Startup and Shutdown Air Permit Limit Development Framework for Combustion Sources Monitored by Continuous Emission Monitoring Systems

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ABSTRACT

This paper is meant to help the air quality industry work towards establishing standardized guidelines to develop startup (SU) and shutdown (SD) air permit limits for large stationary combustion units including boilers and combustion turbines equipped with Continuous Emission Monitoring Systems (CEMS). The concept of monitoring emissions during all operating times and comparing emissions data to appropriate emission limits during startup, shutdown and malfunction (SSM) events are at the center of this development process. Since emissions data during SU/SD events are highly variable for certain monitored parameters including oxides of nitrogen (NO_x) and carbon monoxide (CO), establishing SU/SD limits that both government agencies and the energy industry find satisfactory can be a challenge. This paper discusses an objective framework for developing SU/SD limits that can be applied to any combustion unit equipped with CEMS. The framework is comprehensive and uses a practical data-driven approach to develop optimal unit specific SU/SD duration and emission limits based on CEMS data. The framework has both qualitative and quantitative elements. The qualitative aspects involve gathering preliminary data to identify applicable unit and facility specific requirements, stakeholder participation, regulatory engagements and permitting, as well as data acquisition and handling system (DAHS) programming efforts. The quantitative portion focuses on the development of numerical duration and mass per SU/SD event emission limits using objective statistical methods including the upper prediction bound and linear regression, while avoiding more subjective based limit development processes as well as limits based on emissions concentrations and rates. Our data analysis process uses open source statistical programming packages to develop optimal unit specific duration and mass per SU/SD event emission limits from minute level CEMS data. The paper also discusses lessons-learned from successfully applying these standard guidelines in developing SU/SD limits for inclusion within multiple air permits.

INTRODUCTION

In recent years an increased interest regulating and quantifying emissions during non-steady state operating events such as startups (SU), shutdowns (SD) and malfunctions for large stationary combustion units including boilers and combustion turbines has occurred. Increased regulatory oversight, stricter emission limits, and ever changing electricity generation market demands are some of the factors responsible for the increased interest. The United States Environmental Protection Agency's (USEPA) Startup, Shutdown, and Malfunction (SSM) rule finalized on May 22, 2015 clarified that emission limits must apply continuously during all modes of operation.[1] Unlike unit malfunctions, startups and shutdowns (SU/SD) are planned events; however, due to the variability between combustion units' SU/SD emission profiles, determining appropriate unit specific SU/SD emission limits remain a challenge for the energy industry.

The power generation industry is rapidly evolving. According to the United States Energy Information Administration's (EIA) Annual Energy Outlook, the share of renewable energy sources in the electricity generation mix has grown rapidly in the last decade and is projected to continue growing at a fast pace, impacting the operation of fossil fuel fired combustion units that have historically operated at higher capacity factors.[2] As a result, fossil fuel fired combustion units may need to startup and shutdown more often, or operate at lower loads to stay competitive in the marketplace.[3] In addition, there is a growing number of non-base load fossil fuel fired combustion units to cater to the peak demand and these units commonly startup and shutdown frequently (e.g., daily). Thus, the energy industry is facing regulatory and market pressures to quantify emissions during transient operations including SU/SD events. For this reason, using an objective, data driven, standard approach to propose SU/SD duration and emission limits for inclusion within air permits is in the best interest of the industry.

During the last two decades, state regulatory agencies have sought new methods to quantify and regulate startup and shutdown emissions.[4,5] Some states previously limited the applicability of emission limits to non-startup and non-shutdown periods, while others have implemented various approaches to limit emissions during SU/SD periods. More recently, a trend is emerging to utilize historical Continuous Emission Monitoring Systems (CEMS) data when developing site specific SU/SD emission limits.[4] Newer air permits often include numerical SU/SD event-based duration limits, mass emission limits, as well as startup and shutdown site specific definitions. Facilities subject to these SU/SD duration and emission limits are required to continuously monitor and aggregate emissions data during SU/SD events for continuous evaluation against applicable short-term permit limits.

SU/SD duration and emissions differ depending on unit type, make, model, and operating conditions. Unlike steady state emission limits based on Best Available Control Technology (BACT), standard source category SU/SD emission limits are not currently available. Studies have shown that SU/SD duration and emissions are difficult to standardize;[5,6] however, the approach to develop unit specific SU/SD duration and mass emission limits can be standardized using the approach discussed within this paper.

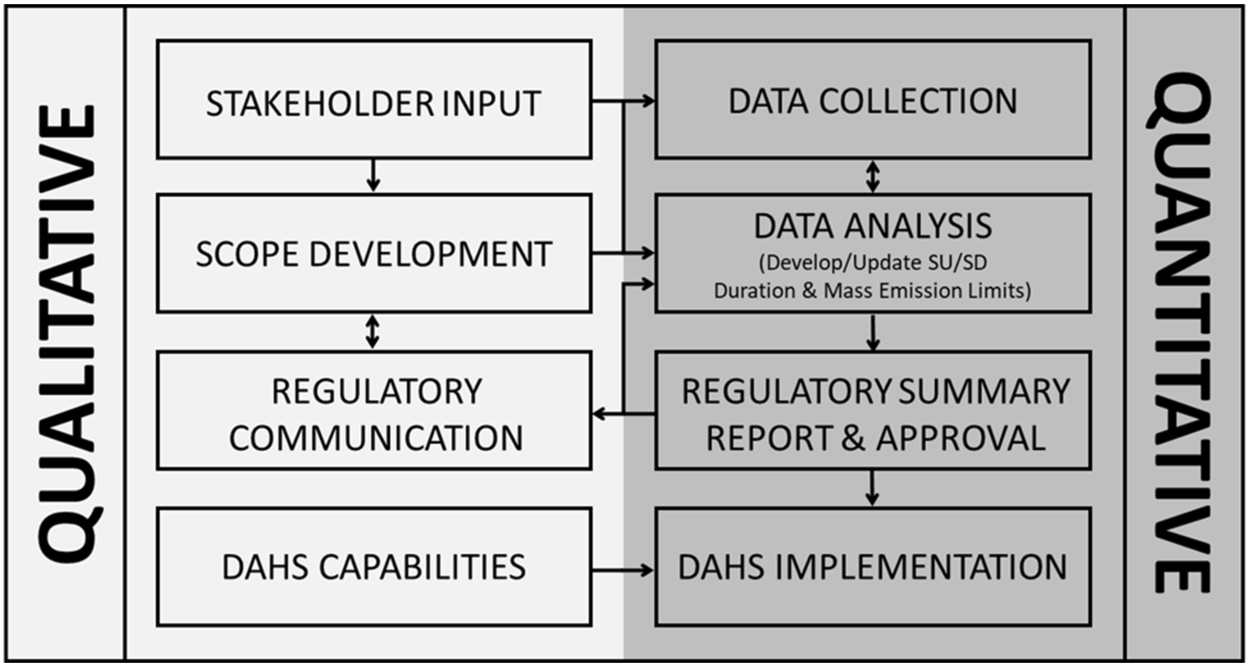
Based on our knowledge and research, there is little formal guidance regarding appropriate methods to develop transient emission limits for use within large stationary combustion units' air permits. The existing methods typically lack structure and transparency, rely on manufacturers' recommendations and/or data that may not reflect actual emissions for the specific installed combustion unit. Based on our extensive experience working with emissions data from large stationary combustion sources, relying on manufacturers' performance data or emissions compliance stack testing data to develop SU/SD air permit restrictions are poor substitutes for actual combustion source operating CEMS data, specifically for unstable operating conditions like SU/SD events. Instead, CEMS data can be leveraged to develop objective, unit specific, representative SU/SD duration and mass emission limits. Using CEMS data during this development process is robust, transparent and reproducible. Moreover, data acquisition and handling systems (DAHS) packages are becoming increasingly sophisticated and are used more frequently to quantify and evaluate complex transient operating modes like SU/SD events against real-time and short term air permit duration and mass emission limits.

This paper attempts to address the gaps in current industry guidelines by providing an update to our previously presented SU/SD duration and mass emission limit development framework[4] with recent refinements/enhancements and case studies. The enhanced data analysis framework is composed of qualitative and quantitative components. The qualitative components provide the flexibility to adjust the data analysis framework to a specific facility's preferences, conditions and requirements, while the quantitative components leverage open source data analysis tools to make this framework transparent, objective and repeatable. For these reasons, the framework can be applied to a wide range of conditions, from developing/proposing SU/SD duration and mass emission limits for a newly installed unit to simply validating/updating SU/SD operating restrictions for an existing unit. The enhanced data analysis framework presented in this paper has been deployed numerous times to help facilities implement site specific SU/SD duration and mass emission limits based upon historical CEMS data. This paper is presented with efforts to help the energy industry standardize SU/SD restriction development efforts that can be applied to any combustion unit equipped with CEMS.

ENHANCED SU/SD DATA ANALYSIS FRAMEWORK

The enhanced SU/SD data analysis framework structure is shown in Figure 1. The framework can be seen as a combination of qualitative and quantitative elements with the lines and arrows illustrating the common process flow and feedback loops encountered during SU/SD duration and mass emission limit development projects. Each element is discussed below.

Figure 1. Enhanced SU/SD Limits Development Framework



Qualitative Elements

Stakeholder Input – The AccountAbility1000 Stakeholder Engagement Standard defines stakeholders as groups who affect and/or could be affected by an organization's activities, products or services and associated performance.[7] Applicable stakeholders for SU/SD limit evaluation projects typically include corporate managers, plant managers, operations managers, environmental managers, instrumentation and controls (I&C) technicians, consultants, DAHS vendors and regulators. Regulatory engagements are discussed within the regulatory communication section below. The primary stakeholders should be kept apprised of the project team's progress and/or any material changes so that the project team is comfortable with the project scope and proposed objectives of the assessment. The stakeholders working at the facility are generally the most knowledgeable about the combustion unit operations and are typically responsible for the project. I&C technicians' or other applicable stakeholders' input should be sought to clarify questions/concerns/anomalies in data, to understand the overall health of the CEMS data obtained for analysis, to understand any related digital control system (DCS) data/logic utilized (e.g., facility implemented SU/SD definitions) and to clarify any related DAHS configuration questions. Consultants working on such projects should have a thorough understanding of the facility's regulatory requirements and maintain an open line of communication with the client throughout the project. When preliminary results are ready, relevant stakeholders should be sought to provide feedback and should approve the project's proposed SU/SD duration and mass emission limits prior to submittal and seeking approval from the applicable local/state/federal regulatory agencies.

Scope Development – The project lead should gather information relevant to the combustion unit for which limits/restrictions are being developed from all relevant stakeholders. The information collected during this step determines the course of the assessment. Therefore, performing a thorough review of all available information sources to gain a comprehensive understanding of the problem statement is vital to the project's success. The scoping process can be further broken down broadly into three main tasks:

> **(1)** Perform a thorough review of the unit specific characteristics such as unit type, operating modes (e.g., base load or peaking, simple cycle or combined cycle, power boiler or auxiliary boiler), year of installation (i.e., age), combustion controls, and any other site-specific details that affect unit operation.
>
> **(2)** Review unit specific and facility-wide regulatory (i.e., local, state, federal) permit requirements and determine how these requirements affect the analysis. Specifically, any requirements related to SU/SD specified within the permit/regulatory approvals should be the foundation for developing/updating SU/SD restrictions. Other important parameters that may affect the analysis include the applicable steady state emission limits and their unit of measure, method of calculation, averaging time, and data validation requirements. Permit definitions of steady state operation, startup and/or shutdown (e.g., hot, warm, cold), if any, should be reviewed to ensure the events/operating modes are distinctly defined. If any ambiguity exists, the project team should clarify the relevant permit definitions prior to proceeding with the quantitative portion of the assessment.
>
> **(3)** Develop a project scope that has clear objectives and deliverables, with a consensus and as needed input from the applicable project stakeholders.

Regulatory Communication – Regulatory communication is critical for successfully proposing and implementing new or revised SU/SD operational restrictions and/or emission limits. Every SU/SD limit development project begins with regulatory communication either in the form of passive or active communication. Passive communication can include reviewing requirements specified within previously issued permits/approvals, while active communication can include submittal of a formal permit modification request to the applicable regulatory agency for updating/modifying certain SU/SD restrictions and/or emission limits, or more informal types of communication (e.g., emails, conference calls) to clarify project expectations prior to beginning project work. In certain circumstances, regulatory requirements and/or requests can be time constrained, or subject to explicit deadlines. Therefore, these projects should be planned such that there is sufficient time to carry out each element of the framework. Before delving into the assessment, having a clear agreement between the facility and the regulatory authority is necessary regarding the interpretation of requirements specified within permits/approvals or the proposed changes in SU/SD restrictions and/or emission limits. If needed, clarification should be sought during scope development for permit requirements/definitions that may affect the assessment. Communication with the regulators for feedback during the project may be recommended depending on the complexity of the assessment, but is not necessary unless there is a material change in the objectives or unforeseen setbacks or delays. Since the framework proposed in this paper is data driven, transparent and objective, all information relevant to the assessment is provided within the regulatory summary report, described below.

DAHS Capabilities – Before beginning the quantitative assessment portion of the project, the applicable DAHS vendor should be contacted to verify that the SU/SD duration and mass emission limits can be programmed into the DAHS for automatic recordkeeping, alarming and compliance reporting purposes in the anticipated manner considering different DAHS software packages have different preferred implementation strategies and capabilities. Conferring with the DAHS vendor (i.e., project stakeholder) during the scope development process will lead to a more efficient project allowing for the project scope to be tailored to the facility's specific DAHS vendors capabilities and allowing for a smooth DAHS implementation of SU/SD duration and mass emission limits.

Quantitative Elements

***Data Collection* –** Data collection is the first step in determining numerical SU/SD duration and mass emission limits. The information gathered in the qualitative assessment should be leveraged to determine which parameters need to be included in the assessment and how those parameters can be retrieved from the DAHS or derived. Typically, the set of parameters required for the analysis depends on whether there exist specific definitions for startup and/or shutdown either specified in the air permit/approval, or within other relevant guidance. In general, when startup and shutdown operational signals are available in the DAHS and accurately represent the duration of individual SU/SD durations, they should be used for the purpose of defining SU/SD events. If SU/SD definitions are not already determined from the air permit(s) or otherwise, or if the DAHS is not equipped with either startup or shutdown signals, then the following general definitions may be adopted or used as a starting point to develop appropriate definitions with relevant project stakeholders for data analysis purposes. Based on our experiences, keeping the SU/SD definitions as simple as possible are in the projects best interest considering the DAHS implementation should mimic the definitions used during the data analysis portion of the project as close as possible.

> **Example Startup Definition** – The period of time between the start of fuel combustion and when the combustion unit of interest satisfies the steady state emission limits in the same unit of measure for all monitored pollutants (e.g., NO_x and CO) on the minute level or for a specified time interval (e.g., 15-minute rolling average or for 15 consecutive minutes). In certain circumstances additional logic is needed and may include the load parameter stabilizing for a specified time interval (e.g., 15-minute rolling average).
>
> **Example Shutdown Definition** – The period of time between when the load (e.g., MW or klb/hr of steam) begins to decrease until the time fuel combustion is complete. In certain circumstances additional logic is needed and may include any monitored pollutants (e.g., NO_x or CO) exceeding the steady state emission limits in the same unit of measure on the minute level or for a specified interval (e.g., 15-minute rolling average or for 15 consecutive minutes).

Over the years, SU/SD emission limits have evolved from being expressed as concentrations to mass rates to simply total pollutant mass during each SU/SD event (i.e., mass per event). This is a positive development in the realm of permitting because using concentrations (e.g., parts per million at 15 percent oxygen) or mass rates (e.g., lb/hr) during highly transient SU/SD events distorts averages and poses additional challenges when dealing with averaging periods (e.g., clock hours that include both SU/SD data and non-SU/SD data). Based on our experience, evaluating SU/SD events on the 1-minute level using CEMS data allows for more clear delineation of SU/SD emissions data from non-SU/SD emissions data; although, depending on the project SU/SD events can be identified using higher level averages (e.g. 1-hour average CEMS data).

Data Analysis – Data analysis is at the center of the quantitative assessment portion of the project. Decisions based on data are practical, transparent and retraceable. Generally, the larger the dataset the better the results, provided the data is of high quality. Navigating through large datasets, applying suitable statistical models, and interpreting the results can seem daunting at first glance. However, the analysis can be broken down into smaller tasks. A step by step process as shown below can be adopted to develop or revise unit specific, reliable SU/SD duration and mass emission limits.

Exploratory Analysis – The first step in any data analysis project is to understand the data and its features, often with visualizations. Visualizations help identify trends, outliers, spread and distribution of datasets. Exploratory data analysis should be carried out on all duration and mass emissions data to become familiar with the data and to prepare descriptive statistics. During this process, the data should be thoroughly reviewed and validated to identify erroneous data or outliers that may need to be removed from a dataset.

Data Wrangling – Data wrangling is the process of cleaning and transforming data into a suitable dataset for analysis and prediction. Applicable SU/SD operational and emissions data can be downloaded at the appropriate resolution (e.g., minute or hour level) from the DAHS and compiled in a usable manner. When accurate SU/SD DAHS signals are not available, or when the SU/SD definitions are not stated within permits/approvals, SU/SD definitions can also be determined empirically including a trial and error approach. Establishing clear definitions for startup and shutdown are important at this stage, as the analysis may need to be repeated if the definitions are revised at a later stage. Soliciting input from the project stakeholders/experts is highly recommended to avoid additional project revisions. The final SU/SD definitions should be adhered to throughout the rest of the data analysis and presented clearly in the project's regulatory summary report. The more SU/SD events utilized in the data analysis the better; however, due to many circumstances the number of SU/SD events may be limited.

Event Duration – The duration of a startup and/or shutdown depends on many variables including the unit characteristics, type of startup, and environmental conditions. Therefore, duration limits estimated using actual operating data are more representative in comparison to relying on manufacturers' performance data or emissions compliance stack testing data. Evidently, the actual SU/SD data is variable and noisy. For such datasets, statistical analysis can be used to describe the properties of the dataset and make estimates or probabilistic predictions. Many standard statistical approaches can be applied to analyze and develop duration limits. Picking the right statistical approach requires a deep understanding of the data and underlying assumptions of data distribution. In addition, the complexity of a model should be considered before applying it to a dataset. All stakeholders, including the regulators should be comfortable with the methods used in the analysis.

The statistical methodology discussed in this paper is adopted from Suess et al., 2009.[4] For variable datasets such as SU/SD durations, it is important to consider the range instead of a point measure, as a starting point. The range of plausible values of distribution are typically determined using confidence intervals and prediction intervals at an acceptable significance level. Confidence intervals bound regions associated with mean and standard deviation, whereas prediction intervals are used to provide intervals within which the next observation is likely to occur. Prediction intervals represent the uncertainty of predicting the value of a single future observation or a fixed number of multiple future observations from a population based on the distribution of previous observations. This study illustrates the application of the 99.9% upper prediction bound to develop duration limits for SU/SD events.

The upper prediction bound formula for Y_0, where Y_0 is a new single observation to be predicted, is:[8]

$$\text{UPB} = \overline{Y} + z \cdot s \cdot \sqrt{1 + \frac{1}{n}} \qquad \text{(Eq. 1)}$$

where:

UPB = The upper prediction bound

$\overline{Y}$ = The sample mean of the data Y

s = The sample standard deviation where: $s = \sqrt{\dfrac{\sum (Y_i - \overline{Y})^2}{n-1}}$

z = The critical value from the standard normal distribution (for a 3 sigma upper bound $z = 3$)

n = The sample size

The upper prediction bound equation takes into consideration the sample size n, which can be limited when compiling startup and/or shutdowns from a combustion source as their frequencies may be limited or only a small amount of accurately monitored data may be available. Future SU/SD duration values are expected to be less than or equal to the 99.9% upper prediction bounds with an approximate 99.9% confidence. The upper prediction bound values may be rounded to the next half hour and can be used to either update previously implemented duration limits not based on CEMS data or to propose new SU/SD duration limits.

Event Emissions – Similar to event duration limit development, mass emission limits can be developed using statistical methods. This paper utilizes the statistical method discussed in Suess et al., 2009.[4] The method uses a regression analysis coupled with a 99.9% upper prediction bound to develop representative mass emission limits for any parameter with historical data. This method leverages the relationship between event duration and total mass emissions to estimate mass emissions for SU/SD durations determined in the previous section. Then, the upper prediction bound is calculated using equation 3. These calculations can be performed using various statistical packages including recent versions of Microsoft® Excel® or the open source R statistical software.

The upper prediction bound can be calculated utilizing the maximum startup or shutdown duration for each dataset. Other options would be to calculate the upper prediction bound at a value less than the maximum (e.g. the 95th percentile value). However, with limited datasets using values other than the maximum observed SU/SD duration, may lead to non-conservative proposed SU/SD emission limits.

The upper prediction bound formula for Y_0, where Y_0, is a new single observation to be predicted from a regression based on *X*, predicted at X_0, is as follows.[8] The linear regression equation is:[8]

$$Y = \beta_0 + \beta_1 X + \varepsilon \qquad \text{(Eq. 2)}$$

where:

β_0	= The y intercept in the regression model
β_1	= The slope in the regression model
ε	= The random error

The upper prediction bound for Y_0 at X_0 formula is:

$$\text{UPB} = \overline{Y} + \hat{\beta}_1 (X_0 - \overline{X}) + z \cdot s_{Y|X} \cdot \sqrt{1 + \frac{1}{n} + \frac{(X_0 - \overline{X})^2}{(n-1){s_X}^2}} \qquad \text{(Eq. 3)}$$

where:

UPB	= The upper prediction bound
$\overline{Y}$	= The sample mean of the data *Y*
X_0	= The *X* value where the prediction of *Y* is made
$\overline{X}$	= The sample mean of the data *X*
$\hat{\beta}_1$	= The estimated slope from the fitted regression model
$s_{Y\|X}$	= The sample standard deviation of Y at X_0, where: $s_{Y\|X} = \sqrt{\frac{\sum (Y_i - \hat{Y}_i)^2}{n-2}}$
$\hat{Y}_i$	= The predicted value of *Y* and X_i where: $\hat{Y}_i = \hat{\beta}_o + \hat{\beta}_i X_i$
$\hat{\beta}_0$	= The estimated y-intercept from the fitted regression model
s_X	= The sample standard deviation of the data *X*, where: $s_X = \sqrt{\frac{\sum (X_i - \overline{X})^2}{n-1}}$
z	= The critical value from the standard normal distribution (for a 3-sigma upper bound *z* = 3)

Regulatory Summary Report and Approval **–** The purpose of a regulatory summary report in the context of developing or updating SU/SD duration and/or mass emission limits is to communicate the newly developed limits effectively to all the project stakeholders including the applicable regulators. The report can be tailored to serve as a supplemental document within a larger part of a regulatory submittal (e.g., permit application) or as a summary document to the facility stakeholders for decision making purposes, or both. The report should typically include: (1) the regulatory requirements that triggered the analysis; (2) a description of the facility and the relevant unit(s); (3) the methodology used to obtain the results; (4) plots and summary tables with the proposed limits; (5) justification for the applicability of proposed limits; (6) proposed language additions/modifications to be made within the applicable air permits/approvals; (7) and supporting raw datasets used within the data analysis portion of the project so others have the capability to reproduce the data analysis if so desired.

DAHS Implementation – Following an approval from the regulatory agency, the new limits should be incorporated within the DAHS. Typically, a project summary and requested updates including early warning and compliance alarms, channels and compliance reports are provided to the DAHS vendor for implementation so the new limits are configured in a consistent manner with the supporting data analysis. Quality assuring the DAHS implementation efforts for accuracy is a key portion of this task.

Case Study Descriptions

Two real world case studies are presented below to illustrate the application of the enhanced SU/SD limit development data analysis framework described above. Using case studies permits a deeper understanding of the emergent constructs and phenomena under study in their rich real-world contexts.[9] A multiple case study design permits a contrast and comparison, which helps emphasize the role of each element in the underlying framework.[10] The case studies discussed below are real projects where the proposed framework was applied successfully leading to revised or new air permit SU/SD limits. The units within each case study are unique in terms of unit type, operation, ownership and permit requirements.

Facility 1 Case Study Overview – Revising SU/SD duration and mass emission limits for combustion turbines based on existing SU/SD air permit definitions and restrictions.

Facility 1 consists of two dual-fuel (i.e., natural gas and ultra-low sulfur diesel (ULSD)) combined cycle combustion turbine generators (CTGs) each equipped with supplementary fired heat recovery steam generators (HRSGs) installed in 2011. The two CTGs serve a common steam turbine. Each CTG/HRSG has a combined rated heat input of 2,581 mmbtu/hr and are equipped with emissions controls that include ultra-low NO_x combustors and selective catalytic reduction for oxides of nitrogen (NO_x) control, as well as oxidation catalysts for carbon monoxide (CO) and volatile organic compounds (VOC) control. Emissions from each CTG exhaust through separate stacks that are each monitored with dry extractive NO_x and CO CEMS. Although VOC emissions are not measured directly, they are calculated within the facility DAHS by using CO CEMS data with VOC stack test results and manufacturer's data as specified in the air permit. Unit heat input is determined using fuel flow meters and fuel sampling in accordance with 40 CFR 75 Appendix D.

The problem statement for this study was defined by the requirement specified within the facility's air permit to track and record emissions of NO_x, CO and VOC for all SU/SD events during the first 5 years of the CTGs operation. The facility was required to submit a SU/SD emissions data report with an opportunity to revise the existing SU/SD duration and emission limits that were considered to be representative of uncontrolled emissions during transient operations according to the manufacturer when the permit was originally developed. The permit also specifically defined startups (hot, warm, and cold), shutdown and steady state operation; hence, these same definitions were used to develop the boundary conditions for the quantitative data analysis.

Facility 2 Case Study – Developing SU/SD duration and mass emission limits for a boiler with no prior air permit/approval SU/SD definitions or restrictions.

The unit in this study at Facility 2 is a steam generating boiler permitted to fire both natural gas and ULSD. The boiler has a rated heat input of 125.8 mmbtu/hr and was installed in 2012. NO_x and CO is monitored by CEMS and heat input is determined using fuel flow meters. The initial air permit required compliance tests for NO_x and CO during startup and shutdown to establish SU/SD limits. Due to concerns regarding developing emission limits from one data point taken during the initial compliance stack test, a request to track and record SU/SD data for a representative period of time to determine SU/SD limits based on CEMS data was approved by the state regulatory agency. There were no SU/SD definitions specified in the initial air permit; hence, the problem statement for this study was to (1) define startup and shutdown for this specific unit; (2) develop suitable duration limits; and (3) develop NO_x and CO SU/SD mass emission limits based on the definitions framed in (1). This project is an example of a comprehensive assessment that requires developing SU/SD duration and mass emission limits using historical CEMS data with no definitions or guidance in the underlying air permit.

RESULTS AND DISCUSSION

FACILITY 1 CASE STUDY – The proposed enhanced data analysis framework was applied to Facility 1 with efforts to review and, if needed, update the existing SU/SD duration and mass emission limits based on historical CEMS data.

Case Study 1 Qualitative Assessment

The scope development process and project goals were discussed and identified during a project kick-off meeting with the facility stakeholders, which included the environmental manager, corporate managers and the consultant (i.e., authors) that performed the data collection, analyses and report writing. As identified in the case description, the newly proposed limits had to be submitted to the state within 60 days after the 5-year data collection period as specified within the permit. Project milestones were planned and scheduled to allow for the project completion within 60 days. A thorough review of the permit and supporting documents was performed to lay the groundwork for the quantitative analyses. Since the DAHS was already configured with the initial SU/SD channels and limits, additional assessment regarding the ability of the DAHS to handle new limits was not necessary. The revised limit magnitudes would be in the same unit of measure as the initially permitted SU/SD mass per event based limits.

Case Study 1 Quantitative Assessment

Quantitative assessment was conducted according to the method and model proposed in Suess et al., 2009.[4] SU/SD duration data and corresponding NO_x, CO and VOC emissions data sourced directly from the DAHS was compiled by the facility. The data was split into two datasets (i.e., 'gas fired' and 'oil-fired'). The datasets were prepared using hourly NO_x, CO and VOC mass emissions data during SU/SD time periods for each CTG. Based on the existing DAHS configuration and SU/SD evaluation processes, hours including at least one minute of startup or shutdown were considered startup or shutdown hours. Hourly NO_x, CO and VOC mass emission rates were multiplied by the hourly operating time to obtain mass of emissions per SU/SD event. The SU/SD duration and mass emissions data were compiled for 1x1 (i.e., startup or shutdown of 1 CTG and 1 steam turbine) and 2x1 (i.e., sequential startup or shutdown of 2 CTGs and 1 steam turbine) operational sequences. Due to limited oil firing data over the five year lookback period, rigorous statistical analysis was not feasible. Instead, oil firing data was evaluated using empirical methods and for this reason is not described in further detail. Therefore, the following analyses were carried out on natural gas fired datasets only.

Following data collection, datasets were reviewed and prepared for statistical analysis. Since the CTGs have different durations and mass emissions during each 2x1 event (i.e., the CTG that starts first will typically have a longer duration and more mass emissions) the maximum values for duration and mass emissions, as well as only those 2x1 startups that occurred with both CTGs in the same startup category (i.e., hot, warm or cold), were included within the final dataset. In addition, startup and shutdown unrepresentative data were excluded from the final datasets as each of the excluded data points could be attributed to trips (i.e., unrepresentative shutdowns), or events that occurred while CEMS data was invalid due to quality assurance activities or analyzer malfunctions. As evident from the above discussion, there were multiple possible operational SU/SD sequences (i.e., 1x1, 2x1, hot, warm, cold conditions) that added unnecessary complexity to the data analysis process. To simplify the analysis, 1x1 and 2x1 events were evaluated together.

The duration datasets were checked for normality. Exploratory data analysis of the SU/SD duration datasets yielded the following features:

- The distributions of each dataset were different, as shown in Table 1. The hot startups dataset showed the least amount of variability, while the cold startups dataset showed the most variability, most likely due to the corresponding dataset size.
- A general upward trend in duration from hot to warm to cold startups was identified.
- The means of the hot, warm and cold datasets were statistically different from one another at the 0.0001 level of significance ($p\text{-value} < 0.0001$). The statistical difference between sample means justified the separate treatment of each dataset (i.e., hot, warm and cold startup duration datasets are not the same because there is a statistical difference between their sample means).

A 99.9% upper prediction bound was applied to each historical SU/SD duration dataset using Equation 1, shown above.

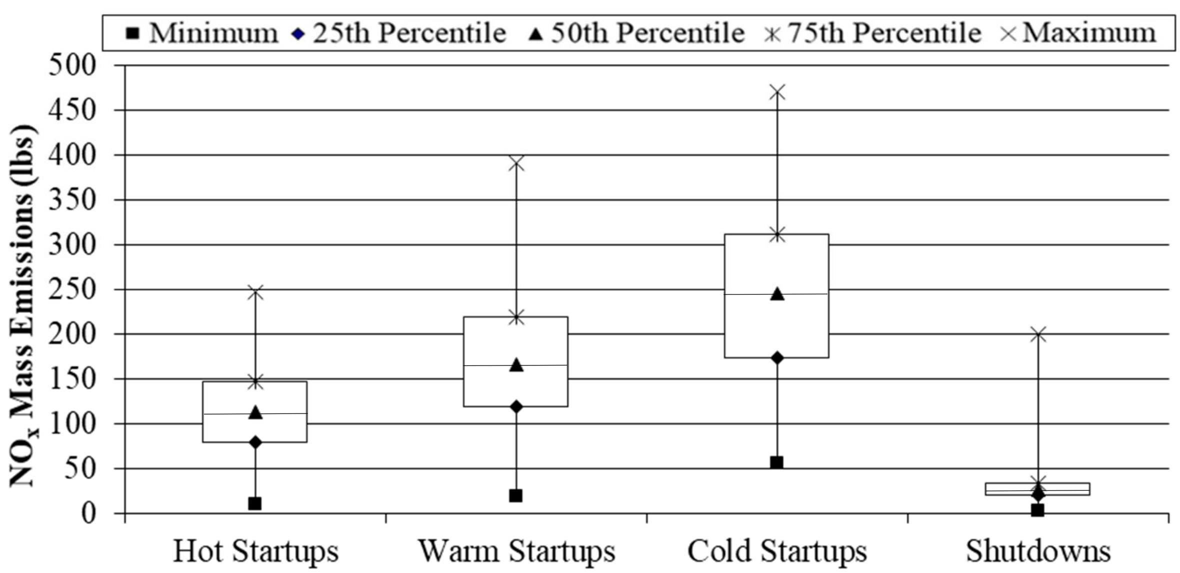
Table 1. Startups and Shutdowns Duration Descriptive Statistics and Proposed Duration Limits

Descriptive Statistics	Hot Startups	Warm Startups	Cold Startups	Shutdowns
Sample size	461	78	31	549
Maximum Duration (hours)	2.3	3.0	3.6	2.2
Mean (hours)	1.4	1.8	2.4	0.9
Standard Deviation (hours)	0.3	0.5	0.6	0.4
99.9% Upper Prediction Bound (hours)	2.2	3.3	4.3	2.1
Current Duration Limit (hours)	1.8	2.0	2.9	1.0
Proposed Duration Limit (hours)	**2.2**	**3.3**	**4.3**	**2.1**

Following the SU/SD duration analysis, the natural gas emissions datasets were checked for normality and outliers identified. Exploratory data analysis of the emissions datasets yielded the following features:

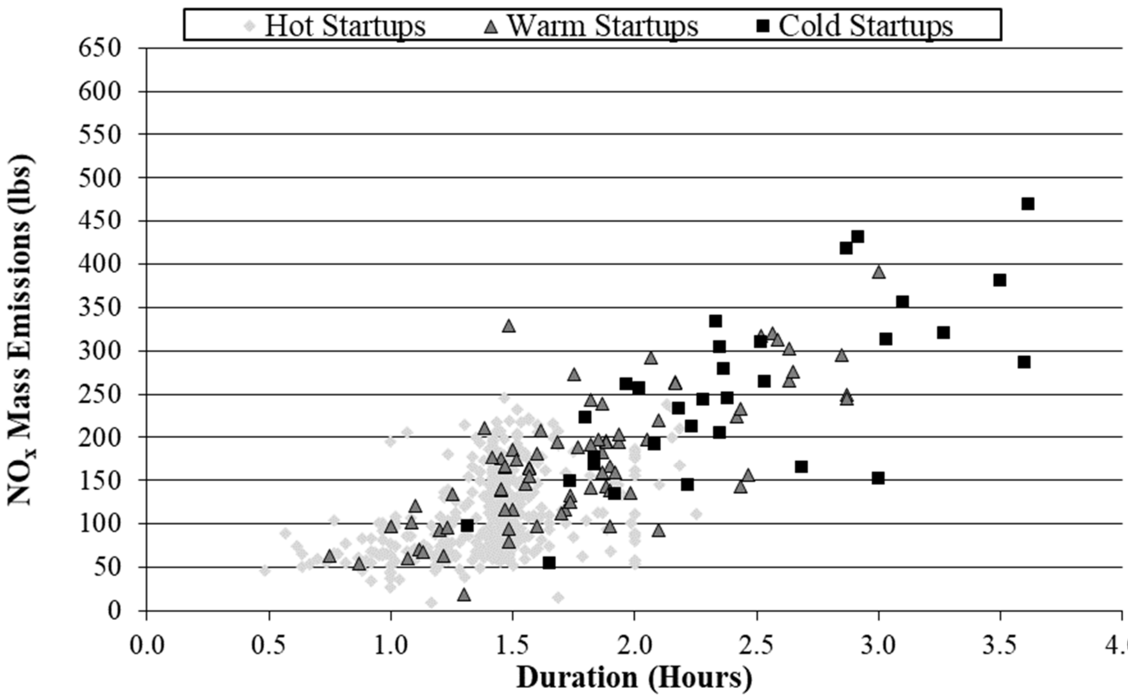
- The distributions of each dataset are different, as shown within the example NO_x mass emissions box plots in Figure 2. The distribution for CO and VOC also exhibited similar relationships. The shutdown datasets generally showed the least amount of variability, while the cold startup datasets showed the most variability.
- A general upward trend in mass emissions occurs from hot to warm to cold startups.
- Other than VOC mass emissions during warm and cold startups, the means were statistically different from one another at the 0.0001 level of significance (p-value < 0.0001), justifying the separate treatment of each dataset (i.e., hot, warm and cold startup mass emissions are not the same because there is a statistical difference between their sample means).

Figure 2. NO_x Mass Emissions Box Plots for CTGs Hot, Warm and Cold Startups and Shutdowns



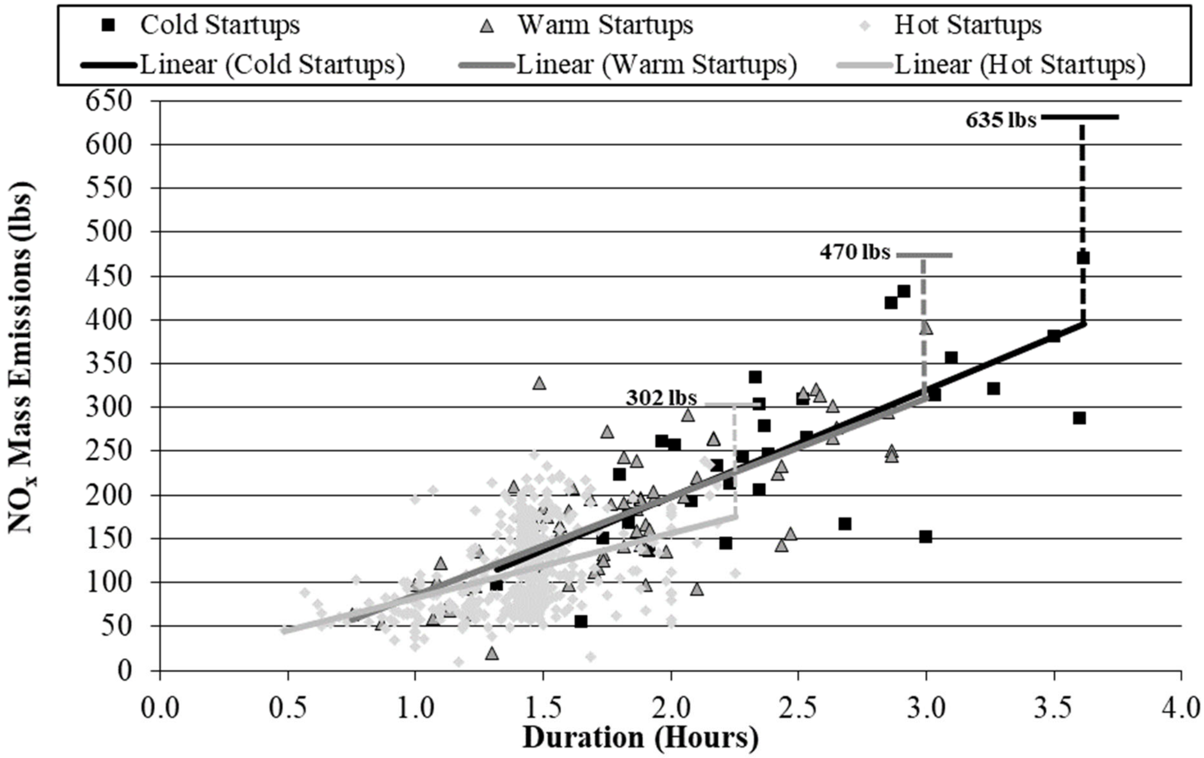
Since mass emissions from the CTGs are dependent upon duration (i.e., the longer a unit operates the more emissions are generated), a regression analysis was performed to calculate the upper prediction bound for NO_x, CO and VOC mass emissions at each of the eight SU/SD categories. Regression analyses were prepared for NO_x, CO and VOC mass emissions versus duration for each SU/SD category. As an example, Figure 3 illustrates the NO_x mass emissions dependence upon hot, warm and cold startup durations by plotting NO_x mass emissions versus duration for each startup event.

Figure 3. NO_x Mass Emissions vs. Duration for Hot, Warm and Cold Startups



For each historical SU/SD dataset, the 99.9% upper prediction bound as discussed in the Event Emissions section above is calculated based on the relationship between NO_x, CO and VOC mass emissions and corresponding duration. Because mass emissions are dependent upon SU/SD durations, the upper prediction bound equation also utilizes the estimated slope from the fitted regression model between mass emissions and duration. Similar to the duration analyses, presented above, the upper prediction bound can be used to predict future SU/SD NO_x, CO and VOC mass emissions values. Future SU/SD mass emissions values are expected to be less than or equal to the 99.9% upper prediction bounds with an approximate 99.9% confidence. Figure 4 shows the 99.9% upper prediction bound NO_x mass values for hot, warm and cold startups.

Figure 4. NO_x Mass Emissions vs. Duration, Best Fit Lines and Upper Prediction Bounds for Hot, Warm and Cold Startups



Each 99.9% upper prediction bound was calculated at the maximum duration value for each NO_x, CO and VOC SU/SD dataset to develop a conservative upper bound for SU/SD mass emissions. These 99.9% upper prediction bound values were then compared against the prior mass per event based emission limits and were used to propose new emission limits, summarized in Table 2, based upon the historical CEMS data analysis method described above.

Table 2. Prior and Proposed SU/SD Duration and NO_x, CO and VOC Mass Emission Limits

Duration and Emissions Limit	Hot Startups	Warm Startups	Cold Startups	Shutdowns
Prior NO_x Mass Emissions Limit (lbs)	224.7	389.3	322.2	60.6
Proposed NO_x Mass Emissions Limit (lbs)	**302.4**	**473.6**	**635.4**	**110.9**
Prior CO Mass Emissions Limit (lbs)	142.3	1914.7	1602.7	49.3
Proposed CO Mass Emissions Limit (lbs)	**310.9**	**2236.9**	**2684.1**	**77.1**
Prior VOC Mass Emissions Limit (lbs)	8.3	53.3	24.2	3.2
Proposed VOC Mass Emissions Limit (lbs)	**8.7**	**56.0**	**60.6**	**3.8**

The mass per event based emission limits were increased for each SU/SD category and the proposed duration and mass per event emission limits were approved by the state regulatory agency.

FACILITY 2 CASE STUDY – The proposed enhanced data analysis framework was applied to Facility 2 with efforts to develop SU/SD duration and emission limits based on historical CEMS data for a boiler with no prior air permit/approval startup and shutdown definitions.

Case Study 2 Qualitative Assessment

As mentioned in the case study overview section above, the facility requested that the state regulatory agency allow for the use of historical CEMS data collected over a representative period of time in lieu of one-time initial compliance testing to develop representative SU/SD duration and mass emission limits. Progress regarding data collection was regularly communicated to the state regulatory agency within periodic air compliance reports.

The scope development process included reviewing the permits/approvals, setting up means of communication with the state regulatory agency, establishing methods to record and manage data for analysis, and selecting the primary and supporting parameters to be recorded. For instance, unit time online, NO_x emissions, and CO emissions are primary parameters and operating parameters such as load and heat input are supporting parameters. The main stakeholders were the facility's environmental manager, plant manager and the consultant (i.e., authors) that performed the data collection, analyses and report writing. Since the initial air permit did not include SU/SD definitions, emission limits or restrictions for this boiler, we leveraged our expertise and experience working with various DAHS software packages to assess the ability of the applicable DAHS software to best implement proposed SU/SD duration and mass per SU/SD event based emission limits.

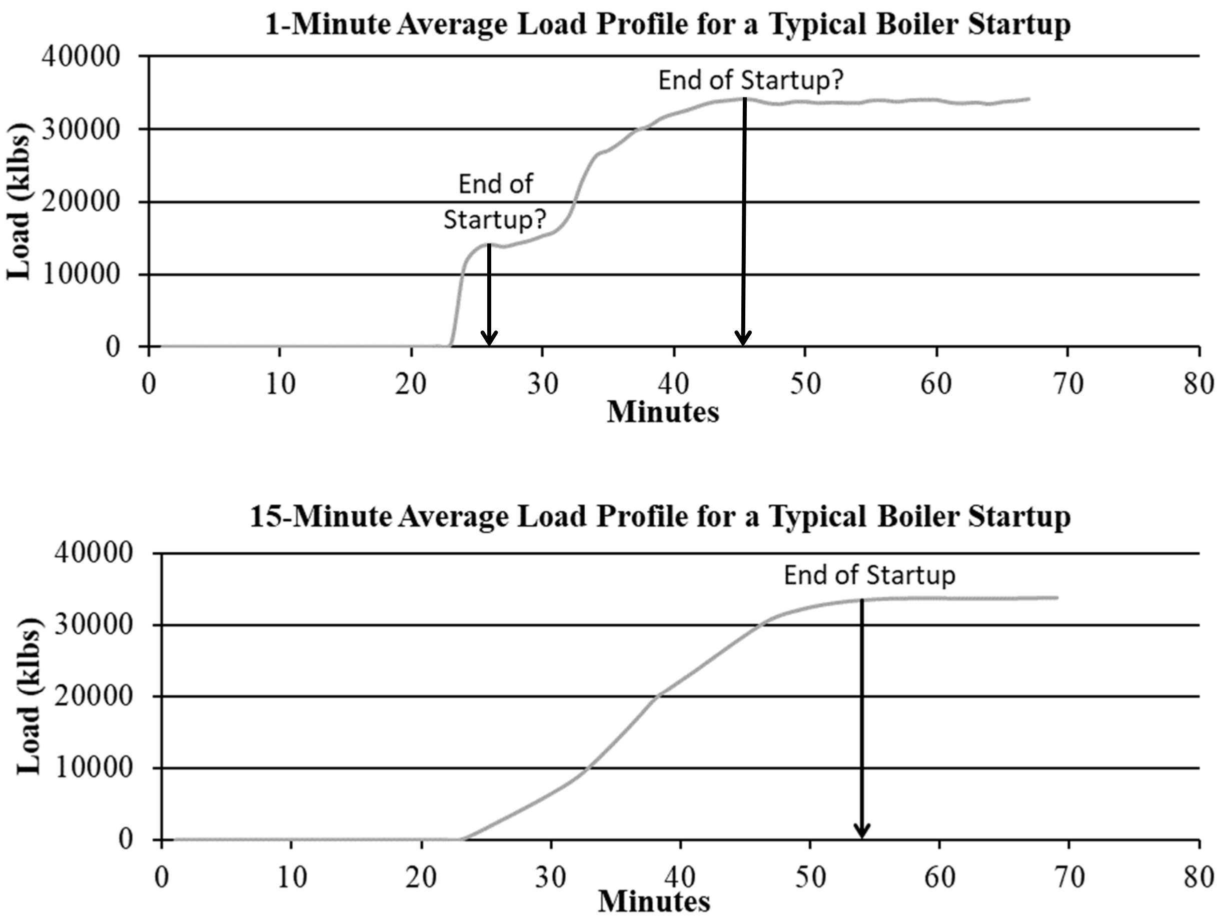
Procedures were also established to make regulatory reporting more transparent. For example, emissions during SU/SD events over the steady state air permit limits were identified within the quarterly air compliance reports including relevant details about the SU/SD emission limit data collection status. Importantly, SU/SD elevated emission events that occurred during the SU/SD emission limit data collection and development process were not treated as monitoring deviations with the applicable state regulatory agency.

Case Study 2 Quantitative Assessment

Quantitative assessment was again conducted according to the method and model proposed in Suess et al., 2009.[4] Minute data monitored by a certified NO_x and CO CEMS was utilized in the assessment. Data was collected for all operating data over a period of 12 quarters to obtain a large enough dataset to account for seasonality and different site specific operating conditions. The data evaluation included identification and documentation of duration as well as corresponding total NO_x and CO mass emissions for each SU/SD event. More than 1.5 million data points were processed for each parameter. Data processing was completed using a combination of open source statistical programming packages and Microsoft® Office® products (i.e., R and Microsoft® Excel®).

Following data collection, raw minute data was processed to exclude offline data and further processed to remove minutes in calibration, maintenance and/or malfunction (e.g., power failure, analyzer fault, false online periods, data affected by adverse weather). After cleaning the data and during the data wrangling portion of the project, durations for SU/SD events were evaluated and determined based on a set of conditions that were deemed appropriate for typical boiler operation. The conditions to determine SU/SD durations were developed from pollutant emission rates in the same unit of measure as the corresponding and existing steady state emission limits (i.e., NO_x lb/mmbtu, NO_x lb/hr, CO lb/mmbtu, and CO lb/hr) as well as boiler steam load (klbs). To reduce the high level of fluctuation (i.e., noise) within 1-minute CEMS data, 15-minute rolling averages were calculated and used to identify the end of each boiler startup period and the beginning of each boiler shutdown period. Figure 5 illustrates that 15-minute rolling averages were necessary to identify the end of boiler startup periods as the 15-minute rolling averages provide a smoother trend and clearer identification of actual SU/SD durations compared to 1-minute data. The same concept applies to identifying the beginning of each boiler shutdown period and shutdown boiler durations.

Figure 5. Load Profile of a Typical Boiler Startup: 1-Minute vs. 15-Minute Rolling Averages Used to Identify SU/SD Durations



With the 15-minute rolling average load and emission rate parameters developed, SU/SD events were identified based on the following definitions:

Startup Definition – Startup begins when fuel combustion begins and ends when the 15-minute rolling average of NO_x and CO emissions (i.e., lb/mmbtu and lb/hr) are in compliance with the steady state BACT permit limits AND the difference between consecutive 15-minute rolling average steam load values is less than 0.5%. Startup events are at least 15 minutes long as 15 minutes are needed to calculate the first 15-minute rolling average.

Shutdown Definition – Shutdown begins when consecutive 15-minute rolling average steam load values differ by more than 0.5% and ends when fuel combustion ends.

Importantly, these SU/SD definitions were only used to develop duration and emission limits and were not used as enforceable regulatory SU/SD definitions specified in the permit/approvals.

The SU/SD events were then divided into two datasets based on fuel combustion and represented as 'gas-fired' data and 'oil-fired' data. Gas-fired and oil-fired SU/SD duration datasets were analyzed separately. The range of plausible values of distribution are typically determined using confidence intervals and prediction intervals at an acceptable significance level. A 99.9% prediction interval was calculated to determine the upper prediction bound for gas-fired and oil-fired SU/SD datasets using equation 1. Then, the upper prediction values were rounded up to the nearest half hour to determine the proposed duration limits as shown in Table 3.

Table 3. Startups and Shutdowns Duration Descriptive Statistics and Proposed Duration Limits

Descriptive Statistic	Gas-Fired Startups	Gas-Fired Shutdowns	Oil-Fired Startups	Oil-Fired Shutdowns
Sample Size	100	115	20	26
Mean (minutes)	43	11	57	19
Maximum (min)	119	46	122	55
Standard Deviation (min)	20	10	25	15
99.9% Upper Prediction Bound (min)	111	45	156	75
Proposed Duration Limit (min)	**120**	**60**	**180**	**90**

NO_x and CO mass emissions during each SU/SD event were calculated based on proposed duration limits summarized in Table 2. The descriptive statistics for NO_x mass SU/SD emissions are summarized for illustration purposes with box plots shown in Figure 6. Then, an upper prediction bound analysis with a significance level of 99.9% was carried out using equations provided above, within the data analysis SU/SD events section, to calculate the upper prediction bound for NO_x and CO gas-fired and oil-fired SU/SD emissions. As an example, Figure 7 shows the NO_x mass emissions upper prediction bound for gas-fired startups.

Figure 6. NO_x Mass Emissions Box Plots for Gas- and Oil-Fired Startups and Shutdowns

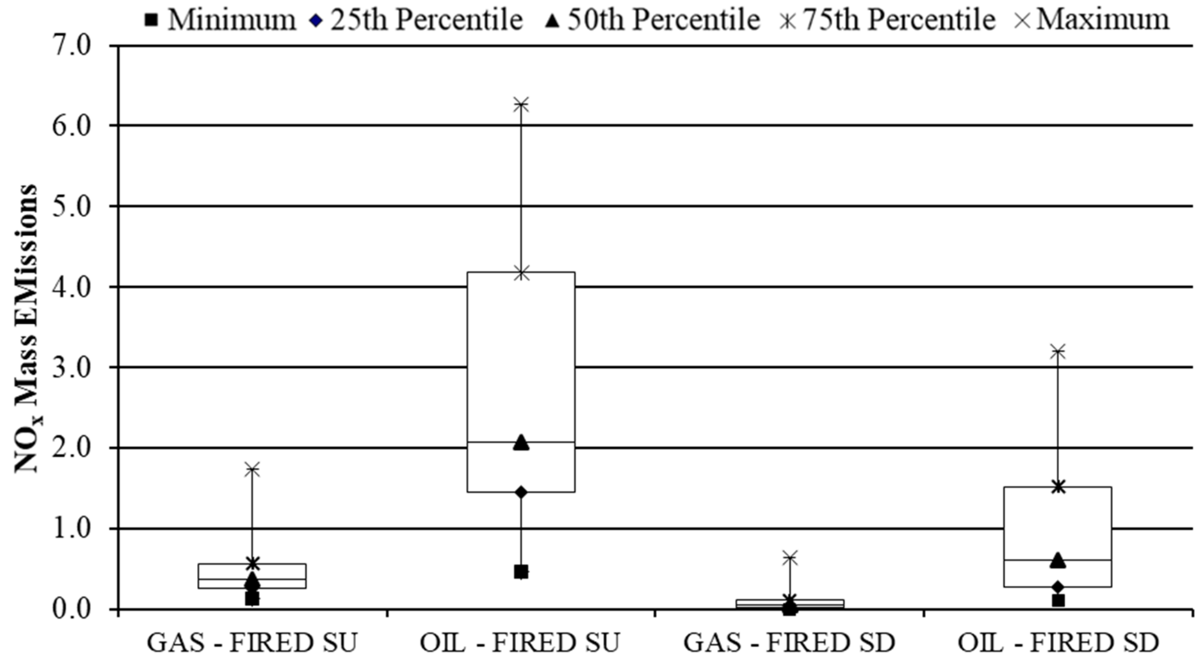
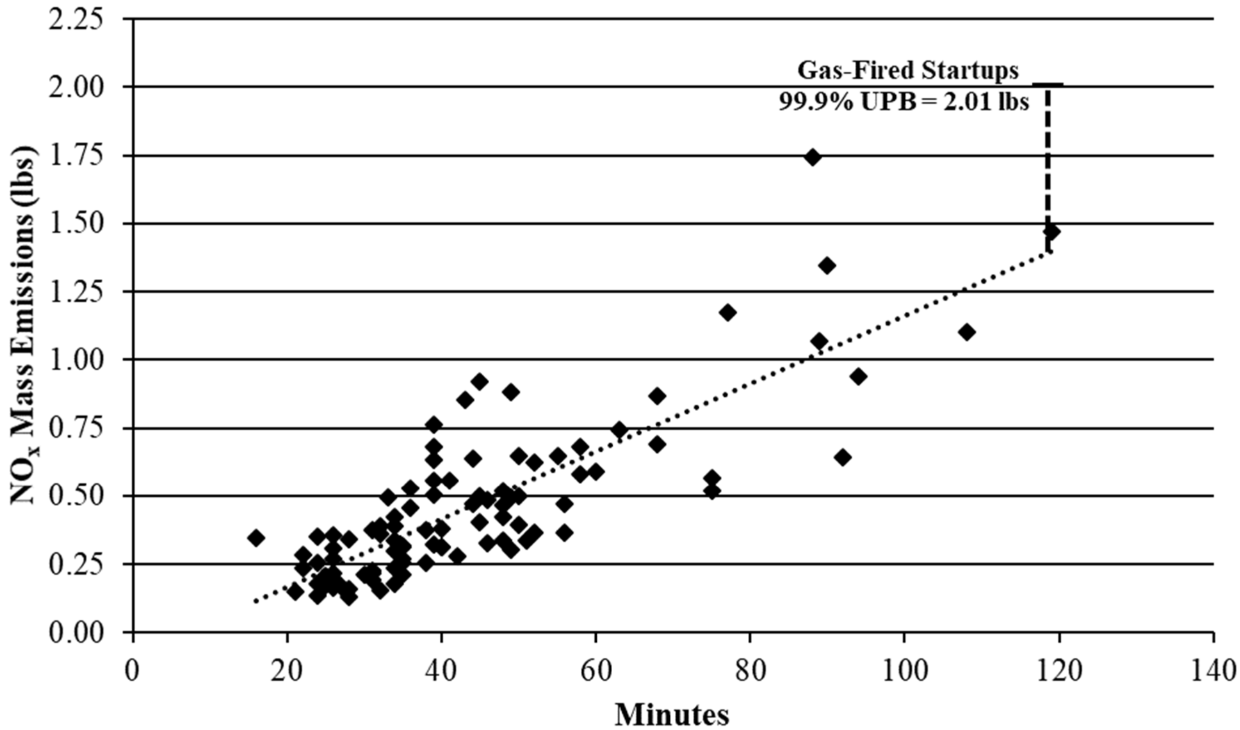


Figure 7. NO_x Mass Emissions vs. Duration, Best Fit Line and Upper Prediction Bound for Gas-Fired Startups



Each NO_x and CO mass emissions (i.e., lbs) 99.9% upper prediction bound for gas- and oil-fired startups and shutdowns were compared against the equivalent amount of NO_x and CO mass emissions that would be allowed based upon the existing steady state BACT NO_x and CO mass emission rate (i.e., lb/hr) limits. The NO_x and CO allowable mass emissions calculations based on the proposed SU/SD duration limits yield values ("Allowable NO_x or CO Mass Emissions") close to the calculated upper prediction bound values. The descriptive statistics, allowed mass emissions and proposed NO_x and CO mass emission limits are summarized for NO_x and CO in Table 4.

Table 4. Descriptive Statistics and Proposed NO_x and CO Mass Emission Limits for Boiler Gas-Fired and Oil-Fired Startup and Shutdown Events

Descriptive Statistics	Gas-Fired Startups	Oil-Fired Startups	Gas-Fired Shutdowns	Oil-Fired Shutdowns
Sample Size	100	20	115	26
Maximum NO_x Mass Emissions (lbs)	1.74	6.27	0.64	3.20
Mean (lbs)	0.45	2.70	0.09	0.97
Standard Deviation (lbs)	0.30	1.66	0.10	0.84
99.9% Upper Prediction Bound (lbs)	2.01	10.62	0.57	3.92
Existing NO_x Permit Limit (lb/hr)	1.38	11.92	1.38	11.92
Proposed Duration Limit (minutes)	120	180	60	90
Allowed NO_x Mass Emissions (lbs)	2.76	35.76	1.38	17.88
Proposed NO_x Emissions Limit (lbs)	**2.76**	**35.76**	**1.38**	**17.88**

Descriptive Statistics	Gas-Fired Startups	Oil-Fired Startups	Gas-Fired Shutdowns	Oil-Fired Shutdowns
Sample Size	100	20	115	26
Maximum CO Mass Emissions (lbs)	8.18	0.32	0.10	0.28
Mean (lbs)	0.60	0.15	0.01	0.02
Standard Deviation (lbs)	1.22	0.08	0.01	0.05
99.9% Upper Prediction Bound (lbs)	6.03	0.58	0.06	0.29
Existing CO Permit Limit (lb/hr)	1.38	4.17	1.38	4.17
Proposed Duration Limit (minutes)	120	180	60	90
Allowed CO Mass Emissions (lbs)	2.76	12.51	1.38	6.26
Proposed CO Emissions Limit (lbs)	**6.03**	**12.51**	**1.38**	**6.26**

The proposed NO_x and CO lbs per startup or shutdown event emission limits were determined as the maximum of either the "Allowable NO_x or CO Mass Emissions" or the 99.9% upper prediction bound values. The data analysis validated the BACT emission limits during SU/SD events for all scenarios except for gas-fired startups CO emissions. The state regulatory agency recently accepted the proposed boiler SU/SD durations as well as NO_x and CO mass emission limits. The DAHS implementation process is currently underway to automate the compliance reporting based on new SU/SD event based duration and emission limits.

Case Studies Comparison

Although the two case studies discussed in this paper differ in their scope, the same framework was applied to successfully revise or develop unit specific SU/SD duration and mass per SU/SD event based emission limits. The Facility 2 case study was more comprehensive and complex compared to the Facility 1 case study. Within the Facility 1 case study, hour level data was organized into medium sized datasets that were analyzed within spreadsheets, and SU/SD duration and mass per event emission limits were already incorporated in the air permit; hence, the goal was to review and update the limits based on historical CEMS data. In contrast, the Facility 2 case study utilized statistical programming packages and minute level data to help define SU/SD conditions using an iterative approach, and new SU/SD duration and mass per event emission limits were developed using historical CEMS data. Raw emissions and operational data within each case study was collected and aggregated from different DAHS software and hardware systems; however, the collected raw data was processed and analyzed using the same statistical approach based on the upper prediction bound.

CONCLUSION

This paper is meant to address the lack of standard publicly available guidelines to review or develop SU/SD duration and mass per SU/SD emission limits by presenting a successfully implemented and proven, objective, data analysis driven framework used to develop and implement SU/SD limits from large stationary combustion units equipped with CEMS. The flexibility and efficacy of the presented framework was demonstrated with two case studies that differed in scope and scale, underscoring the framework's versatility. The success of the enhanced data analysis framework compared to the previous work presented within Suess et al., 2009,[4] heavily relies on the interaction between the qualitative aspects driven by people and the quantitative elements driven by data. The framework is adaptable and can be streamlined to satisfy facility specific regulatory requirements. Using available statistical software packages helps reduce time cleaning and processing data, allows for more creative and flexible evaluation mechanisms to verify critical project startup and shutdown definitions, and helps increase the project efficiency by allowing for multiple data analysis iterations in a shorter period of time. The enhanced data analysis process discussed in this paper may be used by any facility to implement new startup or shutdown limits, or to help mitigate compliance risk by reviewing, validating, or requesting modification of existing startup or shutdown limits, from the applicable regulatory authority, that were developed using other sources besides site specific CEMS data. Furthermore, regulatory agencies may also find this process useful where startup and shutdown emission limits are not currently nor frequently included within their jurisdiction's air permits, but may need to be based upon the current regulatory climate,[1] or where facilities are having problems satisfying existing limits that may need to be revised based on site specific historical CEMS data. The authors hope this paper provides a framework to help both industry and regulators standardize the development of SU/SD limits from large combustion units equipped with CEMS.

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KEYWORDS

Startup, Shutdown, Continuous Emission Monitoring System, CEMS, Upper Prediction Bound, Air Permitting, Emission Limits, Emissions Analysis, Statistical Analysis, Stationary Combustion Source, Simple Cycle, Combines Cycle, Combustion Turbine, Boiler