Design guidelines for continuous emissions monitors and predictive emissions monitors

H. PIERCE RUMPH AND JOHN B. RUDD

ABSTRACT

Continuous emissions monitoring systems traditionally consist of multiple component subsystems installed in hostile environments to measure and deliver timely information for demonstration of environmental compliance. Recent emphasis has concentrated on a predictive emissions monitoring system as an alternative. This system uses a model and has no direct contact with the hostile stack environments. Implementing sensor validation systems as required by the Environmental Protection Agency greatly reduces the maintenance requirement of the systems. Experience gained in recent years has lead to improved design guidelines for continuous emissions monitoring systems and predictive emissions monitoring systems.

Application: *Predective emissions monitoring systems are more reliable and less expensive than continuous emissions monitoring systems. They are an excellent choice for sophisticated mills seeking advanced emissions control.*

WITH THE PASSAGE OF THE 1990 Clean Air Act Amendments (CAAA), industry has had to meet the high cost of compliance. CAAA requires continuous emissions monitoring systems (CEMS) or predictive emissions monitoring systems (PEMS) to provide accurate and reliable measurements of sulfur dioxides (SO2), nitrogen oxides (NOx), carbon monoxide (CO), and opacity. In recent years, total reduced sulfur (TRS) monitoring has also been a requirement for the pulp and paper industry. The regulations require using CEMS or PEMS to ensure compliance with emission standards and mandated emission reductions.

The traditional approach to monitoring emissions is a hardware system that samples gases from the stack and delivers them to a remote conditioning unit for analysis. The initial capital cost of installing hardware for CEMS is very high. For a new installation, the installed cost can easily reach US$150–300K. The U.S. Environmen-tal Protection Agency (EPA) requires 95% uptime for CEMS. The agency has established strict regulatory standards requiring estimating and reporting of substitute data during periods when CEMS is unavailable. Because of the severe penalties of noncompliance, some companies have installed redundant CEMS at an even higher cost. Besides the high capital cost, the maintenance cost of CEMS operations is also considerable. The instruments are delicate and require frequent recalibration. Additional full-time employees are often necessary to keep CEMS operating at a facility within mandated relative accuracy limits *(1)*.

With the implementation of CAAA, industry immediately began searching for better and more cost effective approaches to compliance. This included demands for the CEMS vendors to develop more robust, reliable CEMS and the consideration of alternatives to predict the emissions based upon source operations.

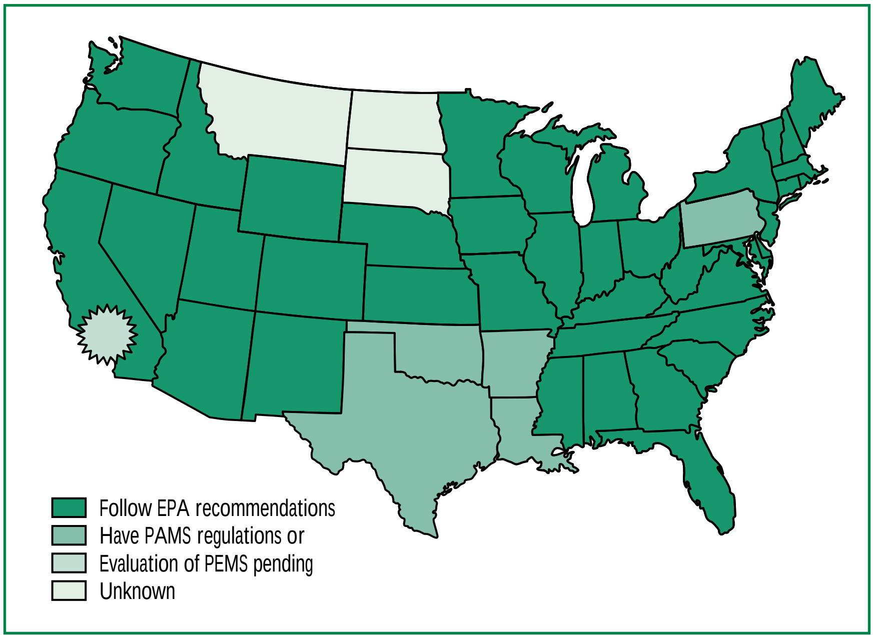
The goals of CEMS and PEMS are the following:

- Reliable and accurate measurement
- Compliant environmental reporting
- Integration into existing mill infrastructure
- Availability of continuing support
- Cost effective.

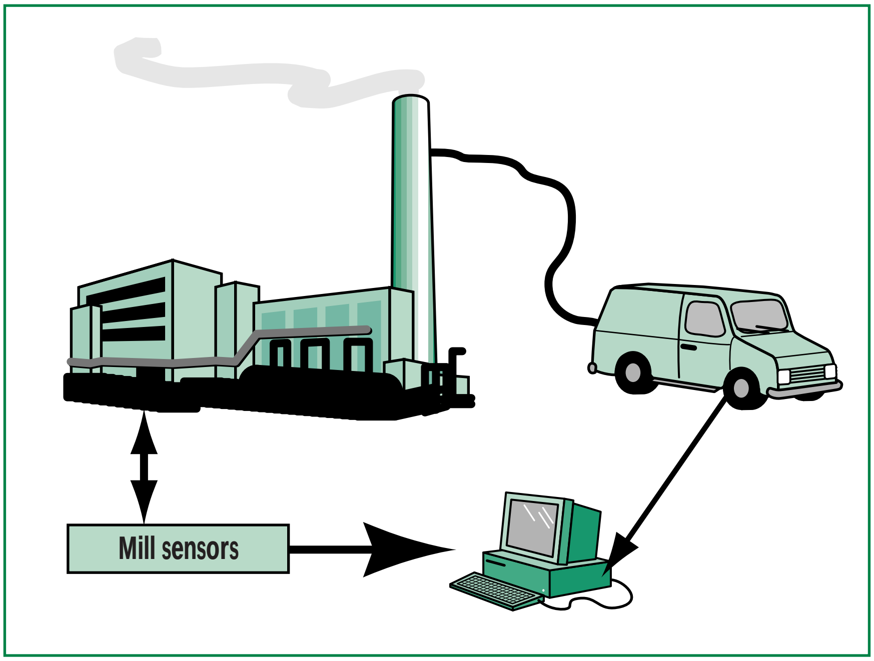
CEMS

The operation of conventional emission monitoring systems involves conditioning a gas sample and then physically analyzing that sample in various ways to determine the desired characteristics. The methods of analysis include ultraviolet, infrared, and chemiluminescent photometric measurement and electrolyte gas analysis. Properties such as TRS require a combination of methods. Conditioning the gas samples and the routine calibrations needed cause the consumable components of the system to require frequent maintenance.

What makes an emission monitoring system continuous is an automated sampling system that periodically extracts a representative gas sample from the stack and delivers it to the emission monitoring system usually installed in a protected environment. Sampling probe designs, system maintenance frequency, sampling cycle time, and system enclosure ratings are criteria that require evaluation for successful implementation. Newer CEMS claim to have a maintenance interval of six months. They have a very rugged package of conditioning and analyzing equipment that allows installation on the stack. This reduces the sample tube runs and minimizes the signal dead time caused by sample transport.



1. State acceptance of PEMS



2. PEMS data collection

PEMS

EPA defines PEMS as "a system that uses process and other parameters as inputs to a computer program or other data reduction system to produce values in terms of the applicable emission limitation or standard *(2)*." The EPA Compliance Assurance Monitoring (CAM) Rule preamble allows predictive emissions monitoring as follows: "The EPA believes that these types of monitoring are preferable from a technical and policy perspective as a means of assuring compliance with applicable requirements because they can provide data directly in terms of the applicable emission limitation or standard *(3)*." Acid rain rules in 40 CFR 75 state the following: ". . . certified predictive emissions monitoring systems would be allowed for peaking units (low-capacity usage) and as an alternative in lieu of hardware CEMS for other units under Subpart E. Subpart E provides certification procedures for alternative systems, which must demonstrate the same or better precision, reliability, accessibility, and timeliness as hardware CEMS *(4)*."

After the passage of CAAA, affected facilities sought alternatives to the expensive installation of hardware *(1, 5–7)*. The first PEMS certified as a sole monitoring device was on a gas fired boiler at the Arkansas Eastman Chemical plant in Batesville, AK. This PEMS was a neural network-based system certified June 9, 1993. Since then, the installation of more than 80 PEMS has demonstrated financial savings *(8)*.

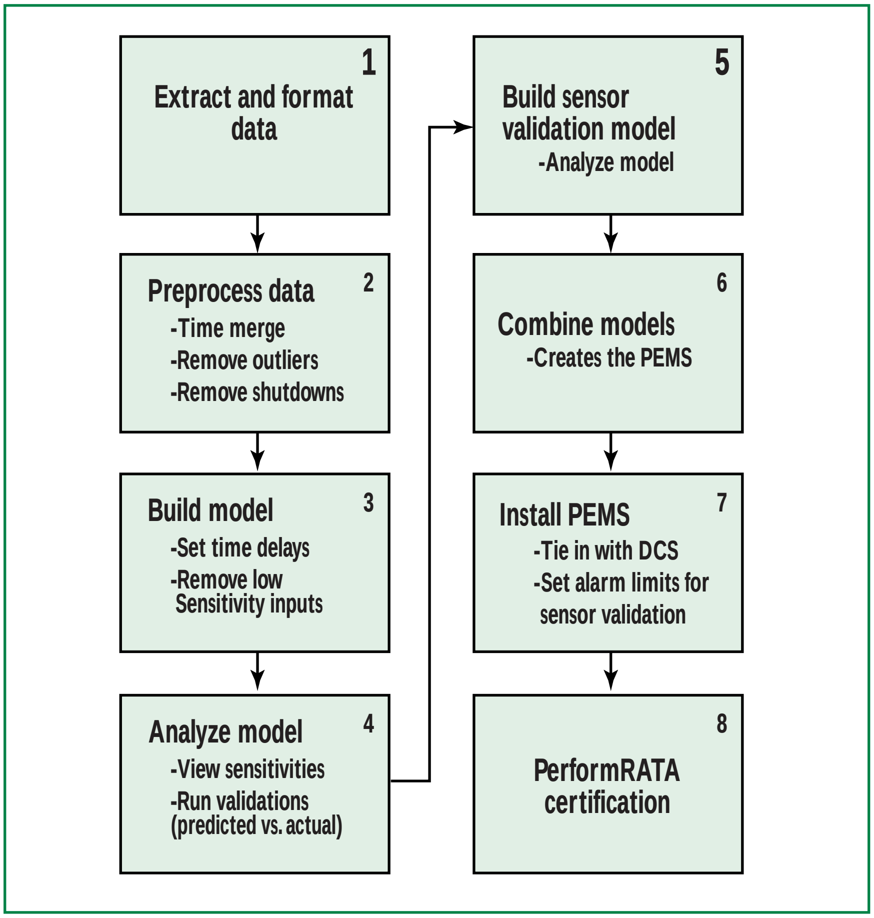
On January 25, 1996, the EPA Emission Measurement Center published five PEMS protocols and a Performance Specification on the CEMS Section of the Emission Measurement Technical Information Center Bulletin Board. The publication of these documents used information submitted by Exxon, Dow Chemical, Houston Light & Power, Arkansas Eastman Chemical, and Pavilion Technologies from five different types of installations. (To obtain an electronic version of the protocols and performance specification, access via modem the EPA Technology Transfer Network Bulletin Board System at (919) 541-5742, select the EMTIC BBS, and then select the CEMS section to download the files.)

The EPA regulations define the requirements for acceptance. Each state must interpret and administer the acceptance of PEMS. The map in Fig. 1 shows the current level of acceptance for each state.

BUILDING THE PEMS SYSTEM

PEMS use an empirical model of the combustion source to predict the level of emissions considering actual operating conditions. The key to building any type of empirical model is the collection of historical data not only from the process but also from actual emissions collected from portable CEMS.

Figure 2 shows the typical arrangement to collect the data required for this effort. Figure 3 shows that the following steps are necessary for building the PEMS:



3. Summary of the steps necessary to build and install a PEMS

1. Simultaneously gather and extract data from the process control system, data historian, or both for combination with the emissions data from the portable CEMS.
2. Process the data to ensure the accuracy of the final model. The data usually requires time merging and screening for outliers, shutdowns, and other events that can corrupt the data. Time merging is necessary to synchronize data sampled and recorded at different frequencies from the process data. Outliers or erroneous data values require removal from the date set so the model does not learn erroneous results. Plant shutdowns also require removal because the values of the process variables during shutdowns are spurious. Remove other bad data from the data set also. To do this properly, an engineer should examine all the data to avoid overlooking anything.
3. After cleaning and time merging the data, build the model. Since processes have dead times and rise times, the input-output relationship is not instantaneous. Determining the proper time delays is extremely important. Determining the important variables uses sensitivities.
4. After training the model, analyze it for behavior and validate it against an independent data set. Then examine the model for low-sensitivity inputs and make it as self-contained and evenly distributed as possible.
5. Using the same procedures as in steps 3 and 4 above, build a sensor validation model.
6. Combine the emissions model and sensor validation model to build the final PEMS.
7. Install the PEMS in the mill and activate it.
8. After verifying the PEMS in actual operation, schedule a relative accuracy test audit (RATA) to certify and permit the PEMS.

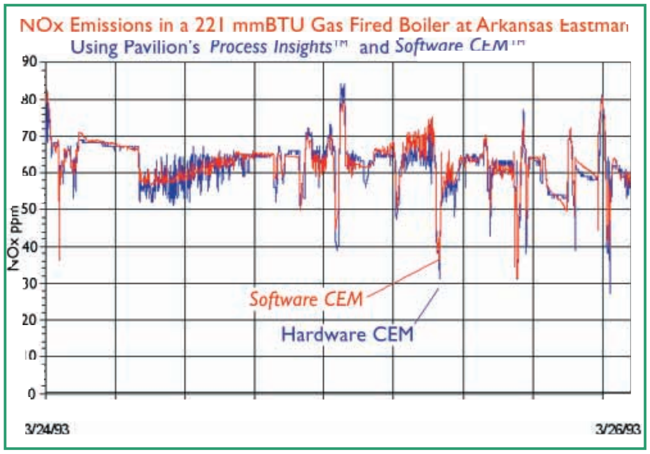
Figure 4 shows an example of the predicted (gray) vs. actual (black) results on the first PEMS system certified in 1993.

REQUIRED SENSOR VALIDATION

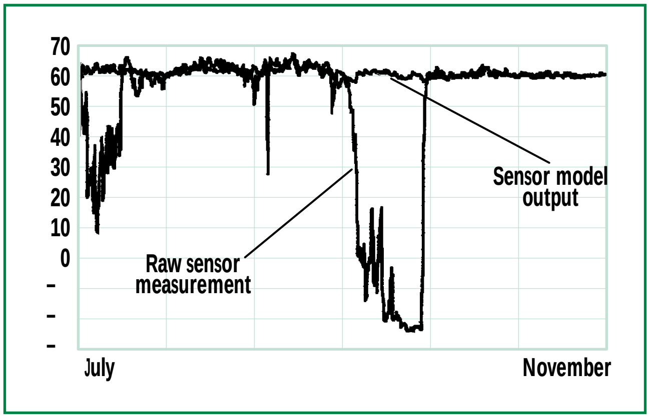
Periodic calibration of CEMS shows the accuracy of measurements. The calibration involves introducing known gas samples stored in cylinders into the CEM gas sampling unit and comparing the measured results with a known standard.

To ensure that the PEMS operates properly, EPA requires installing a reliable system to ensure that the underlying sensors used as inputs to the PEMS are functioning properly. This is a sensor validation system. To accomplish this, the system checks the values of every input against redundant peer information. If any sensor differs from its peer-based model, the sensor validation system emits an alarm and reconciles the raw sensor value.

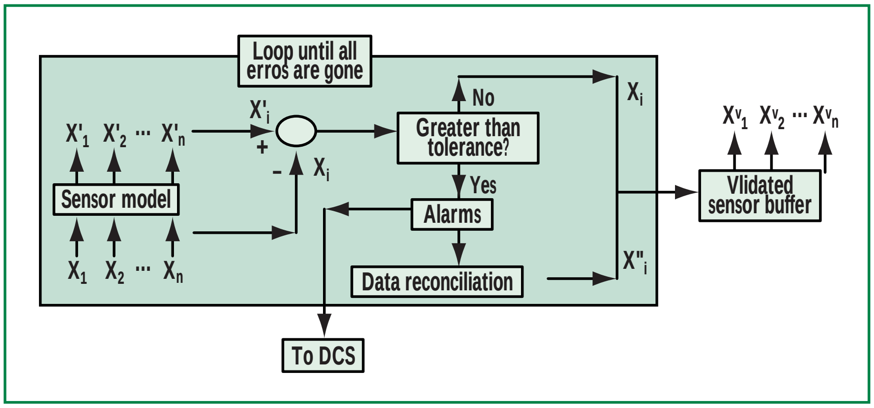
Although sensor validation sounds complicated, it uses the solid principles common to any sensor calibration. It checks one sensor measurement against an independent measurement and then adjusts or replaces it if the signal being



4. *PEMS example*



6. *Sensor model output and raw measurement for temperature transducer*



5. *Sensor validation*

calibrated is incorrect. The sensor validation system compares each sensor with several values of peer information. This is the method for calculating the best value for each sensor using the independent peer information contained within the measurements of other sensors that constitute the PEMS. The comparison of the measured value to the one calculated from the peer information determines whether the sensor is operating correctly. Figure 5 shows the architecture of a sensor validation system. This system takes raw sensor measurements and uses them in a sensor model that calculates the expected value of each sensor based upon peer information. It compares the sensor model outputs with the original measurements for each sensor. If the difference is above a defined threshold, an error alarm occurs. In addition, it substitutes any alarmed measurement with a corrected value to give a validated set of sensor readings.

Figures 6–8 present an example for a PEMS predicting NOx on a 16-cylinder Cooper-Bessimer engine. In this case, a temperature input failed over a certain period. The transducer had a gross failure early in July and intermittent failures throughout the summer. It finally failed catastrophically in September with subsequent replacement.

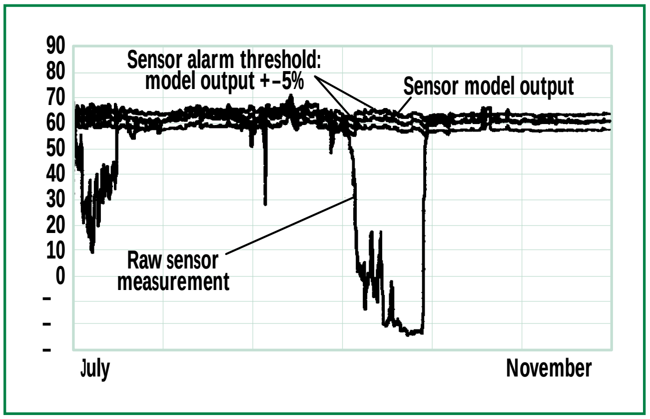
Figure 6 shows the sensor model output and the raw measurement for the temperature transducer. Notice that the sensor validations model uses peer information. Its output calculations remain stable during all phases of gross and catastrophic failure. During normal operation, the calculated sensor model output is also very accurate—within ± 2%. This sensor model output is therefore a very robust redundant sensor—like an extra transducer used as backup.

Figure 7 shows the error detection thresholds set at ± 5%. Any time that the two values differ by more than this threshold value, one value must be wrong. Since the model output is a robust calculation based on several other sensors, the transducer signal is probably wrong. At this point, a high confidence level can substitute for the sensor model output for the failed transducer.

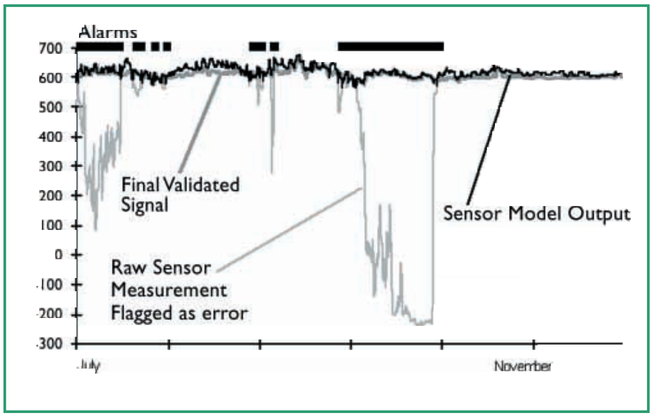
Figure 8 shows this process. Any time that the measured sensor reading is outside the ± 5% band around the sensor model output, an alarm occurs and the sensor model output is substituted as a backup sensor for the original transducer reading. The final validated values for this example are the wide gray line. The light gray line shows the original transducer measurements determined to be erroneous and substituted with the sensor model output (black line).

REPORTING CHALLENGES

Whenever implementing continuous emission monitor (CEM), predictive emission monitor (PEM), or both technologies, existing control systems do not typically achieve the reporting requirements. CEMS have dedicated microcomputers that create reports requiring manual gathering and amending. Due to the lack of networking, the increasing number of CEM points, and micro computer



7. Error detection thresholds



8. Substituting a high confidence level

maintenance requirements, data capture has become the biggest challenge to shrinking environmental staffs.

Systems for centralized data monitoring, analysis, predictive alarming, and automated reporting are now commercially available. They are typically not part of CEMS or PEMS solutions. Determining the use of the emissions measurements and their integration into mill operations are important to ensure that the investment achieves its goals *(10)*.

BENEFITS OF PEMS

Installing PEMS offers many benefits:

- Because the PEMS is a model and is never in direct contact with the process, no failures occur from contact with harsh environments.
- Installation cost is less. In some cases of using PEMS instead of CEMS, the difference has resulted in 50%–60% savings in capital installation cost *(7, 9)*.
- Reduced maintenance is a definite advantage. CEMS are delicate instruments that require regular maintenance. They also drift and require daily calibration. A refinery enjoys US$ 10,000–30,000 savings per analyzer per year *(9)*. This is consistent with a mill that stated that their cost of maintaining hardware CEMS is approximately $62,000 per source (boiler, recovery, kiln, bark boiler, etc.) per year. The maintenance of the PEMS is typically an annual software maintenance fee plus a maximum of quarterly testing to determine if the model needs tuning.
- The final benefit is that some PEMS systems not only report the level of emissions as required by the EPA guidelines but also provide the potential to perform actual control. The sensor validation required with PEMS offers alarming of failing sensors for use in other aspects of equipment control that can benefit from this feature.

Figure 9 demonstrates a boiler example in which PEMS monitored NOx and CO not only to predict but also to control the boiler to ensure that operations were in the ideal environmental operating zone as much as possible. This gave improved operational efficiency.

DESIGN GUIDELINES

This paper presents basic information showing some efforts and aspects involved in successful emissions monitoring solutions. The following guidelines are important for CEMS:

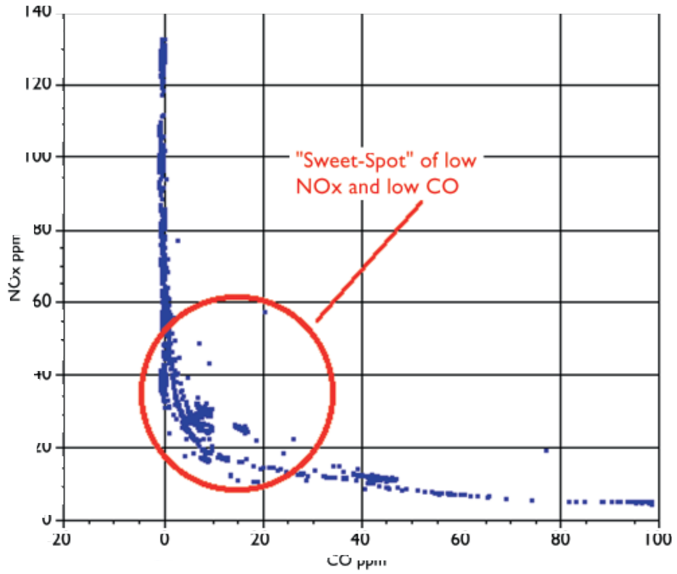
- Keep gas sample transport tubing length to a minimum.
- Know the maintenance and calibration requirements before selecting a measurement technology.
- Know the consumable replacement frequency requirements before selecting a measurement technology.
- Do not install CEM conditioning or analyzing racks in the same room with other electronic equipment due to possible escape of corrosive gases.
- Provide adequate access to system components for maintenance personnel.
- Include a user maintainable sequence controller such as a programmable logic controller (PLC).

Some important guidelines for PEMS are the following:

- Configure the PEM output(s) to the same frequency as the data set used for training the model.
- Specify the computer used for the PEM as a high uptime system.
- Obtain written consensus or agreement from the appropriate state regulatory agency for PEM use on a particular application before installation.
- Know the calibration requirements and maintenance requirements including software license and maintenance fees before selecting a modeling technology.

Some data topic guidelines are as follows:

- A system data store and forward capability is desirable.



9. PEMS example for a boiler

- The system should provide mill data network connection(s) such as "Ethernet."

KEYWORDS

Air pollution, automatic systems, carbon monoxide, costs, emission standards, emission, measurement, models, monitoring, nitrogen oxides, opacity, optical properties, sulfur dioxide, total reduced sulfur.

- The emission monitor should provide raw data not just "corrected" values.
- Monitoring and alarming for system consumables is desirable.
- Remote time synchronization is desirable.
- The data available for reading and writing and the communications protocol provided with the system is important information.

CONCLUSIONS

Having a choice for emissions monitoring is desirable. CEMS are a good technique to add another sensor to meet a specific need with or without integration with other mill systems. It is a good choice when simplicity is the driving motivation for technology selection.

PEMS systems can often offer an alternative to hardware CEMS. They have a high level of reliability, typically lower installation costs, and lower operating costs. PEMS are a good choice where a mill has some sophistication and is seeking a solution that offers the opportunity to control emissions pro actively. **TJ**

Rumph is consulting engineer at Orion CEM Inc., Suite 200, 2920 Brandywine Rd., Atlanta, GA 30341, and Rudd is pulp and paper industry manager at Pavilion Technologies Inc., Suite 700, Metric Blvd., Austin, TX 78758.

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