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CERTIFICATION OF A STATISTICAL HYBRID PREDICTIVE EMISSION MONITORING SYSTEM IN THE U.S.A. AND DEVELOPMENT OF A SMALL GAS TURBINE CLASS MODEL

Andrea Zheng*, Jessica Palmer*, Brian Swanson*†,

CMC Solutions, L.L.C.
23550 Haggerty Rd, Farmington Hills, MI 48335 (†bswanson@cmcsolutions.org)

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ABSTRACT

The Standards of Performance for New Stationary Sources (40 CFR Part 60) mandates continuous monitoring of nitrogen oxides (NO_X) emission rate from gas turbines of nominal size. Following promulgation of Performance Standard 16 (40 CFR Part 60 Appendix B), a predictive emission monitoring system (PEMS) may be utilized as an alternative to continuous emission monitoring systems (CEMS) in the United States. PEMS may be used for determination of NO_x compliance on an ongoing basis, providing the installed PEMS meets the federal performance specification criteria and the site performs ongoing quality assurance tasks such as periodic audits with portable analyzers and annual relative accuracy testing. This paper describes the PEMS certification process for a turbine/heat recovery steam generator (HRSG) certified under 40 CFR Part 60 in the state of Ohio. Certification requires a minimum of twenty seven 21-minute test runs at three loads and statistical analysis of the reference method and PEMS data to assess the accuracy and performance of a newly-installed PEMS. This paper documents the methods and results of the PEMS certification, the requirements of the ongoing quality assurance program for the PEMS and the potential implementation of the statistical hybrid model for similar units - a unit type or class model.

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1 INTRODUCTION

The following describes the process to develop, install and certify a statistical hybrid predictive emission monitoring system (PEMS) as an alternative nitrogen oxide (NO_x) compliance monitoring system for a combined turbine/heat recovery steam generator (HRSG) in the United States. The turbine/HRSG combined unit described in this paper was installed and started up in 2015 at a facility located in the central Midwest under the jurisdiction of Ohio EPA. The unit is a natural gas fired 8 MW Turbine with a maximum heat input capacity of 83.3 mmBTU/hour (87.9 GJ/hour) and a natural gas fired HRSG rated at 130 mmBTU/hour (137 GJ/hour). Data from the plant control system was collected and correlated with emission data obtained from a temporary continuous emission monitoring system (CEMS). The process and emission data was collected at normal operating conditions including startup and shutdown. During this time, the unit was operated through the full load range, firing fuel natural gas. This data was used to train the PEMS to predict the NOx emission rate based on turbine/HRSG operating data.

To comply with federal regulations, this unit was certified under the Standards of Performance for New Stationary Sources (40 CFR Part 60) [1], which mandate continuous monitoring of NO_x emission from large gas turbines. The gas turbine is specifically subject to 40 CFR 60, Subpart YYYY and Subpart KKKK. In addition, Ohio EPA mandates additional requirements for continuous monitoring under the Ohio Administrative Code [2]. An Ohio Environmental Protection Agency (EPA) Air Pollution Permit-to-Install (PTI) was issued for the unit in question in 2014 [2]. This document provides guidelines for monitoring and quality assurance, allowed NO_x emission rates, as well as detailing operating and reporting standards.

PEMS have been used in the U.S. for gas turbine compliance monitoring under 40 CFR Part 60 for more than 20 years [3], and have in recent years been used in Canada and elsewhere overseas. CMC Solutions, L.L.C. has certified PEMS to predict NO_x for several gas turbines in a large power plant in an eastern Canadian province, and PEMS models were developed by an energy company for gas turbines in a western Canadian province. Both 40 CFR Part 60 and 40 CFR Part 75 allow for the use of predictive approaches as an alternative to CEMS, providing the installed PEMS meets rigorous performance specification criteria and the site performs ongoing quality assurance tasks such as quarterly audits and adherence to a quality assurance plan [4] [5]. The certified PEMS installed on this unit is a statistical hybrid SmartCEMS®-60 analyzer provided by CMC Solutions, L.L.C.

Nomenclature

40 CFR, Part 60 – U.S. New Source Performance Standards for industrial and commercial sources published under the Code of Federal Regulation of the United States.

CEMS – Continuous Emission Monitoring System or a gas analyzer based system (with analog output proportional to the emission rate) and sample handling equipment, calibration controls, and separate data acquisition components.

Class Model – a PEMS model that is developed from one or more units of like kind and then applied to other units of like kind with similar input parameters available. Class models are typically deployed and certified for each individual unit.

HRSG – heat recovery steam generator – a boiler with or without duct firing that is coupled to a gas turbine to provide for combined cycled operation.

PEMS – Predictive Emission Monitoring System or a software based solution that generates predicted emission data from turbine operating data and sensors available to the turbine control system that is not a parametric approach.

PS-16 – Performance Specification 16 for predictive emission monitoring systems used in compliance with 40 CFR Part 60 New Source Performance Standards.

Statistical Hybrid PEMS – an empirical predictive emission monitoring system that utilizes historical data (paired process and emission data) to generate accurate predictions of the emission rate from gas turbines and boiler applications.

2 UNIT DESCRIPTION

The gas turbine unit is a natural gas fired 8 MW Solar Taurus 70 turbine with a maximum heat input capacity of 83.3 mmBTU/hour (87.9 GJ/hour) combined with a natural gas fired HRSG rated at 130 mmBTU/hour (137 GJ/hour). See Figure 1 for a picture of the gas turbine and its specifications [6] provided by the original equipment manufacturer (OEM). The unit includes duct burners and a selective catalytic reduction (SCR) utilizing aqueous ammonia injection for NO_x control.

TAURUS 70 PG - GENERATOR SET

ISO Performance/Specifications

Power	7965	kWe
Heat Rate	10 505	kJ/kW-hr
Exhaust Flow	96 775	kg/hr
Exhaust Temperature	505	°C
Steam Production	16.5 - 72.3	tonnes/hr
Axial Exhaust	Yes	
SoLoNOx	Yes	

Figure 1: Gas Turbine Specifications

3 MODEL DEVELOPMENT

A statistical hybrid PEMS model was developed to predict unit emission rate for the turbine/HRSG unit. See Figure 2 for diagram of the turbine/HRSG [7]. This model type is an empirical predictive statistical hybrid system that requires only a fixed sample of paired turbine/HRSG and emission historical training data to generate predictions. The model installed produces predictions with equivalent accuracy as a typical CEM system with minimal maintenance required.

The first step in model development is the collection of emission and process data during normal operational conditions across the full load range. Data collection was performed by a certified testing company from February 2, 2015 to February 4, 2015. The data was collected at all anticipated normal operating conditions, including startup and shutdown. During this time, the unit was operated at full load, minimal load, and other intermediate load points while firing fuel natural gas. After this training period, the data was quality assured and placed into a database table for use as the system's historical training dataset, the basis of the empirical model.

The deployed PEMS system utilizes this training dataset to generate predicted NO_x and oxygen (O_2) concentration in the stack. Although, minor adjustments and tuning may be conducted to account for unit performance degradation, the model is primarily dependent on the data collected during the training period. A model envelope that defines the operating conditions represented in the historical training dataset was developed. Data can be collected at any time and used to retrain the current model onsite in response to installation of pollution control equipment, variations in control or design, or if the operating conditions are changed.

The system predicts the pollutant NO_x and diluent O_2 in real-time utilizing the training dataset. If a particular input parameter is missing, the model utilizes the other available parameters to generate the prediction. This is the hybrid aspect of the model. Only inputs that are available, valid, and fall within the model envelope are used. Alarms detect when the turbine is operated outside the model envelope, indicating the PEMS data is potentially not validated for the current period. As all normal operating conditions including startups, shutdowns, and transitional states were included within the training dataset, these conditions should be rare and will not impact overall data availability of the compliance monitoring solution. The PEMS predicted values presented in this report were generated during normal operation and recorded as they were generated using the PEMS model deployed on February 4, 2015.

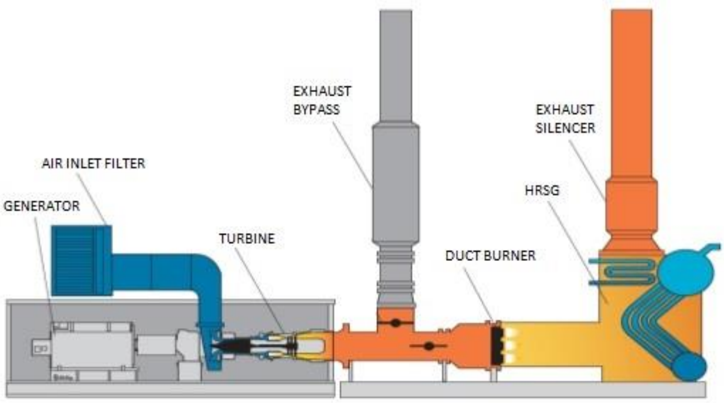

Figure 2: Turbine-HRSG Arrangement

3.1 PEMS SYSTEM OVERVIEW

The system installed on the turbine/HRSG unit is a statistical hybrid SmartCEMS®-60 PEMS developed by CMC Solutions, LLC. The application was designed to execute on a standard workstation or server operating system and utilizes an OPC-compliant database and a compatible data acquisition input device. The application itself consists of three independent components that interact with the database. The database is secured and contains the compliance data (both raw collected data that is not editable and the historical data, formatted as specified by the applicable regulations). The graphical user interface provides a message archive of system error messages and operator comments.

The first application is the data acquisition module that runs on startup of the system and collects data continuously in a protected mode from the configured I/O. This data acquisition service reads, scales, averages, and inserts minute records into the historical database archive. The data acquisition service is the only component that can write to the historical database archive and stamps each record with the current date and time.

Two other independent PEMS components work with the data acquisition service. The first application provides the operator interface for display of real-time data, display and acknowledgement of compliance alarms, and input of operator data including gas sampling results and certification test results. The second application provides the report generation capacities. Both of the applications that support the data acquisition service can be run from any workstation on the plant's local area network. The system hardware is entirely contained within a located in the plant control room. The system is designed to efficiently collect data into the secure database and also to make that data available for use in real-time optimization strategies.

All network cabling and connections are via Ethernet including the interface to the I/O device. The data is made available for display as real-time trends or tabular displays and for generation of reports. Report generation is initiated through the operator interface and includes generation of Part 60 compliance reports, excess emission reports, monitor downtime reports, and custom reports configurable by the end user. Reports and the compliance database are maintained for a minimum of 5 years with capacity for storage of many decades of the compliance data.

PEM systems are capable of predicting many pollutant species when combusting a liquid or gaseous fuel of known quality such as pipeline natural gas or fuel oil. GHG pollutants such as CO_2 can be calculated using an emission factor and known fuel quality and flow. Other pollutants such as such as ammonia and carbon monoxide (CO) can be predicted. Additional pollutant and historical training data may be required for models to provide accuracy for the products on incomplete combustion such as CO or hydrocarbons since normal operations do not typically produce these components.

PEMS have been successfully installed on several plants which must monitor ammonia release through selective catalytic reduction (SCR). Most of these are located in the state of California, one of the first U.S. states to require SCR and NOx limits that are below 10 ppmv. Typically, ammonia levels are limited to less than 10 ppmv also. California and Ohio rules allow for the use of PEMS as an alternative to CEMS even in the case where SCR is used for NOx control. Model development testing for sources with SCR that require ammonia slip monitoring require additional test conditions such as varying the ammonia injection rate at multiple loads.

PEMS can also be used to track thermal efficiency since both heat input, combined cycle output, and pollutant parameters are available in real time. Input parameters that are out of line with historical data can be highlighted to provide predictive maintenance capability to the installed PEMS. Several statistical hybrid models have been deployed for like kind units, both simple cycle and combined cycle gas turbine applications.

4 PEMS CERTIFICATION

The PEMS model for the turbine/HRSG was deployed at the site on February 5, 2015. During the model development stage, minute averaged data was collected and quality assured. This data resulted in 18,886 valid minute records, which were quality assured and loaded in the historical training dataset for the turbine/HRSG compliance PEMS.

This PEMS model was evaluated with the performance specification procedures detailed in 40 CFR Part 60, PS-16 [8]. Under 40 CFR Part 60 PS-16 regulations, a PEMS must pass an initial RATA and corresponding statistical analysis, including calculation of the relative accuracy (RA), correlation, and F-values in order to be certified [3] as a continuous compliance monitor. Data from a temporary CEMS acting as a reference method (RM) was obtained for data comparison at low (minimum to 50% of maximum load), mid (between low and high load), and high (80% to maximum load) operating levels. At least nine runs were performed at each level, obtaining 21-minutes of valid data for each run.

4.1 CERTIFICATION TESTING

The temporary CEMS used was quality assured and certified. The accredited stack testing contractor conducted the RATA for the turbine/HRSG PEMS from February 5, 2015 to February 6, 2015 using the reference method standards in 40 CFR Part 60, Appendix A.

The CEMS consisted of a heated probe and filter, heated sample lines, conditioning system, analyzers, and a data acquisition system. The CEMS instrumentation consisted of a chemiluminescent NO_x analyzer and a zirconium oxide oxygen analyzer. The CEMS was equipped with a data acquisition system and certified calibration gases. The data acquisition system was used to collect the required comparison data. The heated sampling probe was equipped with a probe pipe and placed in the center of the turbine exhaust duct.

The O_2 and NO_x reference method analyzers were calibrated with known concentrations of EPA Protocol gases before and after each test run. A minimum of nine test runs were conducted at the low, mid, and high loads. Because of the low O_2 conditions at the sampling location, with the approval by Ohio EPA, 6 point stratification tests (3 points per port) were carried out for both O_2 and NO_x at each operating load. Single point sampling was conducted at the point with the highest NO_x concentration. The calibration gas was introduced to the sampling train near the probe. The differences between the calibration value and the response were used to calculate the daily calibration drift and to correct the raw data for use in the training dataset and statistical analysis.

Data from the temporary CEMS were used to generate a report presenting the relative accuracy of the installed PEMS. Field data and notes were collected during each day of operation and daily calibrations were performed. After data collection, statistical analyses were performed per the requirements in PS-16.

4.2 CEMS and PEMS RELATIVE ACCURACY

Following completion of the calibration error and response time tests, the relative accuracy tests were conducted. U.S. EPA Reference Methods 3A and 7E were performed as specified in 40 CFR, Part 60, Appendix A. At least nine test runs were completed for a duration of 21 minutes using Method 3A and Method 7E to determine the O_2 and NO_x content, respectively, of the stack gas exhaust. NO_x emission rates were calculated using U.S. EPA Method 7E and compared to the PEMS values for the same time periods.

Table 1: RATA Results (Low Load)

Low Load				
Parameter	O_2	NO_x		
Reference Method	3A	7E		
RA Calculation Units	% vol., dry	lb/ MWhr	lb/ MWhr at 15% O_2	kg/hr
Analyzer Response (RM)	12	0.037	0.0246	1.2
Analyzer Response (CEM)	12	0.036	0.0227	1.1
Mean Difference	0.3	0.002	0.0022	0.1
Confidence Coefficient	0.1	0.003	0.0015	0.0
Percent RA (% of RM)	**3.1**	**12**	**4.3**	**9.7**

The NO_x and O_2 values were compared to the CEMS values at each of the three loads and the average values were used to calculate the NO_x emission rates. The mean of the reference method NO_x emission rates, the mean of the PEMS emission rates, and the differences between the reference method and PEMS rates were calculated for each test run. The difference, standard deviation, confidence coefficient, and relative accuracy was calculated from the 9-run data sets using the equations presented in 40 CFR Part 60, Appendix B. Per the regulations of PS-16, the allowable relative accuracy is 20% or less for concentrations from 10 to 100 ppmv [8]. As seen in Tables 1 to 3, the maximum RA values were 6.0% and 12% for O_2 and NO_x, respectively, which are within the allowable limits.

Table 2: RATA Results (Mid Load)

Mid Load				
Parameter	O_2	NO_x		
Reference Method	3A	7E		
RA Calculation Units	% vol., dry	lb/ MWhr	lb/ MWhr at 15% O_2	kg/hr
Analyzer Response (RM)	9.0	0.053	0.0260	1.7
Analyzer Response (CEM)	9.4	0.053	0.0272	1.8
Mean Difference	0.5	0.000	0.0007	0.1
Confidence Coefficient	0.1	0.001	0.0007	0.0
Percent RA (% of RM)	**6.0**	**1.5**	**5.8**	**4.2**

Table 3: RATA Results (High Load)

High Load				
Parameter	O_2	NO_x		
Reference Method	3A	7E		
RA Calculation Units	% vol., dry	lb/ MWhr	lb/ MWhr at 15% O_2	kg/hr
Analyzer Response (RM)	7.2	0.057	0.0246	1.8
Analyzer Response (CEM)	7.2	0.059	0.0246	1.8
Mean Difference	0.0	0.000	0.0000	0.0
Confidence Coefficient	0.1	0.002	0.0007	0.0
Percent RA (% of RM)	**1.3**	**4.9**	**4.3**	**1.3**

F-test and Correlation Analysis

When calculated according to the specifications in PS-16, the maximum F-value for each load yielded 1.973, below the critical F-value of 3.438 detailed by PS-16 regulations. Correlation of CEMS and PEMS values was calculated to be 0.961 in ppmv (lb/MWhr), and 0.970 in lbs/hour (kg/hour), both well over the 0.8 correlation required for the PEMS to pass under PS-16. Due to insufficient variation in the data across all three loads for NO_x in terms of ppmv (lb/MWhr) at 15% O_2, the correlation analysis was waived per the guidance of 40 CFR, appendix B, PS-16.

A visual comparison of corresponding CEMS and PEMS data output for emission data at low, medium, and high loads can be seen in Figures 3 to 5 below. A comparison of calculated mass emission rates from both data sets is presented in Figure 6.

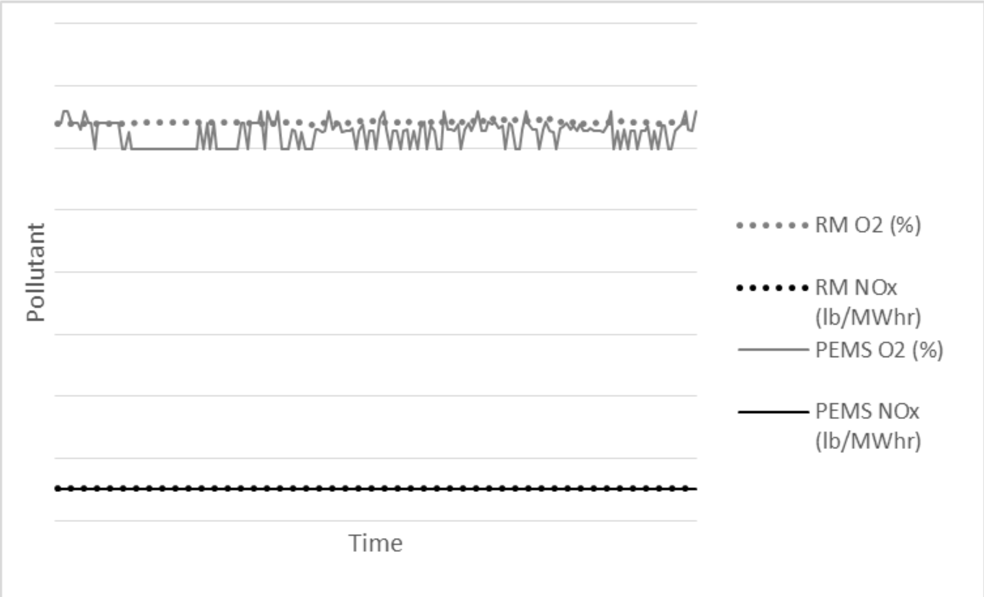

Figure 3: EMS Readings over Certification RATA (Low Load)

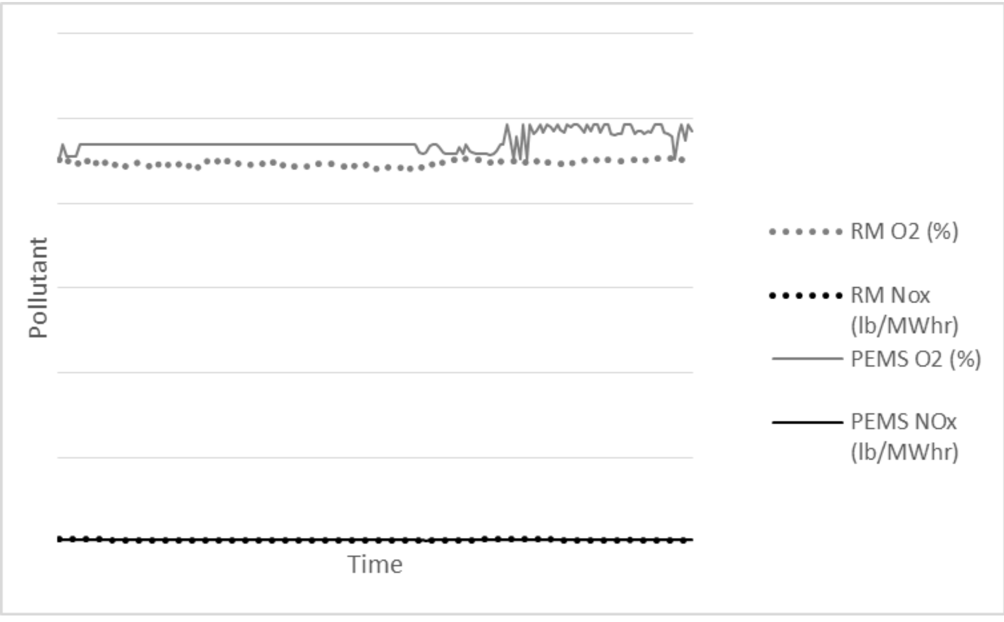

Figure 4: EMS Readings over Certification RATA (Mid Load)

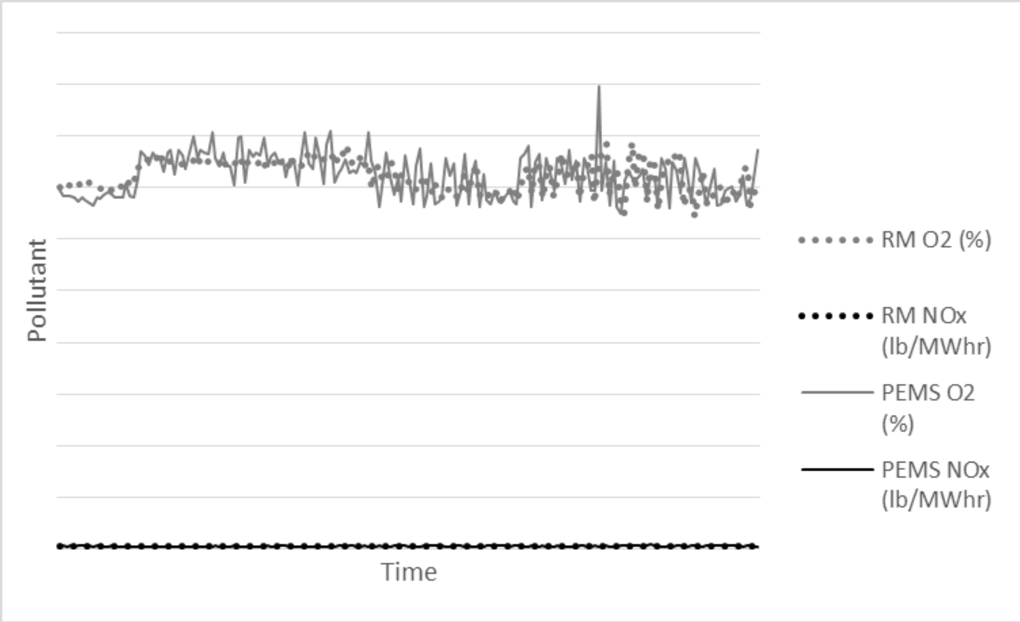

Figure 5: EMS Readings over Certification RATA (High Load)

4.3 PERFORMANCE ANALYSIS

Reliability Analysis

The PEMS produced minute and hour averages for reporting purposes during the entire duration of the demonstration. The rate of data availability from the PEMS was greater than the CEMS over the demonstration period and in excess of the minimum requirements.

Accessibility Analysis

The PEMS was utilized during the demonstration to provide compliance reports including Emission Summary Reports for submittal to the local regulatory agency to meet the reporting requirements as specified in 40 CFR Part 60. The Emission Summary Report provides the operator with hourly average emission data for any period including the previous day by utilizing the summary report option. The summary report selection process starts by determining the start date and time and either the end date and time or a preselected interval (i.e., one hour, 24 hours, one week, one month, quarter, or year). The summary reports provide averaged unit load, NO_x ppm (lb/MWhr), NO_x ppmv (lb/MWhr) at 15% O_2, NO_x lb/hour (kg/hour), O_2 percent, and status associated with the underlying data.

Timeliness Analysis

In addition to the reporting functionality as demonstrated during the demonstration, the PEMS system provides a continuous display of real-time emission data to the operator via the operator workstation located in the control room. The PEMS provides the operator with raw emission data (NO_x ppm [lb/MWhr] and O_2 percent), calculated emission data (NO_x ppmv [lb/MWhr] at 15% O_2 and NO_x lb/hour [kg/hour]), process operating parameters, and status of the process as it relates to the model used for prediction. The status display indicates to the operator when the model is not valid for the current operating condition. Data is updated on the operator display each minute.

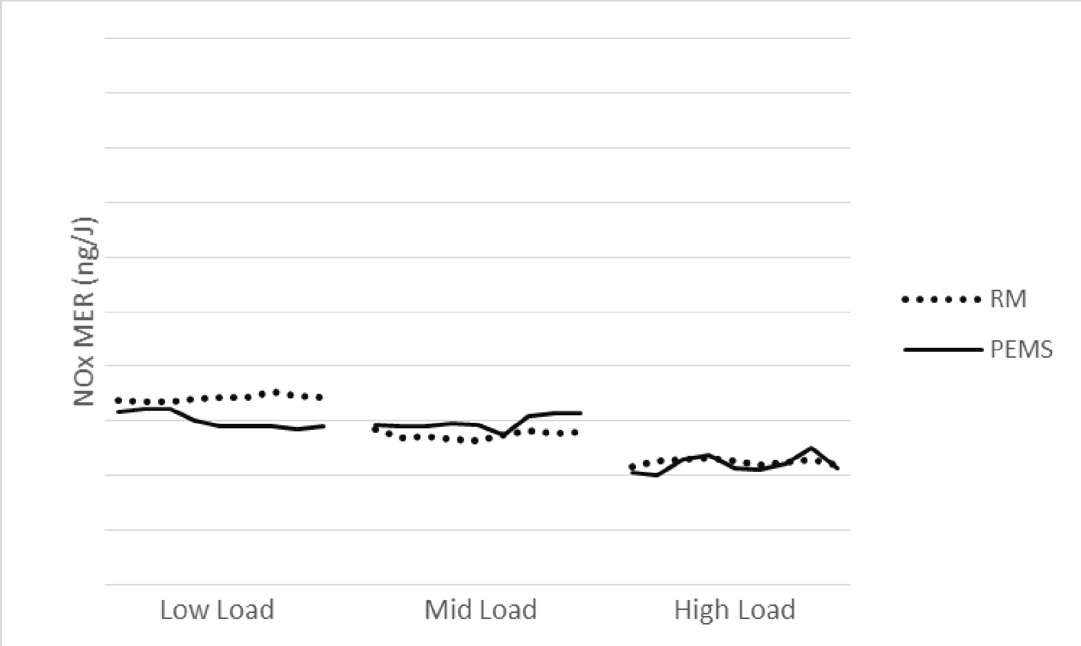

Figure 6: Mass Emission Rates (MERs) over Certification RATA

5 PEMS QUALITY ASSURANCE

A quality assurance (QA) program was established for the site, incorporating requirements of PS-16, the site's air permit, and the PEMS provider. The purpose of the QA plan is to ensure the accurate documentation of pollution emission rates and to verify compliance with the emission limitations specified in 40 CFR Part 60 and the air permit issued by the Ohio EPA.

Each of the devices providing input to the PEMS model is included in the PEMS quality assurance program (Table 4). The major components are evaluated on an annual basis, at a minimum, in some cases using a three-point sensor calibration that is recorded by the data acquisition system downstream of all transmitters and other signal conditioning equipment. This annual primary control check is documented by the plant staff and placed into the quality assurance manual. Any deviation of greater than 10% is noted and adjustment is mandatory. Plant staff typically makes minor adjustments at this time; however, typical deviations for this instrumentation (temperature, pressure, and other sensors) are less than 3% per year.

Table 4: PEMS Model Envelope

Input	Model Level	Description	Minimum	Maximum
25	1	B-3 (HRSG) Duct Burner Natural Gas Flow	0	112.4
35	1	Gas Turbine Natural Gas Flow	0	3608
82	2	B-3 (HRSG) Turbine Exhaust Temperature Entering HR	0	628.7
30	2	B-3 (HRSG) Steam Flow	0	139.9
63	2	Boiler Feedwater Header Pressure A	0	438.5
64	2	Boiler Feedwater Header Pressure B	0	438.5
22	3	APCU Ammonia Flow	0	26.1
4	3	B-3 (HRSG) Stack O_2	0	18
51	3	Deaerator Steam PRV Outlet Pressure	0	9.0
62	3	Generic Analog Input Device	0	438.7
48	3	Steam Main Pressure Transmitter A	0	530.8

Due to the detailed nature of PEMS process input data and the reliability of the sensors, PEMS data can be used for a variety of purposes beyond monitoring pollutants, including the calculation of thermal efficiency and monitoring equipment behavior. Unusual variances in pressures, temperatures, or vibration sensor outputs could be indicative of impending maintenance issues.

Sensor input validation and daily zero and span calibrations are done automatically by the system on a daily basis. Additional quality control activities are scheduled when sensor data appears to be inconsistent or is suspected by plant operations or maintenance staff. Periodic quality control tasks identified in Table 5 below are conducted on instruments and transmitters that are critical to the PEMS model. Typically, this is done at a minimum once annually and documented in the QA manual. The temperature and pressure compensation sensors used by the process control system to control turbine/HRSG operational parameters are checked each year and adjusted as required to manufacturer's recommended level of accuracy.

Table 5: PEMS Input Envelopes

Input	Description	Interval	QC Activity
25	B-3 (HRSG) Duct Burner Natural Gas	Annual	Calibration Check
35	Gas Turbine Natural Gas (Retransmitted by GT	Annual	Calibration Check
82	B-3 (HRSG) Turbine Exhaust Temperature Entering HR	Annual	Calibration Check
30	B-3 (HRSG) Steam Flow	Annual	Calibration Check
63	Boiler Feedwater Header Pressure A	Annual	Calibration Check
64	Boiler Feedwater Header Pressure B	Annual	Calibration Check
22	APCU Ammonia Flow	Annual	Calibration Check
4	B-3 (HRSG) Stack O_2	Annual	Calibration Check
51	Deaerator Steam PRV Outlet Pressure	Annual	Calibration Check
62	Generic Analog Input	Annual	Calibration Check
48	Steam Main Pressure Transmitter A	Annual	Calibration Check

The QA plan is maintained in the plant control room where the PEMS workstation is located. This plan contains log sheets to record the results of QC activities and as a guide to troubleshooting. The data is backed up each week (incrementally) and each quarter completely.

A fuel sampling and analysis program has been developed for the turbine/HRSG unit. This program includes a monthly analysis of the pipeline natural gas supply provided by the gas supplier. Gas sample data is entered into the PEMS and used to verify sulfur content at the prescribed level for reporting the heat input level. A fixed gross caloric value for the pipeline natural gas is used.

The required missing data procedures as specified in 40 CFR Part 60 are followed. Missing data for the PEMS includes identification, alarm, and archiving of any 'critical compliance' parameters outside their respective normal ranges during unit operation or that have failed.

The inputs used in the model for the compliance parameters as identified in Tables 4 and 5 are provided with alarms and set-points that are used to define the envelope of the currently certified model. These alarms are configured in the control system to alert the operator when compliance parameters are outside the range represented by the historical training dataset. When critical compliance parameters are not in line with the data collected in the historical training database, the data is flagged as invalid and details of this missing data are include in the monitor downtime report.

6 CLASS MODEL

A statistical hybrid PEMS model can be applied to similar units and certified for compliance using PS-16 in the U.S. [9]. If the full normal operating range and modes of operation are covered in the initial training dataset, there is no reason the model cannot be used on similar units that have the same input parameters available in real-time. This allows for deployment of PEMS without extensive model development on each unit. A robust historical class model can be used for like kind units; however, a separate PEMS is installed for each unit to allow for adjustments and fine tuning over time as emission rates may be slightly different in individual units due to variations in the manufacture, control, operating or maintenance history of the unit. Certification and validation of the class model is performed as required in PS-16, and a full 27 run relative accuracy test audit is performed on each unit. Several statistical hybrid class models have been deployed in the U.S. and overseas including for simple cycle gas turbines, combined cycle turbines with HRSG, and gas/oil fired boiler applications.

7 CONCLUDING REMARKS

A statistical hybrid PEMS model can be deployed on a small gas turbine in the United States and can be demonstrated to achieve accuracy comparable to a CEMS. The PEMS can be readily certified as an alternative to CEMS under CFR Part 40, PS-16 for the combined cycle unit that includes a small gas turbine. A robust statistical hybrid PEMS model can be deployed as a class model for like kind units. After PEMS installation, certification requires stack testing at multiple load points for each individual unit using reference methods and a corresponding statistical analysis of the data to assess its accuracy and performance. A detailed quality assurance plan is required to be maintained at the site, The QA program details and documents quality control activities required to ensure the input parameters to the PEMS model are available and of sufficient quality to ensure accurate compliance emission data is being collected.

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