhancements (for example, configuration files in Excel spreadsheet format, Pentium equivalent computing processing, standardized Modbus communication protocol, non-proprietary PLC components).

To improve signal to noise ratios, vibration and power isolation had to be improved. The internal cell design became more compact and the next level of vibration and electronic noise isolation was addressed to the point where the demonstrated sensitivity and accuracy further extended its market penetration. Certifiable single digit NO_x and SO_2 concentrations became a reality. Applications on sources such as gas turbines, previously thought to be beyond the capability reach of this technology, were now successful.

Beginning late 2001 the first third generation multi-component infrared analyzer systems were installed. This system featured the following advantages over the first and second-generation multi-component analyzers:

- Sensitivity and low range accuracy were doubled resulting in a more accurate and flexible analyzer
- Sample cell volume reduction resulting in a more compact analyzer
- Parts count was again reduced significantly – this was partially achieved by better "compartmentalization" of the functionalities and separating the system controller from the main analyzer
- Remote diagnostics and better user-interface
- Reduced manufacturing costs resulting in significantly lower purchase price and commercial cost-effectiveness

Figure 4: Typical dimensions of a third generation multi-component IR gas analyzer



Often written off as an overused term, *"user-friendliness"*, also became an area that was seen as a wise investment in further development. On this front, the use of a larger (3 in. x 5 in. screen) color touch pad was a significant refinement to operator interface. A larger screen with color contrast means improved presentation of data, strip chart graphing, system status, calibration, external operating parameters, and configuration settings. This replaced the limited ability to present data on a black and white display. Touch screen menu-driven displays allow for easier and more effective interface. Up to eight levels of password protection was incorporated to ensure security of configuration variables. Having the analyzer and touch pads as network nodes with unique IP addresses brought new meaning to operator interface.

Remote functional control is also a significant advance in the realm of CEMS availability. Remote troubleshooting by experienced technicians and engineers was often painfully slow and had to resort to a sequential iterative process of *"try this and call me back if it still doesn't work"*. The ability to "dial-in" and experience a live calibration with live access to status parameters, analyzer raw signals (absorbance), sample system conditions (flow and temperatures) as well as near term and long term historical trend data has proven to be extremely effective.

At this point, it should be mentioned that even after installing Hot-Wet multi-component CEMS for three generations, there are lessons left to learn. During the installation of the new third generation CEMS we encountered issues related to inlet filters, oxygen sensor temperature setting, sample flowrate measurement and communication issues with third-party Data Acquisition Systems (DAS). These issues have been addressed, lessons have been learned and it is expected that future installations will be even smoother.

INSTALLATIONS

Over the past two decades, Hot-Wet multi-component CEMS have been successfully implemented at facilities ranging from coal-fired utility boilers, gas turbines, cement kilns, waste-to-energy facilities and process monitors.

Table 1. Installations of Hot-Wet Multi-component CEMS

Technology	Time Frame	Installations
First Generation (model MCS 100)	1989-1997	Utilities (Coal, Diesel, Gas/Oil) 119, Cement Industry 64, Glass Manufacture 8, Process Monitoring 6, Waste-to-Energy 119 and other Industrial 74 installations.
Second Generation (model MCS 100e)	1998-2001	Utilities 5, Cement Industry 1, Waste-to-Energy 32 and other Industrial 1 installation.
Third Generation (model MC3)	Late 2001 - 2003	Utilities 5, Cement-Lime Industry 2, Process Monitoring 1, Waste-to-Energy 21 installations

RECENT FIELD PERFORMANCE RESULTS

The Relative Accuracy Test Audit (RATA) and system availability/downtime are two important criteria that can be used to determine the performance of Continuous Emissions Monitoring Systems (CEMS). The RATA results determine not only whether a plant's CEMS is in compliance, but also how often a RATA test series must be performed.

It is important to elaborate on the cost implications associated with CEMS availability and RATA results. Minimal downtime automatically translates into elimination of expenses associated with skilled technical labor and replacement part cost. In addition, during prolonged CEMS downtime there is the possibility of excess emissions that could go unrecorded exposing the plant to regulatory scrutiny and data substitution penalties.

Thus, customers wish to buy a CEMS that has a proven track record of high data availability and minimal downtime. Consider the cost implications associated with the frequency of conducting RATA tests. Under EPA rule 40CFR75, a CEMS must show a relative accuracy of no more than 10%. This must be demonstrated twice yearly unless the accuracy is less than 7.5% in which case the test must be performed only annually. At a cost of approximately $10,000 per RATA, the difference between 7.4% and 7.5% relative accuracy is crucial. A CEMS that consistently delivers accurate measurements automatically results in cost savings for the RATA, as well as plant personnel time and resources needed to prepare for and manage the testing. For a CEMS designed to run for 10 years (and more) the savings can easily exceed $100,000 if an accurate CEMS is installed. Perhaps more importantly, a CEMS that delivers excellent RATA results simultaneously reduces the plant's potential exposure to regulatory noncompliance.

In the first case we discuss the Relative Accuracy Test Audit (RATA) results performed for four third generation Hot-Wet CEMS at a Waste-to-Energy (WTE) facility in Pennsylvania, USA. The CEMS at this facility are located at the inlet and outlet of the pollution control devices (Spray Dryer Absorber and Fabric Filter) for two units. The demonstrated relative accuracies of the certified CEMS at this installation are within the allowable regulatory requirements[3].

Table 2: RATA Results for a Waste-to-Energy Facility (Unit operating Two Third Generation CEMS)

Location	Gas	Reference Monitor Mean	CEMS Mean	Mean Difference (MD)	**Relative Accuracy**	**Relative Accuracy Criteria**
INLET #1						
Spray Dryer Absorber Inlet	SO_2 (ppm)	210.3	209.1	1.2	4.5%	20%
Spray Dryer Absorber Inlet	O_2 (%)	8.7	8.9	0.2	6.9%	20%
Spray Dryer Absorber Inlet	CO_2 (%)	10.4	10.3	0.1	2.3%	20%
Spray Dryer Absorber Inlet	CO (ppm)	18.5	14.8	3.7	NA	5 ppm MD*
OUTLET #1						
Fabric Filter Outlet	O_2 (%)	9.7	9.8	0.1	2.4%	20%
Fabric Filter Outlet	NO_x (ppm)	143.3	153.1	9.8	8.5%	20%
Fabric Filter Outlet	CO (ppm)	18.5	14	4.5	NA	5 ppm MD*
Fabric Filter Outlet	SO_2 (ppm)	20.9	16.7	4.2	NA	10% Standard or 5.8 ppm MD*
Fabric Filter Outlet	HCl (ppm)	21.0	20.5	0.5	NA	5 ppm MD*
	SO_2 Removal Efficiency (%)	90.7	92.2	1.5	NA	2% MD*

*MD – Mean Difference

In the second case study we discuss a third-generation Hot-Wet multi-component CEMS installed in Rhode Island, USA. Since 2001, these CEMS have monitored gas-fired turbine emissions and have performed very successfully. Each installation has provided measurement challenges ranging from low NO_X measurements, load swings and ammonia being present in the flue gas stream. For this installation, RATA results are presented for two plant units. As for the first case study, the demonstrated relative accuracies of the CEMS here are within the allowable regulatory requirements.

Table 3: Results of RATA Series #1 at a Gas-Fired Turbine

Unit #	Gas	Emission Standard	Reference Method Mean	CEMS Mean	Relative Accuracy	Relative Accuracy Criteria
3	O_2	--	14.4 %	14.42 %	0.39 %	20 %
3	NO_x	9 PPM	7.92 PPM	7.74 PPM	4.92 %	20 %
3	CO	25 PPM	1.01 PPM	1.03 PPM	1.71 %	5 %
3	NH_3	30 PPM	5.32 PPM	5.03 PPM	1.4 % std	10 % std
4	O_2	--	14.49 %	14.490 %	0.38 %	20 %
4	NO_x	9 PPM	8.55 PPM	8.42 PPM	5.8 %	20 %
4	CO	25 PPM	1.330 PPM	1.58 PPM	1.69 % std	5 % std
4	NH_3	30 PPM	2.49 PPM	5.08 PPM	9.75 % std	10 % std

Note: O_2 concentrations are % Dry; NO_x, CO and NH_3 are PPMVD @ 15% O_2

CONCLUSIONS

In this paper we have focused on CEMS based on Hot-Wet Multi-component IR gas analyzer technology. These versatile and robust CEMS have provided high-availability and accurate data over the past two decades in a wide variety of sources ranging from utility boilers to hazardous waste incinerators. Cost-effective and low maintenance performance has been achieved for these CEMS by judiciously selecting components and optimizing operating variables specific to the application challenges. The present generation of hot-wet multi-component CEMS has evolved over time and now has the necessary accuracy to meet single-digit NO_x and SO_2 requirements.

On a parting note, the requirements of a CEMS in general, with the perpetuation of credit-based emissions, have increasingly expanded into accounting and legal domains. For this reason as much as any, the access to CEMS data, not just hourly averages, but right down to the analyzer platform from remote workstations is key to the success of a CEMS going forward. The CEMS team no longer consists of a shift Instrument technician and an Environmental engineer submitting annual reports. In many cases, the necessary CEMS team has expanded to include the corporate environmental director, the operations manager, the CEMS vendor technical support engineer, the plant's environmental consultant and the IT (information technology) manager. The loss of emissions data can now mean loss of **revenue** derived by the sale of emissions credits. It is this perspective that has pushed CEMS to advance in this decade and will continue to push the CEMS evolution even further.

ACKNOWLEDGEMENT

The authors acknowledge the guidance provided by Dr. Wolfgang Berkhahn and David Dillehay who pioneered the development and commercialization of the Hot-Wet Multi-component IR CEMS technology discussed in this paper.

REFERENCES

1. Jahnke, J.A., 2000, Continuous Emission Monitoring, John Wiley & Sons, New York, NY.

2. Dillehay, D., 1990, Computerized Control and Signal Processing for Infrared Analyzers, In Proceedings – Specialty Conference on Continuous Emission Monitoring – Present and Future Applications, pp. 215-226, Pittsburgh: Air and Waste Management Association.

3. Continuous Source Monitoring Manual, 2003, Rev. 7, Dept. of Environmental Protection, ttp://www.dep.state.pa.us/dep/deputate /airwaste/aq/cemspage/ cemshome.htm.