2014 Colorado Oil and Gas Drill Rig Field Study
Model Evaluation Database - Technical Support Document

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1. Introduction and Next Steps

The Drill Rig 1-hour Nitrogen Dioxide (NO_2) Collaborative Monitoring Study (2014 Colorado Field Study) was performed at two well pad sites in the Denver-Julesburg Basin near Platteville, Colorado over a six-week period in October and November of 2014. The objective of the study was to measure drill rig diesel generator emissions and associated ambient air concentrations in proximity to the drill rigs. Continuous 5-minute and 1-hour average ambient concentrations of NO_2 and oxides of nitrogen (NO_x) were measured, along with meteorological variables such as wind direction and wind speed.[1] This document describes the efforts of the Colorado Field Study Workgroup that resulted in the development of a model evaluation database (2014 Colorado Model Evaluation Database) based on the field study measurements. The Colorado Field Study Workgroup was formed to evaluate the data sets collected from the 2014 Colorado Field Study and to develop a model evaluation database. The agencies and organizations that participated in the workgroup included ERM, API, AECOM, Earth Systems Sciences (ESS), Bunyak Consulting (under contract with WESTAR), WESTAR-WRAP, City and County of Denver, EPA, and BLM.

The data collection activities for both the 5-minute and 1-hour averaging periods included:

- NO_x, Nitric Oxide (NO), and NO_2 stack concentrations were continuously monitored from three diesel engines that powered a drilling rig;
- Carbon Dioxide (CO_2), Ozone (O_3), temperature, and pressure of the engine exhaust were continuously monitored to obtain exhaust flow rates and to calculate mass emissions of NO_x and NO_2;
- Ambient concentrations of NO_x and NO_2 were continuously monitored at 12 sites to capture upwind, downwind, and crosswind concentrations relative to the drilling rig;
- Ambient levels of O_3 were continuously monitored at one upwind and one downwind site; and
- Wind speed, wind direction, and additional meteorological parameters were continuously monitored on a 10-meter tower.

The 2014 Colorado Field Study was conducted at two adjacent well pads (Pad 1 and Pad 2), where three oil and gas wells were drilled near the center of each pad. Each well took six to ten days to drill and the same equipment was used at each well pad. The ambient levels of NO_2 and NO_x were monitored at up to 12 locations upwind, downwind, and crosswind to the drill rig. At the same time, emissions were measured from the five stacks associated with three diesel generators. Meteorological variables that disperse the stack emissions were also monitored, along with the ambient levels of O_3. Ozone is important because this pollutant regulates the conversion of NO emissions to NO_2 through ozone titration. Additional details can be found in the "WESTAR Drilling Rig 1-hour NO_2 and NO_x Emissions and Ambient Air Impacts" report.[2]

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[1] Note that all 5-minute and hourly values were reported in the original data set as "hour beginning", thus reported hour 0 is the first hour (hour 1) of the day. This is the case for emissions, ambient, and meteorological measurements. To be consistent with model input requirements, references in this document and the 2014 Colorado Model Evaluation Database follow the "hour ending" convention where reported hours 0 to 23 have been changed to hour 1 through hour 24.

[2] WESTAR Drilling Rig 1-hour NO_2 and NO_x Emissions and Ambient Air Impacts, April 10, 2015. Revised August 7, 2018 (see SUPPORTING_DOCUMENTS folder: 1-hour NO2 Study Report_Final_14APR2015_Rev7AUG2018.pdf).

The next steps for the Colorado Field Study Workgroup will be to initiate activities related to Phase 2 for the workgroup – data analysis and model evaluation using EPA's AERMOD model and the 2014 Colorado Model Evaluation Database. The group will investigate AERMOD's ability to predict air quality impacts resulting from drill rig operations based on the dispersion of total NOx concentrations, downwash, and chemistry of NOx to NO_2 conversion. The evaluations will include sensitivity studies and model to measurement comparisons. The 2014 Colorado Model Evaluation Database is also available for interested parties to conduct model evaluation studies.

The 2014 Colorado Field Study was co-sponsored by the United States (U.S.) Bureau of Land Management (BLM) and the American Petroleum Institute (API). The Western States Air Resource Council (WESTAR) provided project oversight and was advised by a Study Management Team (SMT) with representation from BLM, API, the U.S. Environmental Protection Agency (EPA) and the Wyoming Department of Environmental Quality – Air Quality Division (WDEQ-AQD). The owner of the two well pads provided access to the test sites, while the drilling company provided logistical support to the contractor measurement teams.

BLM initiated the project to improve information about drill rig impacts for National Environmental Policy Act (NEPA) assessments. The project goal from the BLM perspective at the time was to provide information about AERMOD's ability to effectively characterize the air quality impacts resulting from drill rig operations and associated emissions. The BLM also anticipated using the data to determine whether improvements to AERMOD may be needed to more accurately represent these sources or how NEPA decisions could account for the uncertainty associated with these sources.

This document does not impose binding and enforceable requirements or obligations on any person or organization, and it is not final agency action. The development of the data sets does not imply any pre-approval for usage and no single or collection of data contained in the 2014 Colorado Model Evaluation Database have been reviewed or determined to be complete, correct, or acceptable by any regulating agencies for air quality applications. The use of any single or collection of data can only be used in regulatory air quality analyses that have been approved by the appropriate reviewing authority. These measurements of temporary sources do not reflect any violations of the 1-hour NO_2 National Ambient Air Quality Standard (NAAQS). The measurements taken during the 2014 Colorado Oil and Gas Drill Rig Field Study also reflect the emissions control technology that was used at the time of the study and not the emission control technology that may currently be used by oil and gas operators. The emissions from drilling rigs will continue to be reduced as the emission control technology continues to improve.

2. 2014 Colorado Model Evaluation Database

The data sets collected at the Colorado drill rig site between October 10 to November 16, 2014 include NO_x, NO, and NO_2 emissions, meteorology, and ambient measurements of O_3, NO_x, and NO_2 at 5-minute and hourly intervals. Amec Foster Wheeler developed the original data sets that contained all the measurement data collected from the 2014 Colorado Field Study[3]. The 5-minute and hourly data included in the original release were subjected to comprehensive quality control/quality assurance (QC/QA) procedures as described in the Amec Foster Wheeler report.

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[3] Review of the Drill Rig 1-hour NO_2 Monitoring Study Data, Findings, Data Modification, and Work Completed, Contract No. 15-11. July 27, 2015 (see SUPPORTING_DOCUMENTS folder: Memorandum_AFW_WESTAR_NO2_Data_Review_20150727.pdf).

This Technical Support Document (TSD) describes a review process that provided additional evaluation of data collected from the field study. The review process resulted in the development of the 2014 Colorado Model Evaluation Database. Briefly, the review process employed procedures involving interpolation, substitution, and correction, where appropriate, to ensure that the evaluation database is as complete and accurate as possible. These procedures have been developed and implemented primarily for NO_x emissions, but were also applied to the meteorological data set on a limited basis. No interpolation or substitution procedures were applied to ambient measurements, but two hours were invalidated at one of the 12 sites. This was due to anomalous NO_2/NO_x ratios and finding that the wind direction did not substantiate an impact from the drill rig engines for these two hours. The data sets provided as part of the 2014 Colorado Model Evaluation Database clearly identify all the data points that were substituted, corrected, or invalidated, and include all original values and missing indicators. These modifications were only applied to the hourly data sets, while the 5-minute data set includes the unmodified data. Thus, analyses that rely on the 5-minute data will be inconsistent. In particular, the 5-minute data will have missing data points, while the hourly data will have values for every data point. The hourly data set will not show any missing data points because of the procedures implemented to gap-fill the data set. As a result, these inconsistencies should be noted accordingly. The 2014 Colorado Model Evaluation Database includes several data sets that are listed at the end of this document.

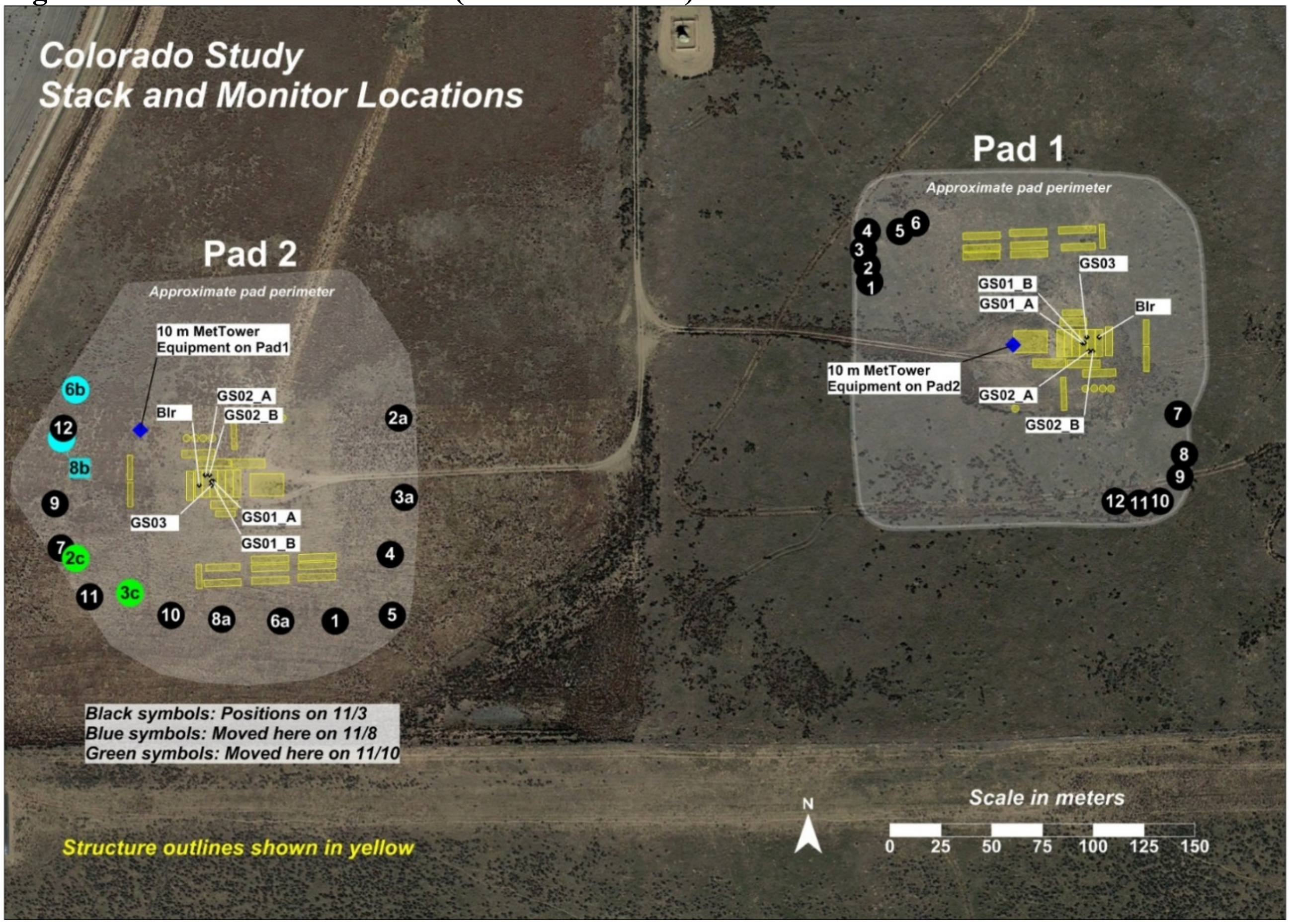
2.1 Overview of Equipment, Measurements, and Layout

The drilling rig was powered by two diesel fired Caterpillar 3512B generators (Genset 01 and Genset 02) and one diesel fired Caterpillar C27 generator (Genset 03). These diesel engines were rated as EPA Tier 2 engines,[4] which was verified by comparing reported emissions with publicly available vendor data. The exhaust from both Gensets 01 and 02 was split between two separate stacks (Genset 01A, Genset 01B, Genset 02A and Genset 02B) approximately one to two meters (m) apart, while the Genset 03 exhaust was routed to a single stack. The site also included a boiler that was used during cold weather. Emissions and stack parameters from these four fuel-fired units (six separate stacks) were monitored on a 5-minute and hourly basis. Several other smaller potential sources of NO_x at the sites included diesel generators for night-time lighting, a front-end loader, a forklift, a portable flare, and gasoline and diesel on-road vehicles. Emissions from these smaller sources were not calculated or considered explicitly in the reported data sets.

Figure 1 displays emissions sources and the 12 ambient measurement locations for both Pad 1 and Pad 2. In addition to measuring NO_x and NO_2, monitoring sites 1 and 12 were equipped to measure O_3 and meteorological variables, including wind speed and direction, the standard deviation of horizontal wind direction (sigma-theta), and temperature. More comprehensive meteorological measurements, including 2-m to 10-m temperature difference, humidity, and rainfall, were taken on a 10-m on-site tower. This tower was located on Pad 2 during drilling on Pad 1, and on Pad 1 during drilling on Pad 2. During drilling on Pad 2, weather forecasts indicated a significant shift in the wind patterns. This prompted the study measurement team to relocate four of the measurement sites (2, 3, 6 and 8), as depicted in Figure 1. Sites 2a, 3a, 6a and 8a represent the original locations, while 2c, 3c (relocated on November 10), 6b and 8b (relocated on November 8) indicate the new location of these sites.

[4] EPA Emission Standards Reference Guide: https://www.epa.gov/emission-standards-reference-guide

Figure 1. Locations of Well Pads (Pad 1 and Pad 2) and Monitor/Measurement Sites.



2.2 Data Review Procedures

It is important to have an accurate and a comprehensive model evaluation database for model evaluation studies. If data points are missing for at least one unit or time-step, the hour cannot be used in a model evaluation study. As a result, the Colorado Field Study Workgroup closely examined the data reported as missing and filled those data points using various analytical techniques.

The Colorado Field Study Workgroup conducted additional QC/QA analyses of the original data sets provided by Amec Foster Wheeler. The workgroup also employed procedures involving interpolation, substitution, and correction to develop accurate and comprehensive data sets for the purpose of model evaluations. Note that the procedures were only applied to the hourly data sets and primarily developed and implemented for the NO_x emissions. No modifications were applied to ambient measurements and 5-minute data sets. The final data sets, along with the original data sets, are included as part of the 2014 Colorado Model Evaluation Database. Appendix A of this TSD includes figures associated to the data review procedures or graphical displays depicting the analytical techniques applied to the final data sets included in the 2014 Colorado Model Evaluation Database. The calculations used for the data modifications in all cases are fully highlighted and illustrated in documents and data files provided with the 2014 Colorado Model Evaluation Database.

The following sections describe the data sets and data review procedures used to generate the 2014 Colorado Model Evaluation Database. A total of 912 hours was reported in the original data sets provided by Amec Foster Wheeler, including several days when the drilling equipment was moved from Pad 1 to Pad 2. Following the data review process described here, final data sets include 723 hours. The beginning and end dates and times of each data set (Pad 1 and Pad 2) were set by considering the availability of valid emissions, meteorological, and ambient measurement data. Since monitors were relocated during the measurement period for Pad 2, the Pad 2 time period was split into three parts (Pad2a, Pad2b, Pad2c) to reflect times when locations were changed and to ensure that receptor locations used for model evaluation studies are specified correctly for each of four time periods (Pad 1, Pad2a, Pad2b, and Pad2c). Table 1 outlines the beginning and end dates and times, the total number of hours, and the number of hours affected by the modifications made to the data sets described in this document. Note that all dates are in 2014.

Table 1. 2014 Colorado Model Evaluation Database: Data Time Periods

Description	Start	End	# Hours	# Hours with Data Modifications
Pad 1	October 10 Hour 1	October 26 Hour 14	397	148
Pad 2a	November 3 Hour 1	November 9 Hour 10	154	34
Pad2b	November 9 Hour 11	November 10 Hour 14	29	6
Pad2c	November 10 Hour 15	November 16 Hour 14	143	106
Pad2 Total	November 3 Hour 1	November 16 Hour 14	326	146

3. Emissions Data Set

Mass emissions of NO_x and NO_2 were calculated from three independent in-stack measurements consisting of: (1) stack NO_x gas concentrations; (2) stack temperatures; and (3) pressure difference (in-stack delta-p). The stack NO_x gas concentrations were measured by routing a gas sample through a heated sampling line from the stack to a TECO Model 42C chemiluminescence analyzer. This instrument measured and recorded NO_x, NO, and NO_2 concentrations. In-stack delta-p was measured with a pitot tube, and in-stack temperature was measured with a Type-K thermocouple. These measurements were taken and recorded separately. The in-stack delta-p measurements were used to calculate exhaust velocity and subsequently mass emissions when combined with the stack diameter to calculate flow, temperature, and measured NO_x/NO_2 concentrations. Concentrations were measured for Gensets 01 and 02 prior to the split in the exhaust. For these units, stack temperature and delta-p were measured independently in each stack. The characteristics of the stack NO_x concentrations, temperature, and delta-p measurements over time and inter-relationships between the measurements were examined in order to assist with filling gaps in the final database.

3.1 Independent Measurements Review

The Colorado Field Study Workgroup conducted a detailed review of the three independent measurements associated with stack emissions. The results of the review are discussed below.

3.1.1 Stack NO_x Concentrations

In-stack concentrations were reported as Not Available (NA), or missing, numerous times during the data collection period. Some of the missing values (one or two hours per day) were due to the performance of a calibration check on the instrumentation. There were also some longer periods of missing data (Genset 02, October 21, hours 1 through 17) when other parameters (temperature, delta-p) indicated that the unit was operating. Missing codes were also recorded during some hours when temperature and delta-p indicated that the unit was not operating (i.e., valid zero emissions - not missing). Additionally, during the final week of measurements on Pad 2 (November 10th through November 16th), an atypical cold outbreak occurred across the region. This cold outbreak brought temperatures well below freezing, coupled with strong and persistent northeast winds. Forecasting these conditions led to the relocation of some of the monitoring stations, as depicted on Figure 1. The extreme cold led to freezing of the lines carrying stack gas to the analyzer, which resulted in data points that were incorrectly recorded as zero concentration. During this 1-week period, NO_x concentrations were recorded as zeros (invalid) for 37 hours at Genset 01, 10 hours at Genset 02, and 16 hours at Genset 03.

3.1.2 Stack Temperatures

In-stack temperatures were reported as valid for all 723 hours of each of the stacks in the final database. A review of these data points reveals that the in-stack temperature measurements appear to provide a reliable indicator of whether the generator engines were in operation. This is illustrated in Figures A.1 and A.2. These figures display hourly stack and ambient temperatures for each of the three generators. The solid data points in these figures represent hours when the reported temperatures are consistent with the reported NO_x concentrations. The open data points represent hours when the two measurements are not consistent, or when the NO_x concentration is missing or zero and the temperature is greater than 500 degrees Fahrenheit. These data points represent hours that would be considered missing. Periodically, a close correlation is seen between stack and ambient temperature, preceded by a steep decline and followed by a steep increase in stack temperature. This indicates that the stack temperature follows ambient temperature when a unit is not operating and that higher temperatures are associated with unit operation.

3.1.3 In-Stack Delta-P

The in-stack pressure differential (delta-p) was measured with a pitot tube, with one leg pointed into the flow and the other leg pointed at a right angle to the flow. Note that higher values of delta-p reflect greater exit velocities from the stacks. The methodology for calculating velocity from reported values of delta-p and temperature was based on U.S. EPA's Method 2[5]. Details on the inputs and formulas used for this procedure are provided in the 2014 Colorado Model Evaluation Database.

In-stack delta-p values were reported for each of the 723 hours in the final data sets of the 2014 Colorado Model Evaluation Database. There was no indication of validity (e.g. NA) for any data point. For the hours when stack temperatures indicated that the emission unit was not operational, a small positive, zero, or small negative value of delta-p was reported for Gensets 01 and 02. For Genset 03, delta-p measurements during some periods appeared to be erroneous, specifically:

- Several hours on November 14 and November 15 reported negative values of delta-p when NO_x concentrations and stack temperatures were in the normal range, which indicates that the delta-p measurements are erroneous;
- During the cold outbreak and immediately after the period when the sampling line froze (starting on November 11, hour 16), the reported delta-p values increased significantly, reaching 10 inches of H_2O with associated calculated exit flow reaching nearly 14,000 acfm and associated mass emissions reaching nearly 25 pounds per hour. These values are greater

[5] https://www.epa.gov/emc/method-2-velocity-s-type-pitot

than 2.5 times the values reported in the publicly available vendor data (see section 2.3.2 below – Table 2);

- Between November 13 (hour 18) and November 14 (hour 7), stack and ambient temperatures (Fahrenheit) were in the single digits, indicating that the unit was not operating, but delta-p for Genset 03 reached as high as 5 inches H_2O.

The Colorado Field Study Workgroup conducted further analyses that examined the variability of delta-p values as recorded in the 5-minute data set. The results are shown in Figures A.3, A.4, and A.5 for Gensets 01, 02, and 03, respectively. These figures show delta-p variations over hours when the units were operating and highlight the increase in delta-p for Genset 03 starting on November 11, 2014.

Based on these observations and analyses, the delta-p values for Genset 03 were considered invalid for the time periods indicated, and were replaced with substitutions developed in accordance with the methodology outlined in Section 3.3 below.

3.1.4 Independent Measurements: Inter-relationships

Inter-relationships among stack NO_x concentrations, stack temperatures, and in-stack delta-p were explored by creating a set of figures accompanied by statistical analyses involving linear regression. Figure A.6 shows NO_x concentration cumulative frequency analyses for each of the three generators. As shown in Figure A.6, there is a steep slope from zero to approximately 300 parts per million (ppm) for Gensets 01 and 02 before becoming more gradual. This transition around 300 ppm of NO_x likely represents the transition of startup/shutdown and normal operating modes.

Genset 02 and Genset 03 appear to exhibit this transition at a slightly higher NO_x concentration (approximately 330 and 380 ppm, respectively). Therefore, the minimum NO_x concentration to represent normal operations and for the analyses was set to 300 ppm for Genset 01, to 330 ppm for Genset 02, and to 380 ppm for Genset 03.

Figures A.7 through A.9 display NO_x concentrations as a function of temperature and delta-p for each of the five generator stacks. These figures display scatterplots and the results of the regression analyses for three time periods:

- Period 1: October 10 (hour 1) to October 26 (hour 13) (Pad 1)
- Period 2: November 3 (hour 1) to November 10 (hour 16) (Pad 2, prior to the cold outbreak)
- Period 3: November 10 (hour 17) to November 16 (hour 14) (Pad 2, during and after the cold outbreak)

Three figures are presented for Genset 01 (Figure A.7) and Genset 02 (Figure A.8), where the first-two figures (i.e., a. and b.) are associated to each individual stack and the third figure (i.e., c.) is based on average temperature and delta-p across the two separate stacks for each genset. Figure A.9 presents the results from Genset 03. Note that concentrations are measured prior to the split in flow.

A significant correlation is shown between NO_x concentrations and both temperature and delta-p for most of the time period/genset combinations. However, exceptions include:

- Genset 01, Period 3: Regressions indicate weak correlations for both temperature and delta-p;

- Genset 03, All Periods: Regressions indicate a very weak correlation with large amounts of scatter in the data for temperature, and indicate no correlation for delta-p.

Generally, the temperature correlations are stronger than the delta-p correlations. Temperature also appears to be a more stable measurement and appears to experience less variability than the delta-p measurements.

Several periods of more than just a few hours occurred in the data when NO_x concentrations were missing, including the periods with frozen sample lines. Two techniques were developed for gap filling during these periods based on an examination of the figures and the statistics that describe the inter-relationships among NO_x concentrations, stack temperature, and stack delta-p. The choice of technique was based on whether adequate correlations existed for the generator and time period in question. The techniques and the selection of the technique for each generator and time period requiring gap filling across multiple hours are described here and further summarized in Table 2 below.

1. Temperature Regression: Missing NO_x concentrations were filled using slope and intercept values calculated for the temperature regressions;
2. Similar Period Delta-P Scaling: Missing NO_x concentrations were filled by first locating a different period where NO_x concentrations were available, and which had similar stack temperature, delta-p, and ambient temperatures to the period with missing data. NO_x concentrations during the missing period were then scaled, based on delta-p measurements, to the period with available NO_x data, and the resulting NO_x values were reviewed to ensure that they were within normal ranges.

To maximize the number of useable hours of data, the Colorado Field Study Workgroup closely examined hourly data and applied analytical techniques including gap-filling procedures for data reported as missing (described in Section 3.2 below) and substitution procedures for data determined to be erroneous (described in Section 3.3 below). The analytical techniques included simple interpolation for short gaps and, for emissions, techniques that were based on the examination of inter-relationships among the three independent measurements described above. The analytical techniques were used to fill gaps in the data sets, to substitute data where appropriate, and to correct hours during which emissions were reported as missing ("NA") but were actually hours when the unit was not operating (i.e., a valid zero emission rate).

3.2 Data Gap-Filling Procedures

Data gap-filling was accomplished through the application of the below procedures.

1. As part of the quality assurance process, periodic calibrations were performed on the in-stack analyzers, resulting in missing concentrations. If the NO_x concentration, temperature, and delta-p values were similar before and after the missing hour(s), linear interpolation was performed to fill the gap. Most interpolations were conducted across one or two hours, but a small number extended up to four hours. Most interpolations were implemented for NO_x, NO_2, O_2, and Carbon Dioxide (CO_2) measurements. Only a few interpolations were used on temperature and pressure. Longer periods of missing O_2 and CO_2 were filled with average values.

2. If NO_x ppm was recorded as missing (NA) and the temperature and delta-p values indicated that the unit was down, NO_x and NO_2 ppm were re-assigned to "0" (i.e., a valid 0, not missing).

3. If NO_x ppm was recorded as missing (NA) for more than a few hours (i.e., interpolation could not be performed), or for periods when the Continuous Emission Monitoring System (CEMS) lines were frozen, but pressure and temperature indicated that unit was operational, NO_x and NO_2 concentrations were filled in based on the inter-relationships and techniques described above. The best approach was determined for three different time periods, including Pad 1 (Period 1), Pad 2 prior to the cold outbreak (Period 2), and Pad 2 during and after the cold outbreak (Period 3). A description of the technique for each generator and time period requiring gap filling for more than a few hours is summarized in Table 2.

Table 2. Data Gap-Filling Procedures for NO_x Concentrations.

Generator	Period	Data Fill Technique Used
Genset 01	1	Based on temperature regression
Genset 01	3	Based on similar period delta-p scaling
Genset 02	1	Based on temperature regression
Genset 02	3	Based on temperature regression
Genset 03	3	Based on temperature regression
Period 1: October 10 (hour 1) to October 26 (hour 13) (Pad 1)		
Period 2: November 3 (hour 1) to November 10 (hour 16) (Pad 2, prior to the cold outbreak)		
Period 3: November 10 (hour 17) to November 16 (hour 14) (Pad 2, during and after the cold outbreak)		

4. Genset 03 - 12 hours starting on November 14 (hour 19): Stack delta-p was reported as -0.62 (missing), but stack NO_x concentration and stack temperature were within normal ranges. A period with similar stack NO_x concentration, stack temperature, and ambient temperature was used to create an average delta-p, which was assigned in place of the missing values.

5. Genset 03 - 10 hours starting on October 24 (hour 9): Stack NO_x concentration, delta-p, and stack temperature were within normal ranges, but O_2 and CO_2 stack concentrations were missing. Average values of O_2 and CO_2 were assigned in place of the missing values.

3.3 Data Substitution Procedures

Data substitutions were used for the period when delta-p values for Genset 03 were considered erroneous. The following was applied to substitute data points.

- Genset 3 - Pad 2 starting on November 11 (hour 16): During this time period, recorded stack delta-p increased to an order of magnitude greater than previously recorded, while stack temperatures and stack NO_x concentrations were within normal ranges. The delta-p values were considered invalid and an upper limit to delta-p was applied for those data points. The upper limit was set at a value (1.6 inches H_2O) that resulted in NO_x mass emissions consistent with reported maximum NO_x emissions for this generator type.

3.4 Effects and Comparisons of Data Gap-Filling and Substitution Procedures

The Colorado Field Study Workgroup reviewed publicly available vendor information (documents provided in the database) to assist in providing "ground truth" insights into the generator stack parameters and emission rates. In particular, the vendor information was compared to exhaust flow from the gensets, NO_x concentrations and mass emissions, and stack temperature to determine whether the data were deemed representative. The information was obtained for both types of generators, including model 3512B (Gensets 01 and 02) and model C27 (Genset 03). Table 3 summarizes the characteristics and emissions obtained from the vendor information. The vendor information documents that provided these data points are included in the 2014 Colorado Model Evaluation Database.

Table 3. Summary of Generator Characteristics.

Engine	Parameter	Percent Load				
		100	75	50	25	10
3512B – Gensets 01 and 02	Engine Power bhp	1476	1107	743	384	157
	Exhaust Temp F	792.68	713.66	696.2	614.3	479.84
	Exhaust Flow ACFM	7,335	5,424	3,779	2,444	1,737
	NOx Emissions lbs/hr Nominal	30.19	25.06	18.95	10.22	5.2
	NOx Emissions lbs/hr Site Variation	36.23	30.07	22.74	12.27	6.23
C27 – Genset 03	Engine Power bhp	950	713	475	238	95
	NOx Emissions lbs/hr Nominal	8.25	6.25	4.65	2.41	1.26
	NOx Emissions lbs/hr Site Variation	9.98	7.56	5.63	2.92	1.52
	Exhaust Temp F	914.1	1172.8			
	Exhaust Flow ACFM	5,380	3,472			
	Exhaust Flow SCFM	1,925	1,046			
	Exhaust Flow SCFMd	1,755	918			
	Implied % Moisture	10%	14%			

The effects of the data gap-filling and substitution procedures for the three gensets are displayed in a series of figures included in Appendix A (see Figure A.10 to Figure A.15). Comparisons are also presented with the vendor data described in Table 3 on these figures.

3.4.1 Exhaust Flow

Figures A.10 and A.11 display exhaust flow from all three gensets for Pad 1 and Pad 2, respectively. The horizontal red bars in these figures represent information from the publicly available vendor information, with the range from 75 to 100 percent load. Reported stack flows for Gensets 01 and 03 are generally lower than this range, while reported stack flows for Genset 02 are generally within or higher than this range. For Genset 03, the adjustment made to delta-p during the last part of Pad 2 resulted in stack flow near the top of the range.

3.4.2 NO_x Concentrations and Stack Temperature

Figures A.12 and A.13 display NO_x concentration in ppm and stack temperature from all three gensets for Pad 1 and Pad 2, respectively. The horizontal red bars in these figures represent information from the publicly available vendor information, and as with exhaust flow, the range is from 75 to 100 percent load. Reported stack temperatures for Gensets 01 and 02 are generally lower than this range. For Genset 03, the temperature range derived from the publicly available data was higher than the range of reported temperatures (see Table 3). The open symbols in the NO_x concentration figures represent hours that were filled in based on the data completion procedures described here.

3.4.3 NO_x Mass Emissions

Figures A.14 and A.15 display NO_x emissions in pounds per hour (lbs/hr) from all three gensets for Pad 1 and Pad 2, respectively. The horizontal red bars in these figures represent information from the publicly available vendor information. For Gensets 01 and 02, reported NO_x emissions were typically 2-3 times lower than the vendor data provided in Table 3. Reported NO_x emissions for Genset 03 are generally about half the vendor data range, as shown in Table 3. The adjustment for Genset 03 made to delta-p during the last period of operation at Pad 2 resulted in emissions near the top of the engine design range.

The primary purpose of Figures A.10 through A.15 is to demonstrate that the data review procedures result in values that are reasonably consistent with other reported data. The comparisons shown in these figures also indicate consistency with the vendor information, with the following exceptions:

- Stack temperature for Genset 03: Reported lower than the vendor information;
- Mass emissions for Genset 03: Reported lower than the vendor information except for the adjusted values after the cold outbreak;
- Mass emissions for Gensets 01 and 02: Reported considerably lower than the vendor information.

4. Meteorological Data Set

A review of the meteorological data collected as part of this study revealed that these measurements are complete for time periods when emissions and ambient data were collected during the study. Note that temperature measurements were collected at 2-m, and wind measurements were collected at 3-m and 10-m heights. Additionally, wind measurements were collected at two of the ambient monitoring stations (Site 01 and Site 12). The substitutions or interpolations applied to this data set include:

- Interpolated pressure and temperature for the periods November 10^{th} (hours 11 to 13), and November 16^{th} (hours 0 to 12);
- Substituted missing on-site temperature with Greeley National Weather Service Automated Surface Observing System (ASOS) temperature for the first 13 hours of operation on Pad 2 (starting on November 3^{rd}).

Ambient pressure measurements are used (1) in AERMET, the meteorological pre-processor to AERMOD and (2) to convert the ambient NO_x and NO_2 measurements from parts per billion (ppb) to microgram per cubic meter ($\mu g/m^3$) for use in comparing measurements to modeled concentrations. A review of the pressure values supplied as part of the original data set revealed that the calculated elevation associated with the reported pressure levels was approximately 6,300 feet, compared to the site elevation of 5,030 to 5,040 feet. A correction of 40 millibars (mb) was added to the recorded values, which is the elevation associated with the resulting pressure that were in the range of the site elevation plus or minus approximately 60 feet.

The AERMET input files provided with this data set include surface characteristics (Albedo, Bowen ratio, and roughness length) for each pad in the Stage 3 input files. These characteristics were developed using both the then-current version of AERSURFACE (13016) and similar methods as the 13016 version for later land use files. Land use files from 1992, 2001, 2006, and 2011 were processed and very little differences were found between the different land use years. Canopy and impervious surface data were obtained and used with the 2001 land use files; however, use of these supplemental files had no effect on the results. The characteristics supplied in the Stage 3 inputs were developed based on the 2001 land use data. Some adjustments were made to the surface roughness values in certain sectors to account for conditions in October and November 2014 including small clumps of trees and the locations of equipment adjacent to the pads at the time. The Stage 3 input files also contain alternative inputs that adjust the roughness length (increases and decreases) that can be used for sensitivity testing. Notes included in the Stage 3 surface characteristic files provide additional detail on the adjustments made.

5. Ambient NO_x/NO_2 Data Set and Hourly Background Concentrations

The reported ambient NOx and NO_2 data were not modified through gap filling or substitution. However, a review of the data for the purpose of model evaluation revealed two data points that were invalidated. On November 3 (hour 12), the NOx and NO_2 concentrations were both high and nearly identical at Site 2. Further investigation revealed that during this hour, winds were from the northeast and Site 2 was also located to the northeast (i.e., upwind of the emission sources). This hour also immediately preceded a calibration hour. For these reasons, this hour is likely erroneous, and the data were invalidated. Figure A.16 provides a graphical display of observed NO_2/NOx concentrations and shows the data point that was invalidated. A review of the 5-minute data reveals that the inconsistent NO_x/NO_2 concentrations started at the end of the previous hour. As a result, November 3 (hour 12) was invalidated as well.

Initial sets of hourly background concentrations of NOx and NO_2 were developed for the 2014 Colorado Field Study. Background concentrations were developed by considering the difference between wind direction and the direction from the drill rig engine stacks towards each monitoring location. Two wind direction difference tests were applied. If the hourly wind direction was within 45 degrees of the direction to a monitor, that monitor was considered to be influenced by exhaust plumes from the drill rig engines and not considered in calculating the background concentration. Similarly, if the smallest of the 12 5-minute wind direction differences was within 30 degrees of the direction to a monitor, that monitor was also considered to be influenced by engine emissions and not considered in calculating the background concentration. The background concentration for each hour was calculated as the average of all measurements not influenced by engine emissions (as determined by these wind direction comparisons).

A spreadsheet is provided, along with the hourly background files, which includes documentation of the background concentration calculations. Each record in the spreadsheet represents an hour, and shows minimum and maximum NOx and NO_2 concentration, calculated background concentration, the peak-to-mean ratio for NOx, overall ambient NO_2/NOx ratio, and ambient ratios calculated for background/not background values. Concentrations recorded at each monitor are shown, and wind direction differences for the hour and for the closest 5-minute wind direction are also shown.

Figure A-17 illustrates the relationship of background NOx and NO_2 concentrations to wind direction. In this figure, the ambient ratios which represent the values used to calculate the background concentration are also illustrated. Most of these ratios are high (greater than 0.50), indicating "aged" NOx that has had time to transform. A noticeable increase in background values can be seen in the wind direction range from approximately 180 to 280 degrees, likely representing transport from the Denver and other metropolitan areas.

6. Ozone Data Set and Hourly Ozone File

Two ambient monitoring sites (1 and 12) measured ozone concentrations during drilling for both Pad 1 and Pad 2. Based on the review of the data set, the data capture for ozone was deemed poor. As a result, a monitor located in Greeley, Colorado (AQS Site ID 08-123-0009, "Greeley – Weld County Tower"), which is approximately 19 kilometers (km) north of the drill rig site, was identified as a possible supplemental source of ozone concentrations. Hourly ozone data from Greeley were downloaded from EPA's Air Quality System (AQS)[6] site for the time period covered by this study (i.e., October 10 to November 16, 2014). Table 4 provides a summary of data from all three monitors. Correlation is calculated based on the relationship between the measurements at Site 1 and Site 12 and Greeley.

Table 4. Ozone Statistics

	Site 1	Site 12	Greeley
# hours	723	723	723
# good >0	356	481	692
Pct Capture	49%	67%	96%
Avg PPB	24.7	26.4	23.8
Stand Dev	12.3	12.4	14.8
R^2	0.622	0.689	---

Figure A.18 displays time series of hourly ozone concentrations for each measurement location, separately for Pad 1 and Pad 2. There is reasonably good correlation between the on-site and Greeley measurements. The time series shows that ozone concentrations follow a similar diurnal pattern, and that the Greeley measurements follow the site measurements closely when site measurements are available. There are some exceptions to this during the period of November 3 to November 16 at Pad 2, where the Greeley night-time concentrations are noticeably lower than values recorded at the sites. Given the overall reasonably good correlations, Greeley ozone concentrations can be used as a substitute when site measurements are not available, and for analyses that need ozone concentrations for estimating the atmospheric conversion of NO to NO_2.

An hourly ozone concentration file, to assist with modeling the atmospheric conversion of NO to NO_2, was created using the following approach to determine ozone concentrations for the hourly file:

Step 1 – If Site 1 and Site 12 data are both missing: use hourly value from Greeley O_3

Step 2 – If either Site 1 or Site 12 data is valid: use hourly O_3 from the valid site.

[6] *U.S. EPA Air Quality System.* https://www.epa.gov/aqs

Step 3 – If Site 1 and Site 12 data are both valid, this step was carried out by determining whether one of the two sites was downwind based on the wind direction being ±30 degrees from the center of the engine stacks. If one site was downwind, the assumption was made that the other was upwind. Out of the 723 hours in the data set, 306 hours had valid measurements at both sites. These hours were evaluated based on the wind direction for that hour to determine if one of the two sites were downwind (and, consequently, the other was upwind). Based on this evaluation, the ozone concentration for the hourly file was determined as follows:

- If one site is downwind, use upwind O_3 (total of 66 hours)
- If neither is downwind, use the average O_3 of the 2 sites (total of 240 hours)

Figure A.19 illustrates the relationships between ozone measurements at the two sites. The figure includes data points representing all 306 hours with valid measurements at both sites. The symbols represent one of three conditions: (1) no upwind/downwind monitor (based on wind direction), (2) upwind/downwind data points where the downwind monitor showed decreases in ozone concentration, and (3) upwind/downwind data points where the downwind monitor showed increases in ozone concentration. All the increases occurred when concentrations at the two monitors were similar. However, most of the 66 hours where an upwind/downwind determination could be made showed a decrease in ozone concentration, some of them significant. Although this analysis represents a relatively small set of data points, the comparisons should prove useful in further analysis of the atmospheric transformation of NO to NO_2.

7. Summary

The data measured during a six-week drill rig study field campaign were reviewed for data completeness and suitability as an air dispersion model evaluation database. Careful consideration was given to preparing a complete, model-ready database. A list and a description of each of the files that are included in the 2014 Colorado Model Evaluation Database are provided in Section 7.1.

7.1 List of Data Sets in the 2014 Colorado Model Evaluation Database

1. **Main Documentation:**
   Key documents that users should read include the Technical Support Document for the 2014 Colorado Model Evaluation Database (this document) and Readme file:
   - 2014_Colorado_ModelEvaluationDatabase_TSD.docx
   - 2014_Colorado_ModelEvaluationDatabase_README.docx

2. **Original Data Sets of the 2014 Colorado Field Study:**
   AECOM (a study contractor) collected the field study data and generated the original data sets. Amec Foster Wheeler (another study contractor) then conducted a Quality Assurance/Quality Control review of the AECOM data to generate a more refined data base. The Amec Foster Wheeler data base served as a starting point for the Colorado Field Study Workgroup's review and analysis of the field study data. These files are contained in the sub-folder titled "AFW_ORIGINAL_DATA". The .csv (text) files contain all 5-minute and hourly data including emissions, meteorology, and monitoring as noted in the file names. The spreadsheet provides descriptions of the fields contained in the .csv files:
   - field_descriptions.xlsx

- emis_1h_fill.csv
- emis_5m_fill.csv
- met_1h_fill.csv
- met_5m_fill.csv
- monitor_1h_fill.csv
- monitor_5m_fill.csv

3. **Supporting Documentation:**
   These reports provide additional details regarding the 2014 Colorado Field Study. These files are contained in the sub-folder titled "SUPPORTING_DOCUMENTATION":
   - WESTAR Drilling Rig 1-hour NO2 and NOx Emissions and Ambient Air Impacts, April 10, 2015. Revised August 7, 2018.
   - Review of the Drill Rig 1-hour NO2 Monitoring Study Data, Findings, Data Modification, and Work Completed, Contract No. 15-11. July 27, 2015.

4. **Primary Hourly Data Set of the 2014 Colorado Model Evaluation Database:**
   This comprehensive spreadsheet identifies all the calculations, substitutions, and interpolations carried out to develop the database. It also includes the original distribution files (as separate worksheets) for the purpose of comparison, and contains readme, index, and glossary worksheets that provide further detail regarding the spreadsheet contents. The primary source of information is in the consolidate worksheet, which contains all meteorological, emissions, and ambient data for each hourly period. The .csv file was created as a text file to contain all the same data in a format that can be used as input to processing programs (python, R, etc).
   - 2014_Colorado_ModelEvaluationDatabase_HOURLY.xlsx
   - 2014_Colorado_ModelEvaluationDatabase_HOURLY_TEXT.csv

5. **Primary 5-Minute Data Set of the 2014 Colorado Model Evaluation Database:**
   This spreadsheet contains a consolidated list of all 5-minute data developed from the original distribution files. No modifications were made to the 5-minute data (i.e. sub-hourly variations are not available for the hours when the hourly values were modified). Thus, analyses that rely on the 5-minute data will be inconsistent with the final hourly data, and these inconsistencies should be noted accordingly. The primary source of information is in the consolidate worksheet, which contains all meteorological, emissions, and ambient data for each 5-minute period. The .csv file was created as a text file to contain all the same data in a format that can be used as input to processing programs (python, R, etc).
   - 2014_Colorado_ModelEvaluationDatabase_5min.xlsx
   - 2014_Colorado_ModelEvaluationDatabase_5min_TEXT.csv

6. **Vendor Files:**
   These files were obtained from public sources and contain certain emissions, stack, and operational data for the two types of generators used to power the drill rig. These data were used to provide a limited comparison with study data as explained in the TSD. These files are contained in the sub-folder titled "SUPPORTING_DOCUMENTATION":
   - 3512b_CM20170327-10532-10349.pdf: CATERPILLAR 3512B Generator Set Electric Power Specifications; LEHE0301-04; Date: 21/03/2017; www.cat.com/electricpower

- C27_CM20170815-11465-45410.pdf: CATERPILLAR C27 Diesel Generator Sets; C27 PGBG; LEHE1212-03 (5-17); Date: 17/05/2017; www.cat.com/electricpower

7. **Model Input Files and Associated Information Files:**
These files were created to provide information on the physical layout of Pad 1 and Pad 2 including receptor locations, stack locations and characteristics, and building/structure information used to create downwash parameters. Receptor files that represent monitor locations, as well as 5-meter gridded receptors for each pad, to assist in evaluating spatial distribution patterns, are included. In addition, hourly ozone files, hourly emissions files, and hourly files containing background concentrations of NOx and NO_2 are provided. All files are in a format compatible with U.S. EPA's AERMOD model.[7] These files are contained in the sub-folder titled "MODEL_INPUT_FILES". This folder also contains input files for the AERMET processor, along with spreadsheet files documenting the AERMET input files and the creation of hourly ozone and background concentrations. The file names are as follows:
    - Pad1.src
    - Pad2.src
    - Pad1.rec
    - Pad2a.rec
    - Pad2b.rec
    - Pad2c.rec
    - pad1_grid.rec
    - pad2_grid.rec
    - Pad1_BPIP.inp
    - Pad2_BPIP.inp
    - Pad1.bld
    - Pad2.bld
    - Colorado_HourlyNO_2_Pad1.dat
    - Colorado_HourlyNO_2_Pad2.dat
    - Colorado_HourlyNOx_Pad1.dat
    - Colorado_HourlyNOx_Pad2.dat
    - Colorado_NOx_bg_ugm3_Pad1.dat
    - Colorado_NO_2_bg_ugm3_Pad2.dat
    - Colorado_NOx_bg_ugm3_Pad1.dat
    - Colorado_NO_x_bg_ugm3_Pad2.dat
    - Colorado_NO_2_NOx_ratios.txt
    - Colorado_HourlyO3_ppb_Pad1.dat
    - Colorado_HourlyO3_ppb_Pad2.dat
    - Colorado_Ambient_Sequential_BackgroundAnalysis.xlsx
    - Colorado_HourlyO3_UpDownAnalysis.xlsx
    - 2014_Colorado_ModelEvaluationDatabase_AERMET_Inputs_Readme.xlsx
    - 2014_Colorado_ModelEvaluationDatabase_AERMET_Inputs.zip

[7] AERMOD: https://www.epa.gov/scram/air-quality-dispersion-modeling-preferred-and-recommended-models#aermod

APPENDIX A: SUPPLEMENTAL FIGURES

Figure A.1: Pad 1 Stack Temperature Illustrations.

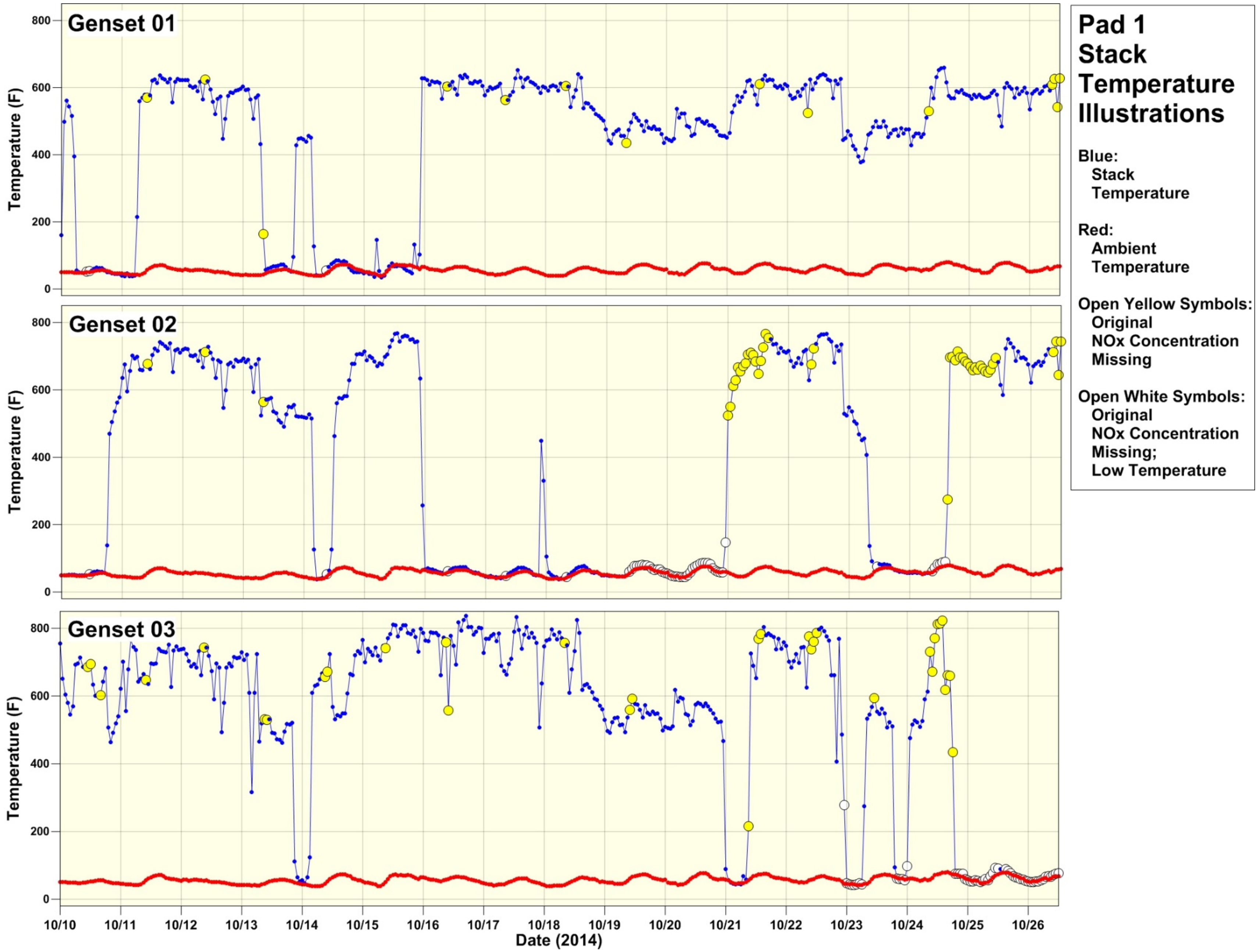


Figure A.2: Pad 2 Stack Temperature Illustrations.

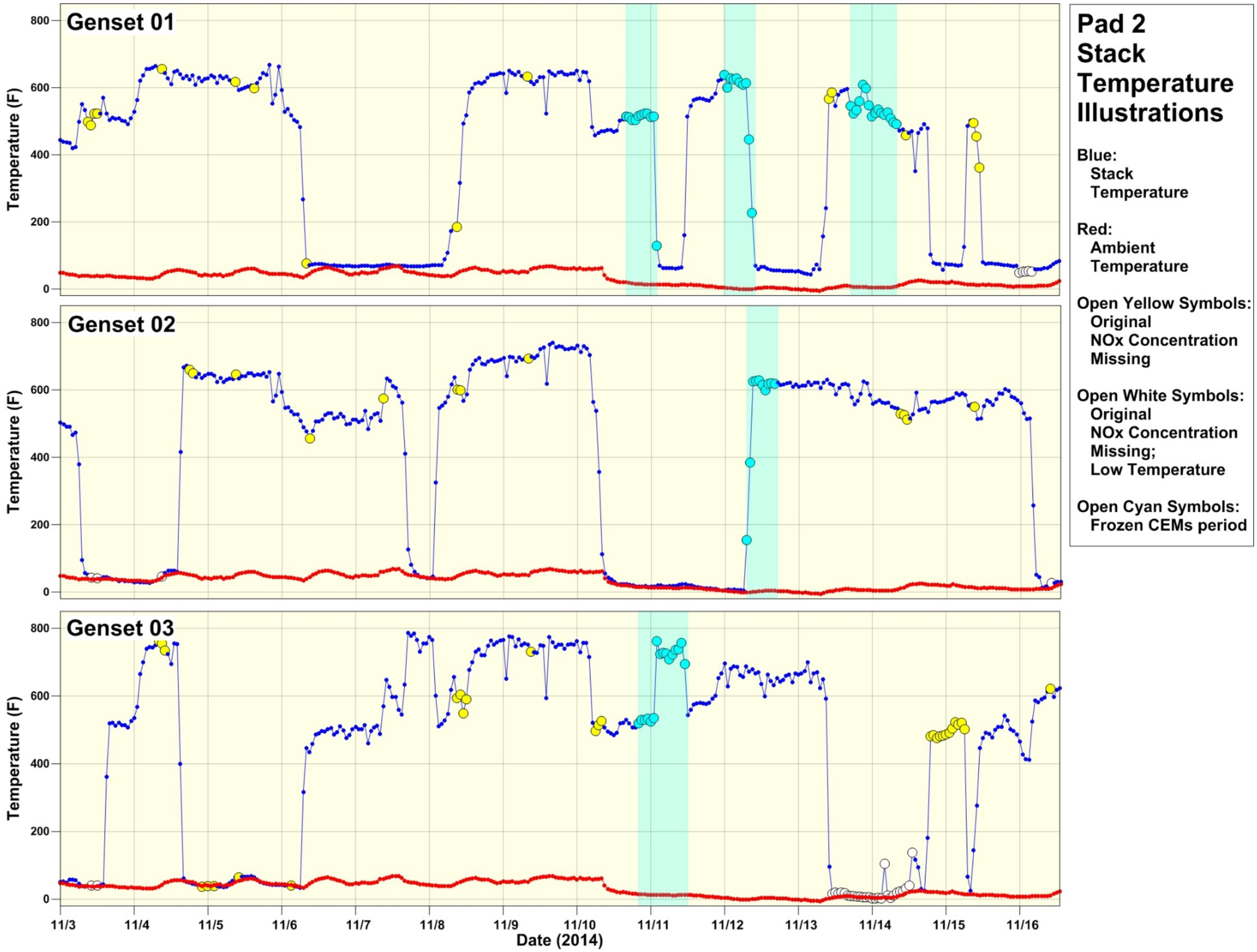


Figure A.3: Genset 01 - 5 Minute Delta-p Illustrations.

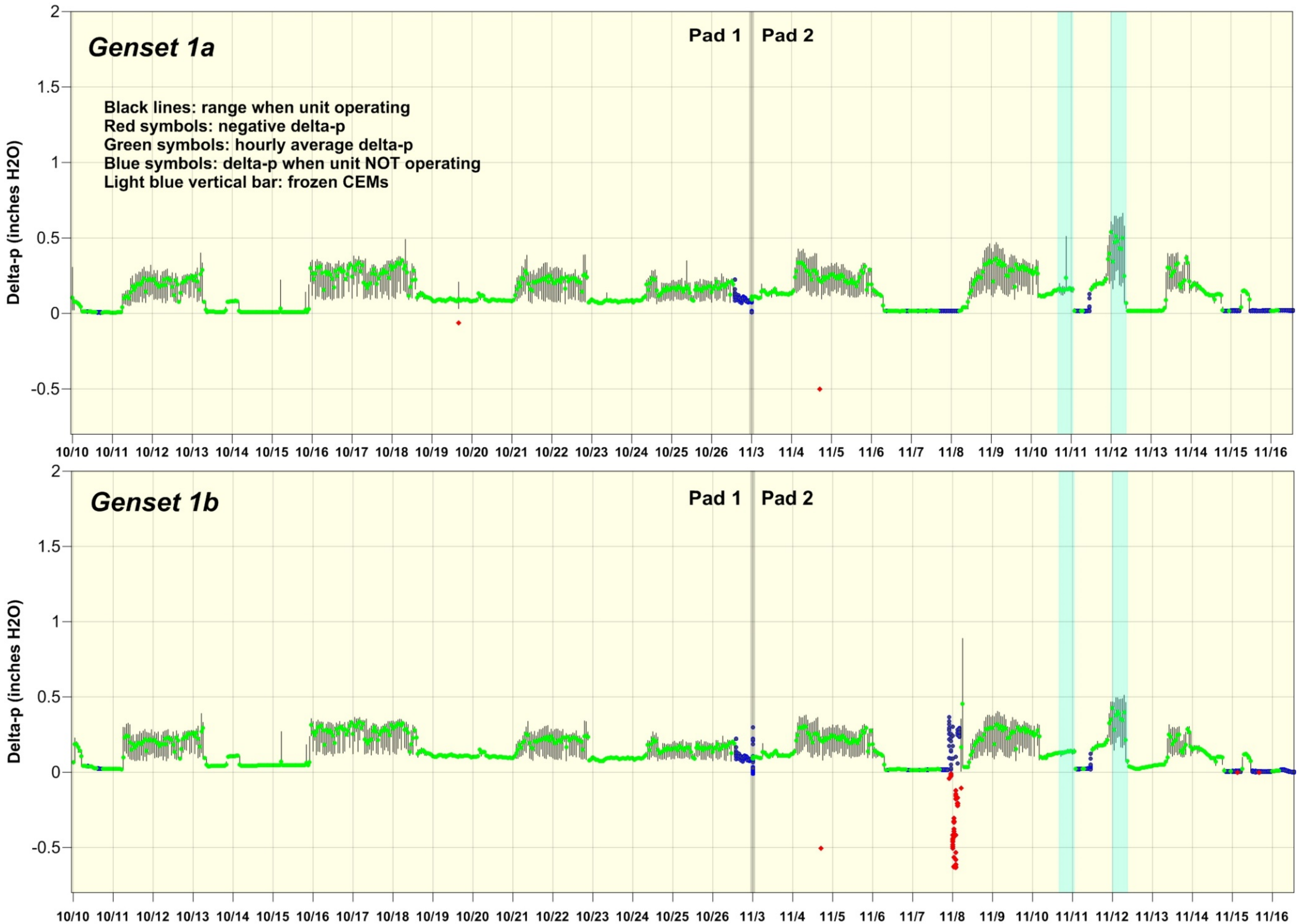


Figure A.4: Genset 02 - 5 Minute Delta-p Illustrations.

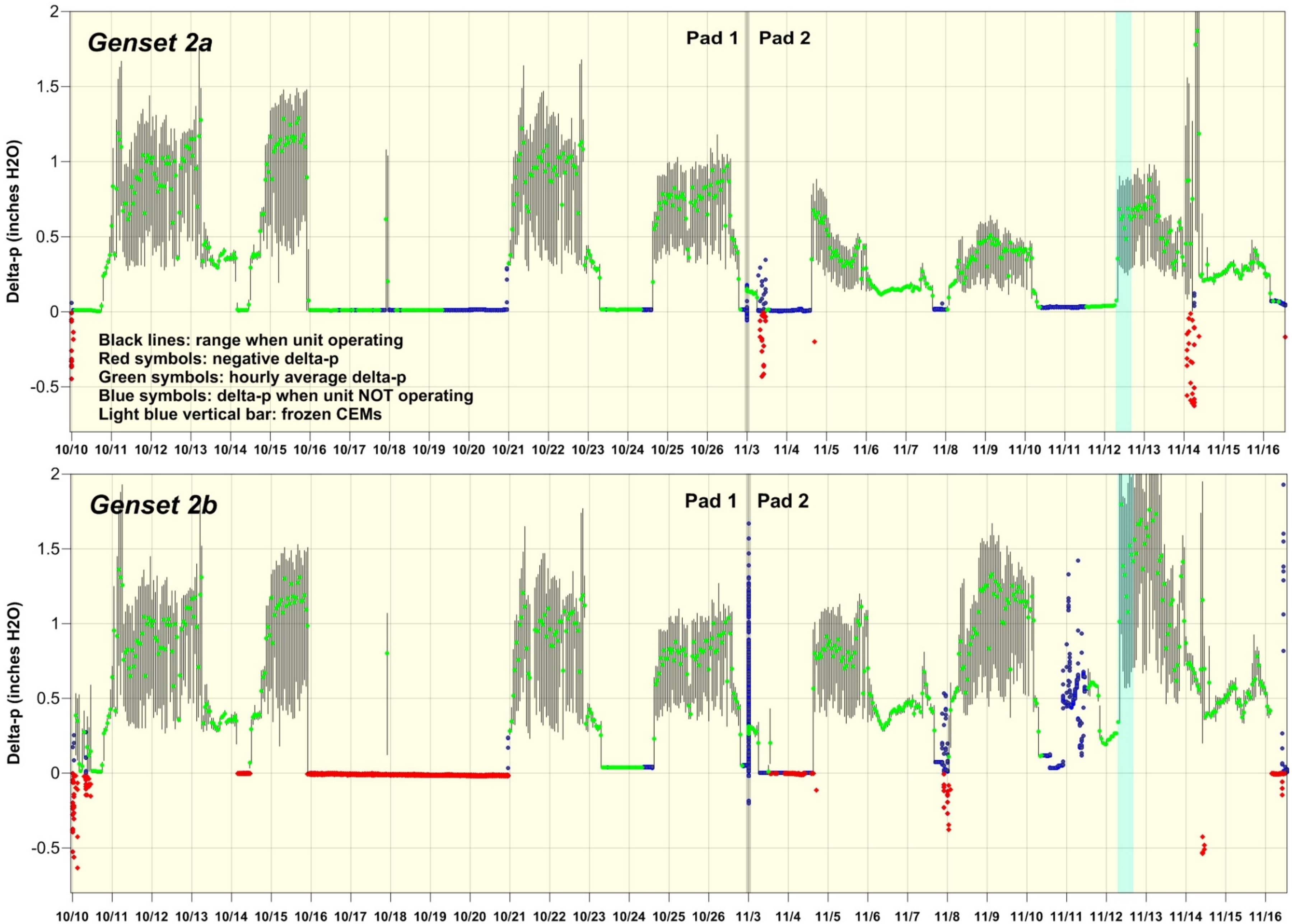


Figure A.5: Genset 03 - 5 Minute Delta-p Illustrations.

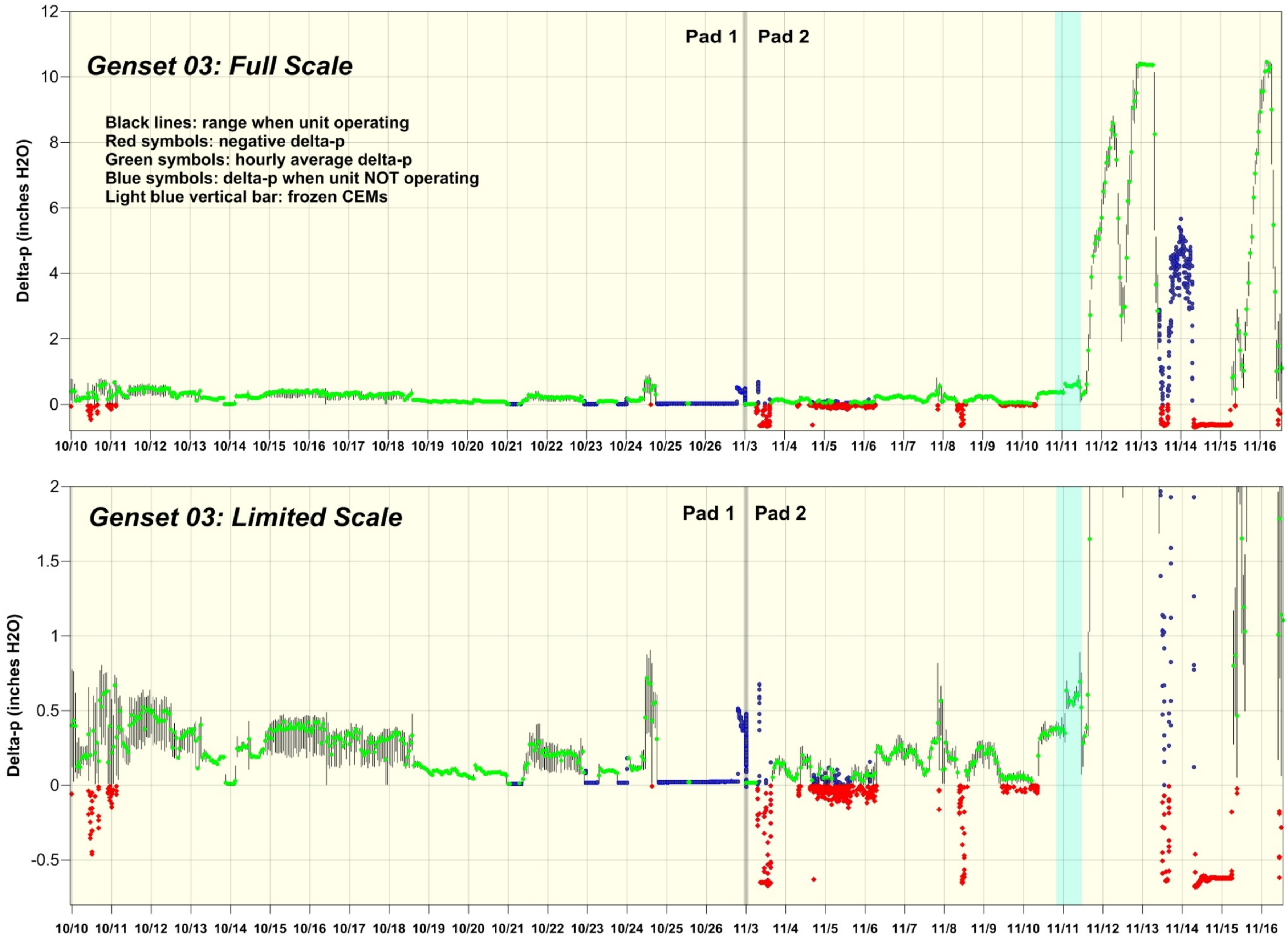


Figure A.6: NOx Concentration Cumulative Frequency Distributions.

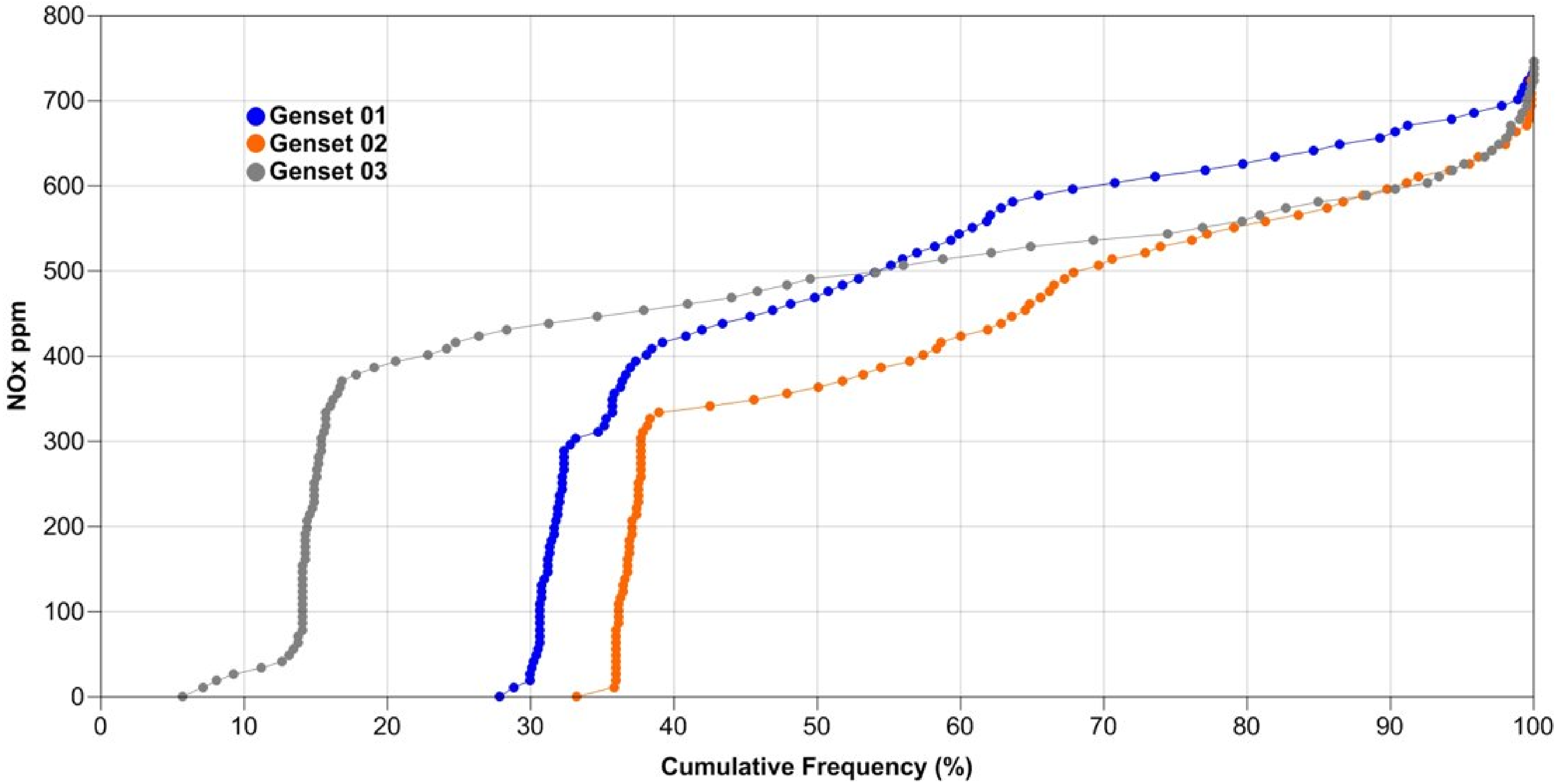


Figure A.7.a.: NOx Concentration Regressions for Genset 01a.

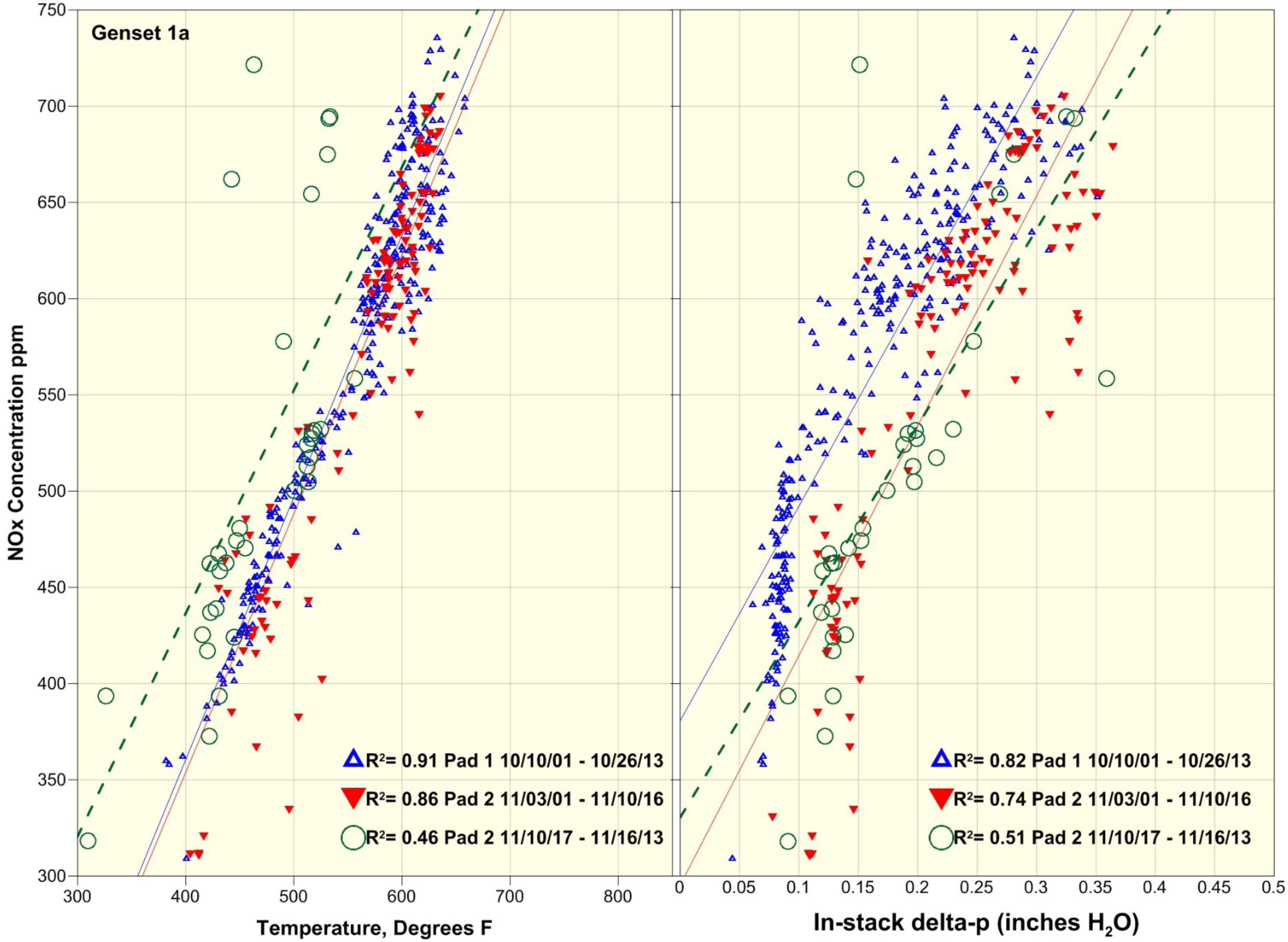


Figure A.7.b.: NOx Concentration Regressions for Genset 01b.

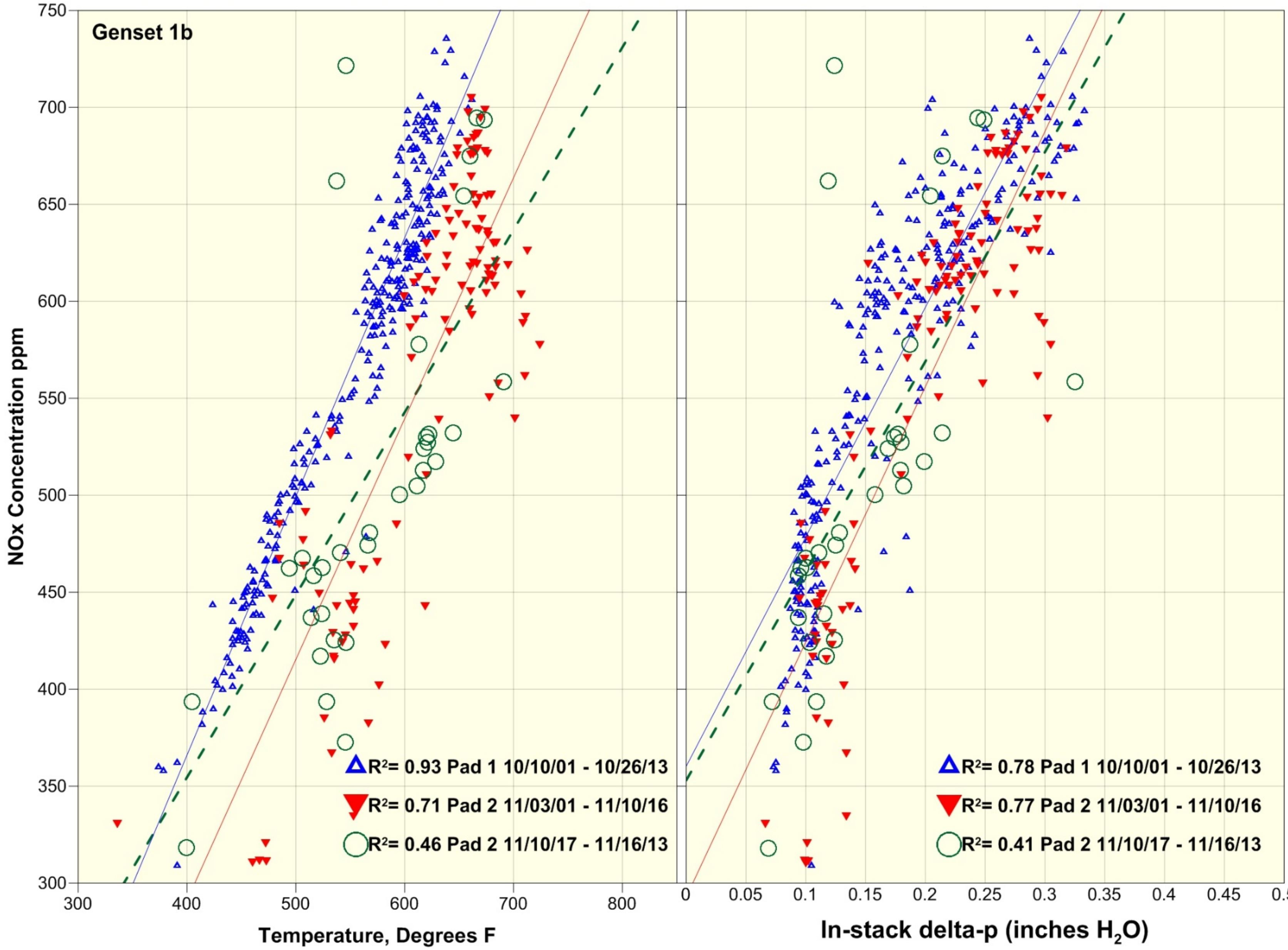


Figure A.7.c.: NOx Concentration Regressions for Genset 01 Based on Average Temperature and Delta-P Across the Two Separate Stacks.

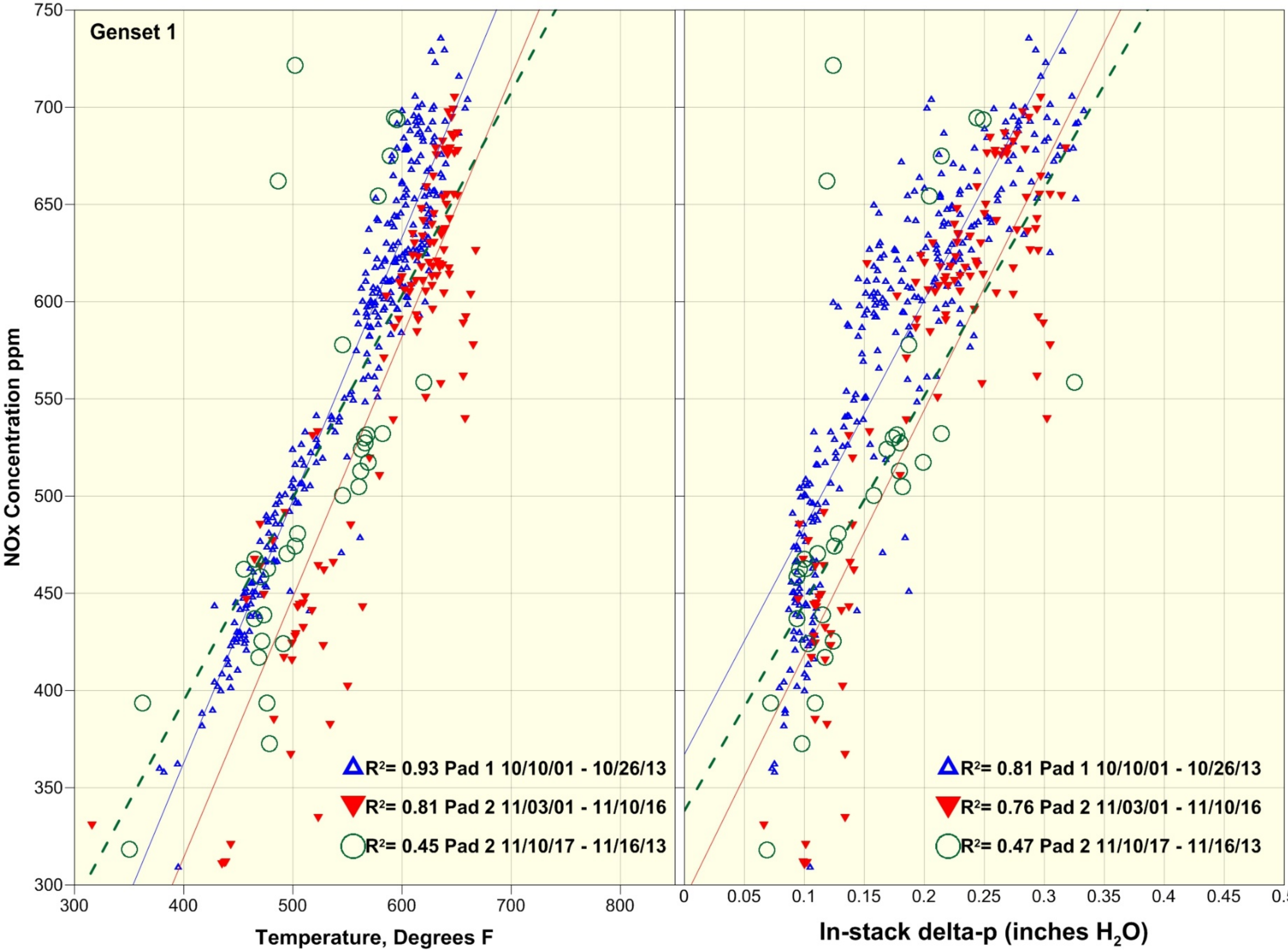


Figure A.8.a.: NOx Concentration Regressions for Genset 02a.

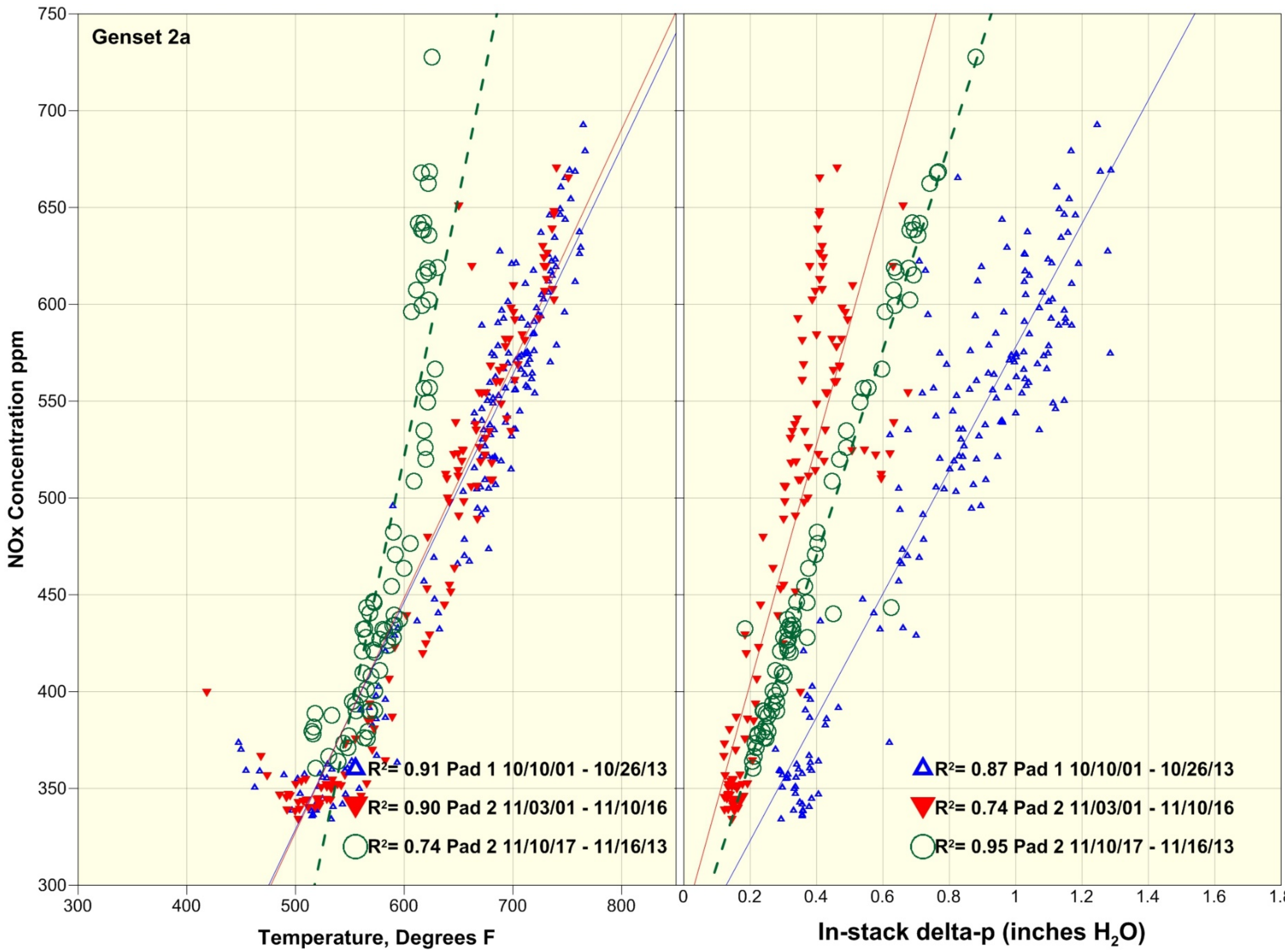


Figure A.8.b.: NOx Concentration Regressions for Genset 02b.

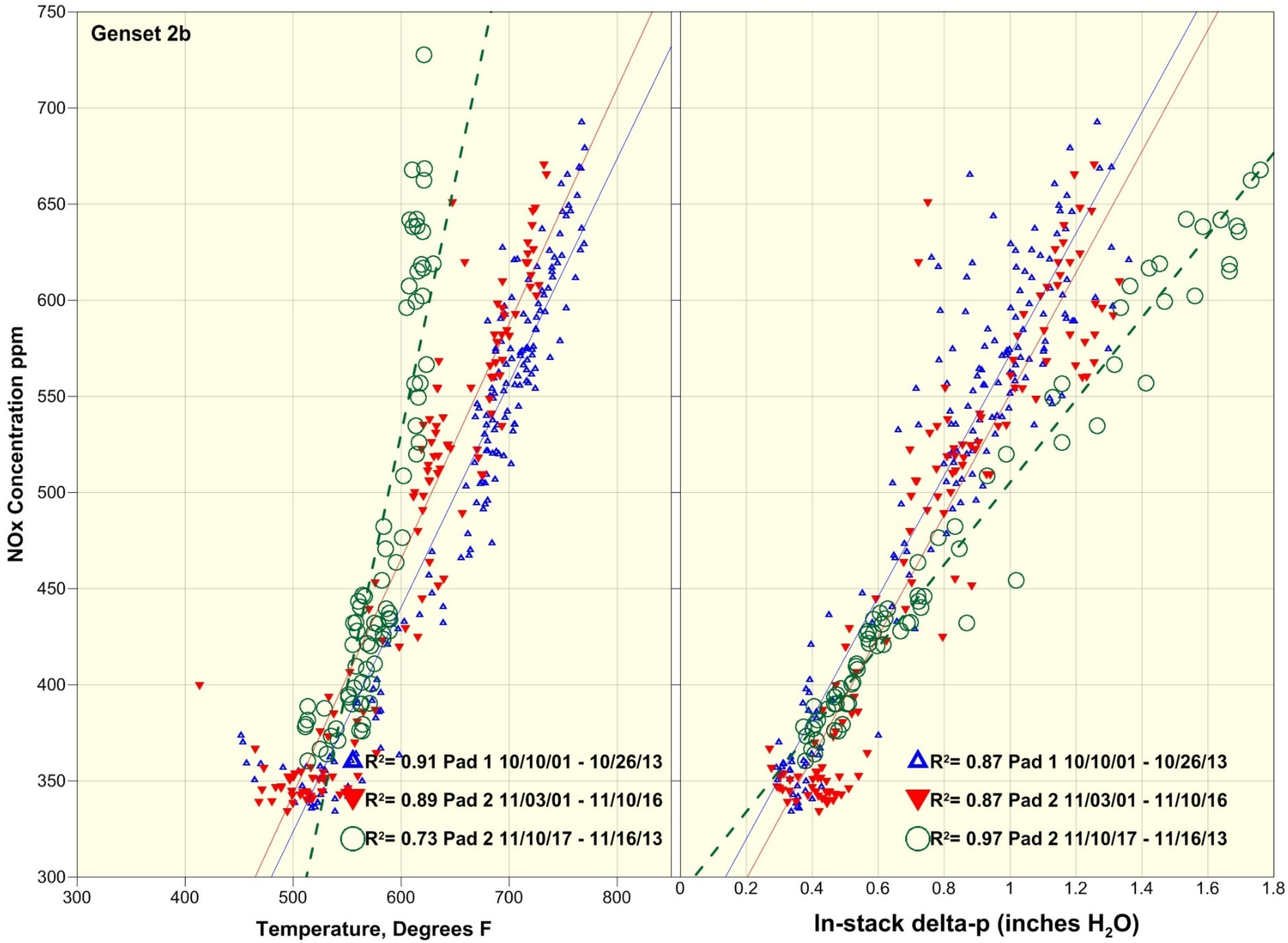


Figure A.8.c.: NOx Concentration Regressions for Genset 02 Based on Average Temperature and Delta-P Across the Two Separate Stacks.

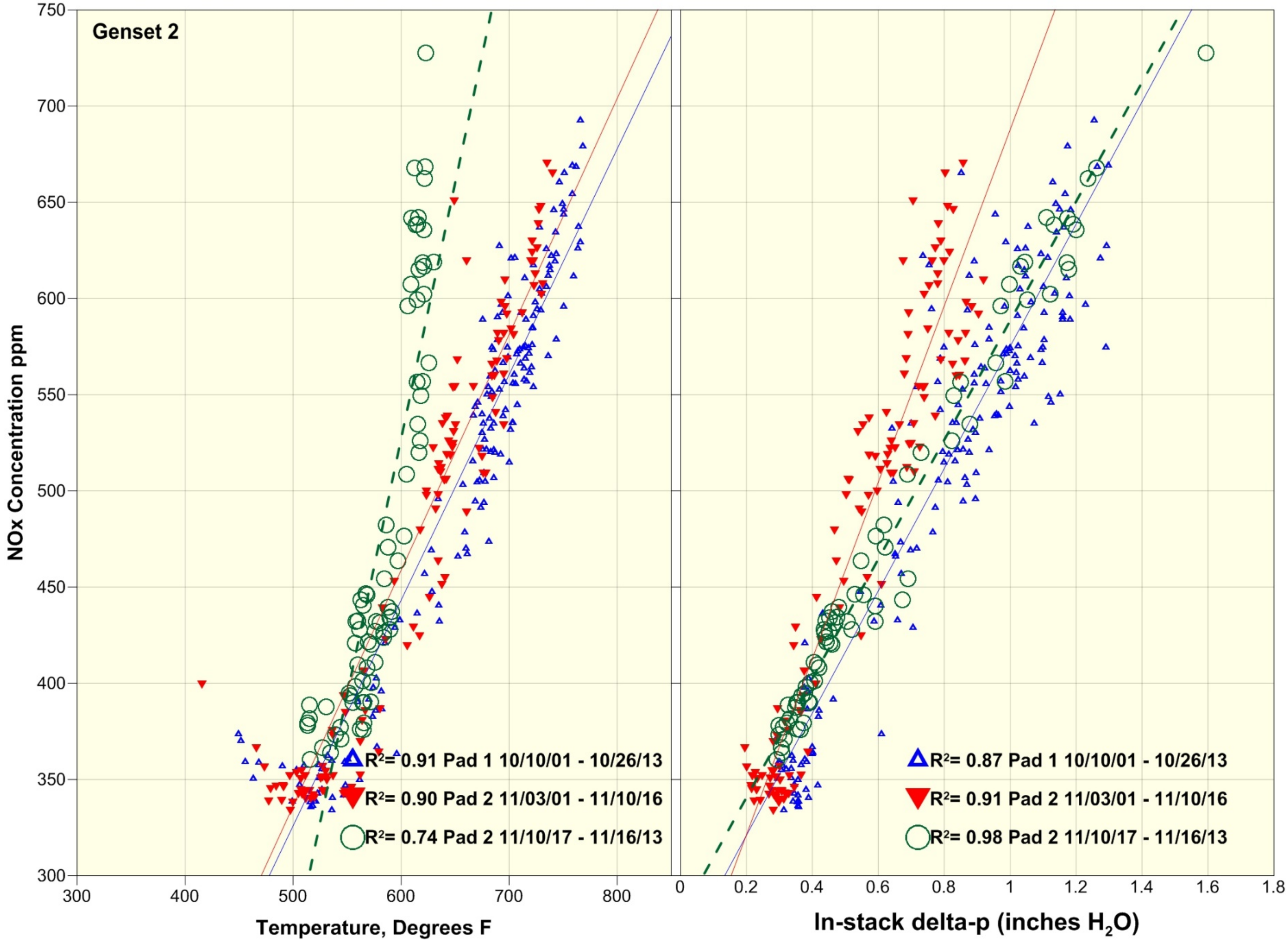


Figure A.9: NOx Concentration Regressions for Genset 03.

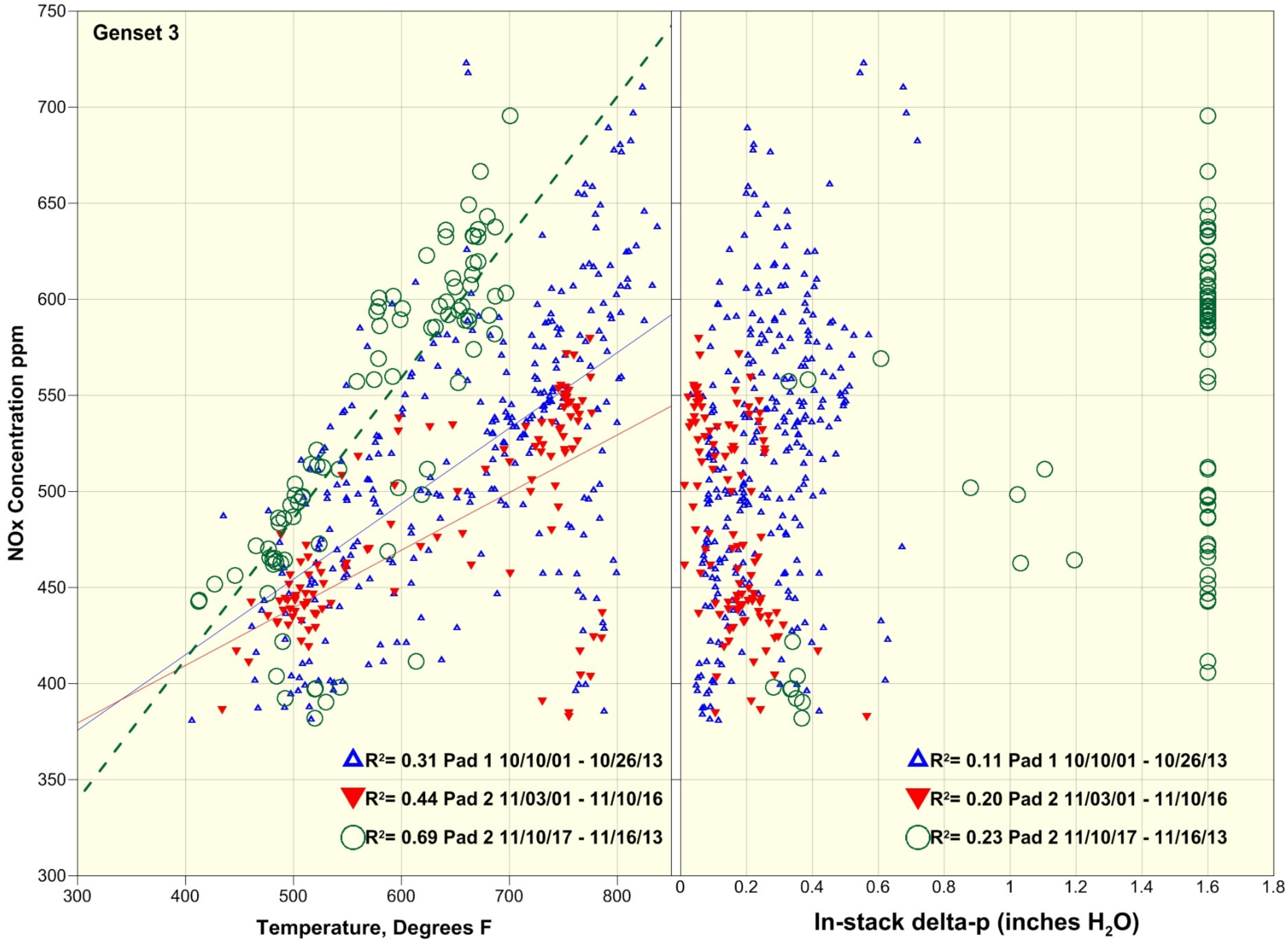


Figure A.10: Pad 1 Stack Exhaust Flow Illustrations.

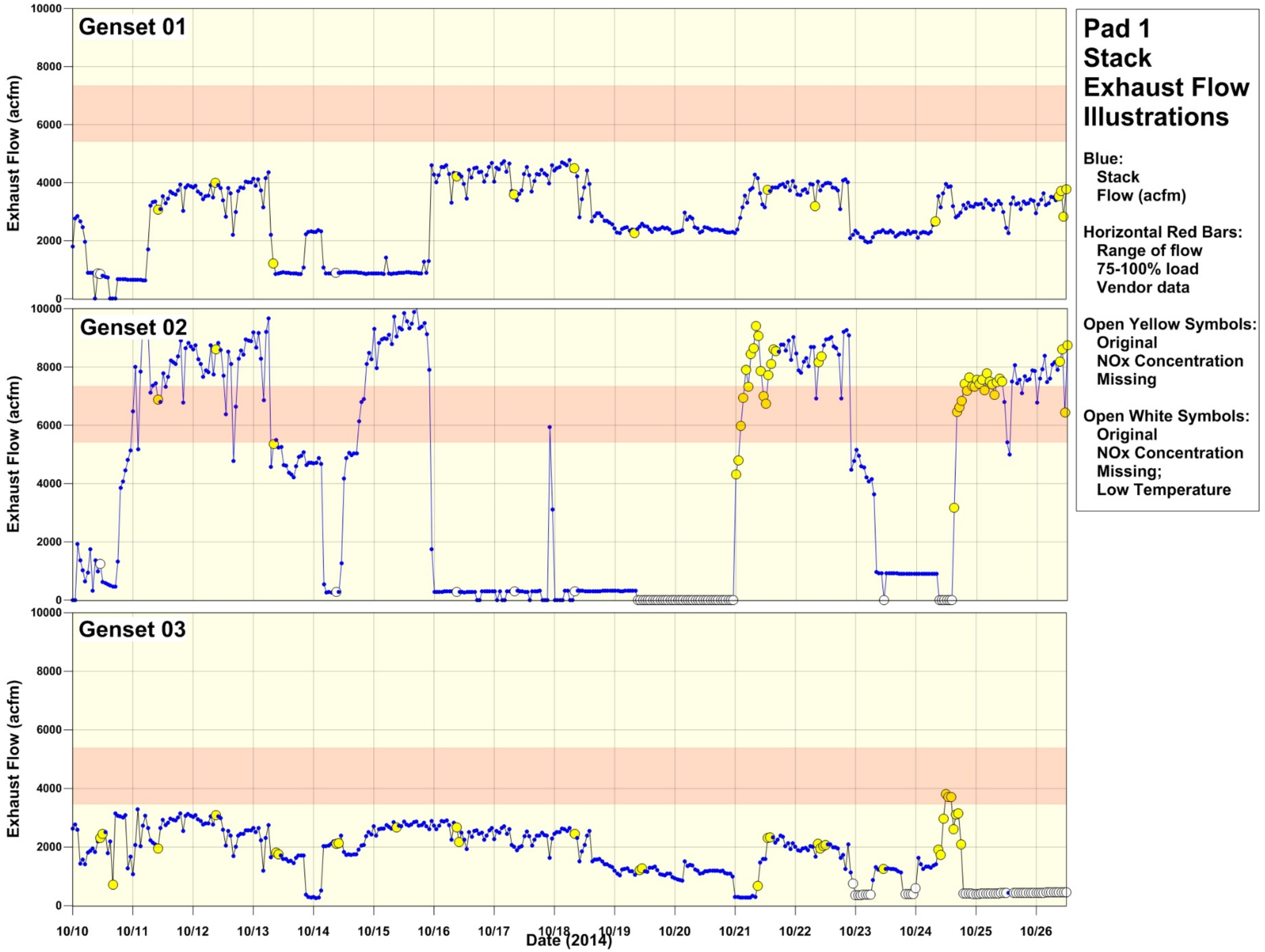


Figure A.11: Pad 2 Stack Exhaust Flow Illustrations.

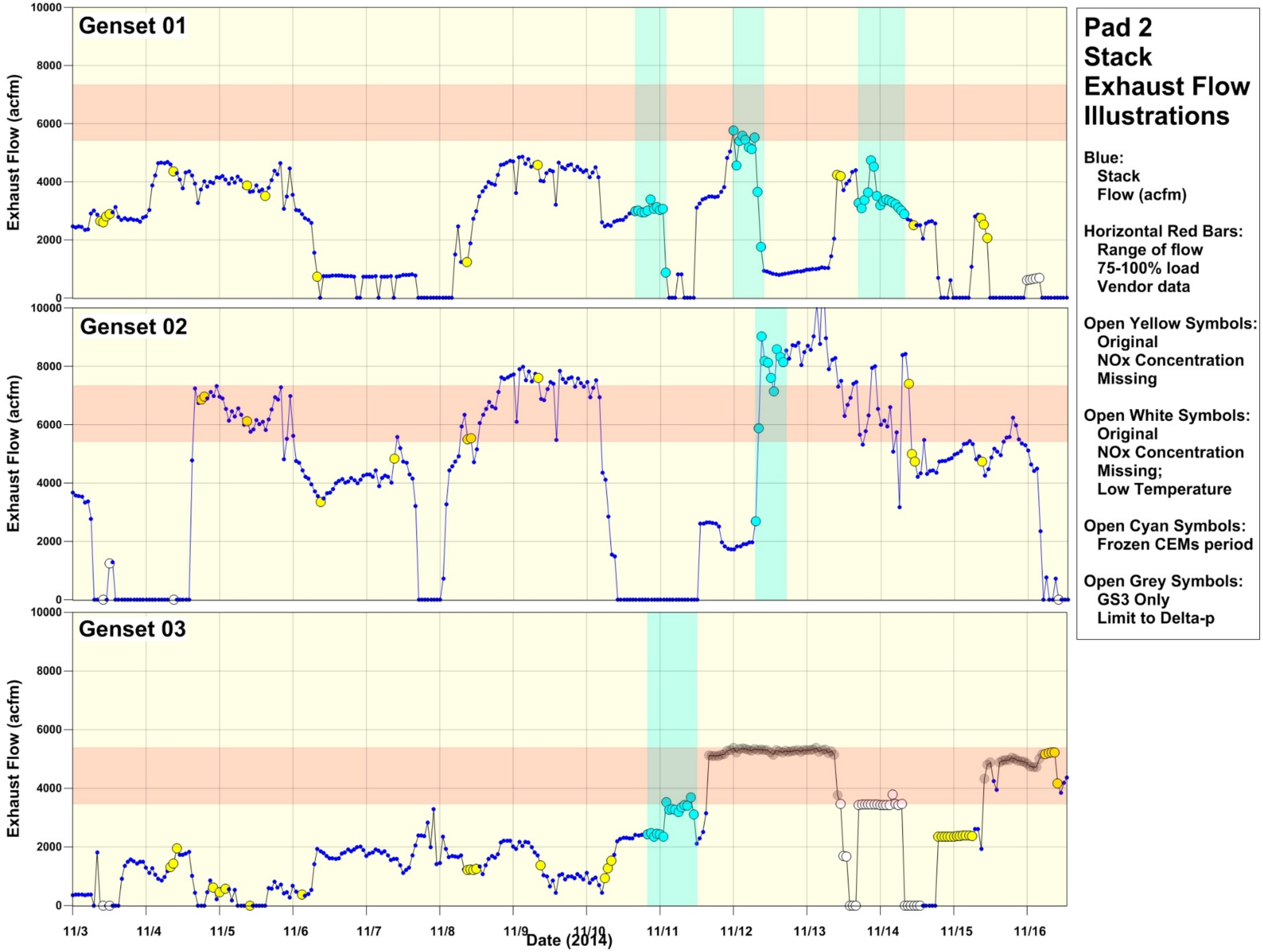


Figure A.12: Pad 1 NOx Gap-Filling Illustrations.

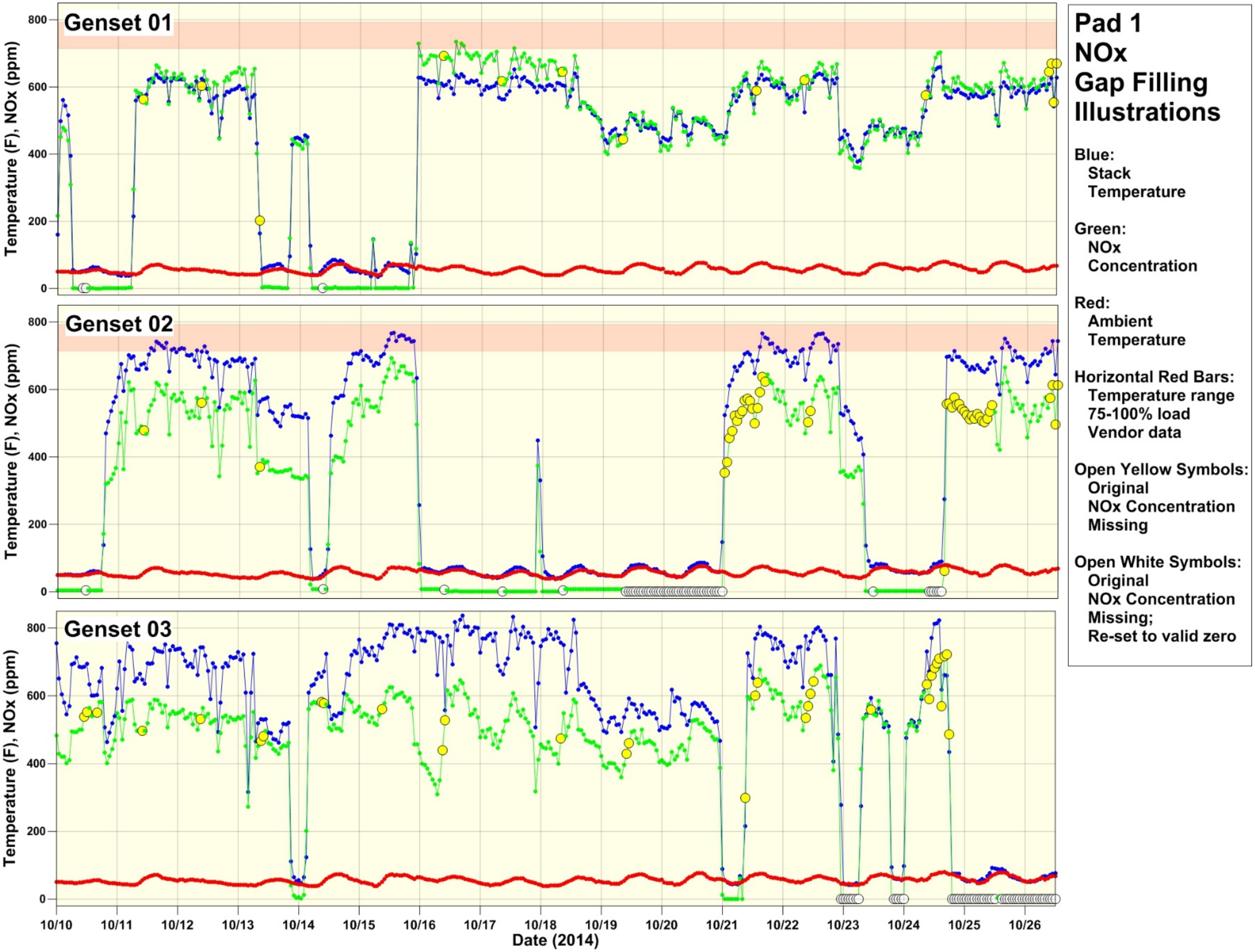


Figure A.13: Pad 2 NOx Gap-Filling Illustrations.

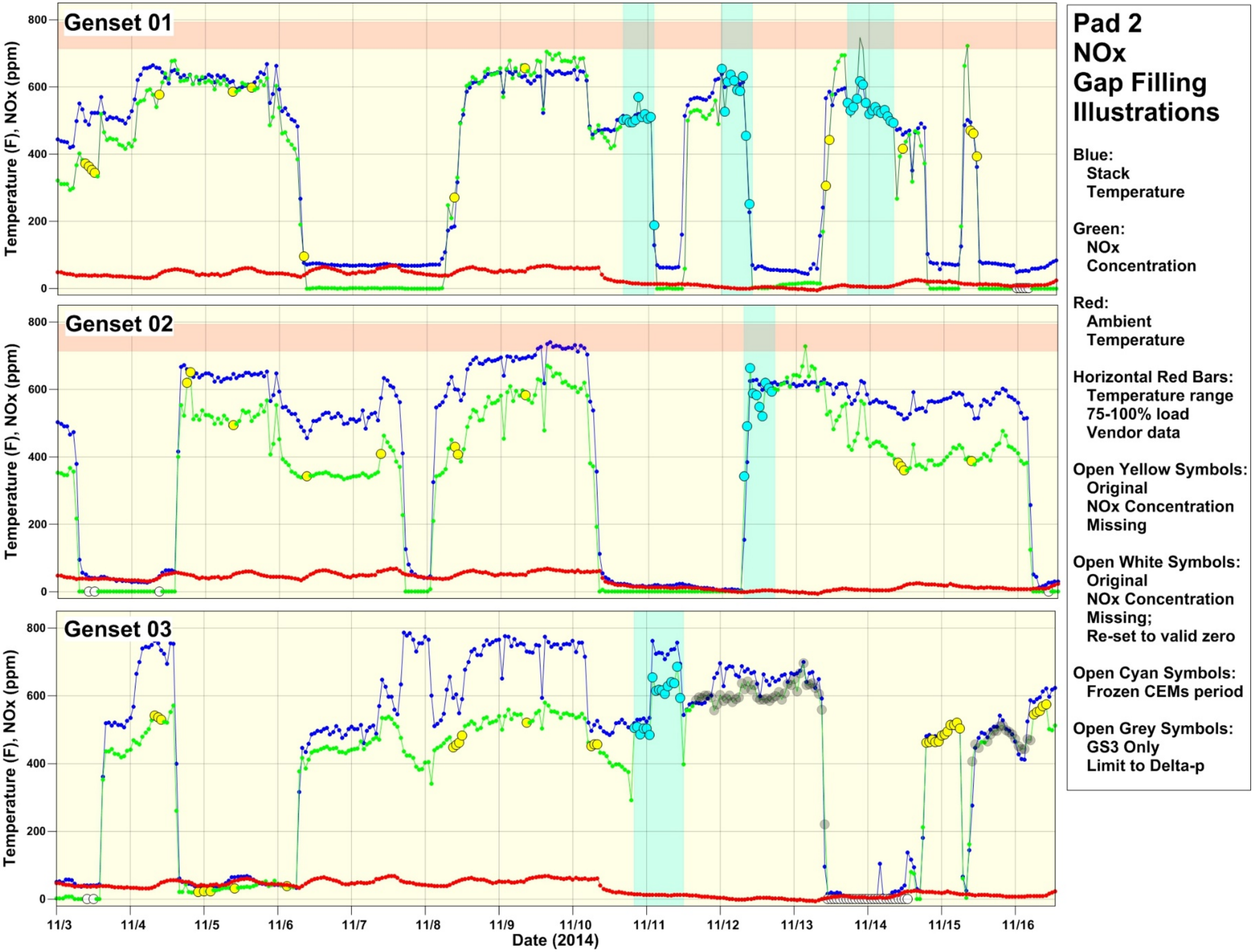


Figure A.14: Pad 1 NOx Mass Emissions Illustrations.

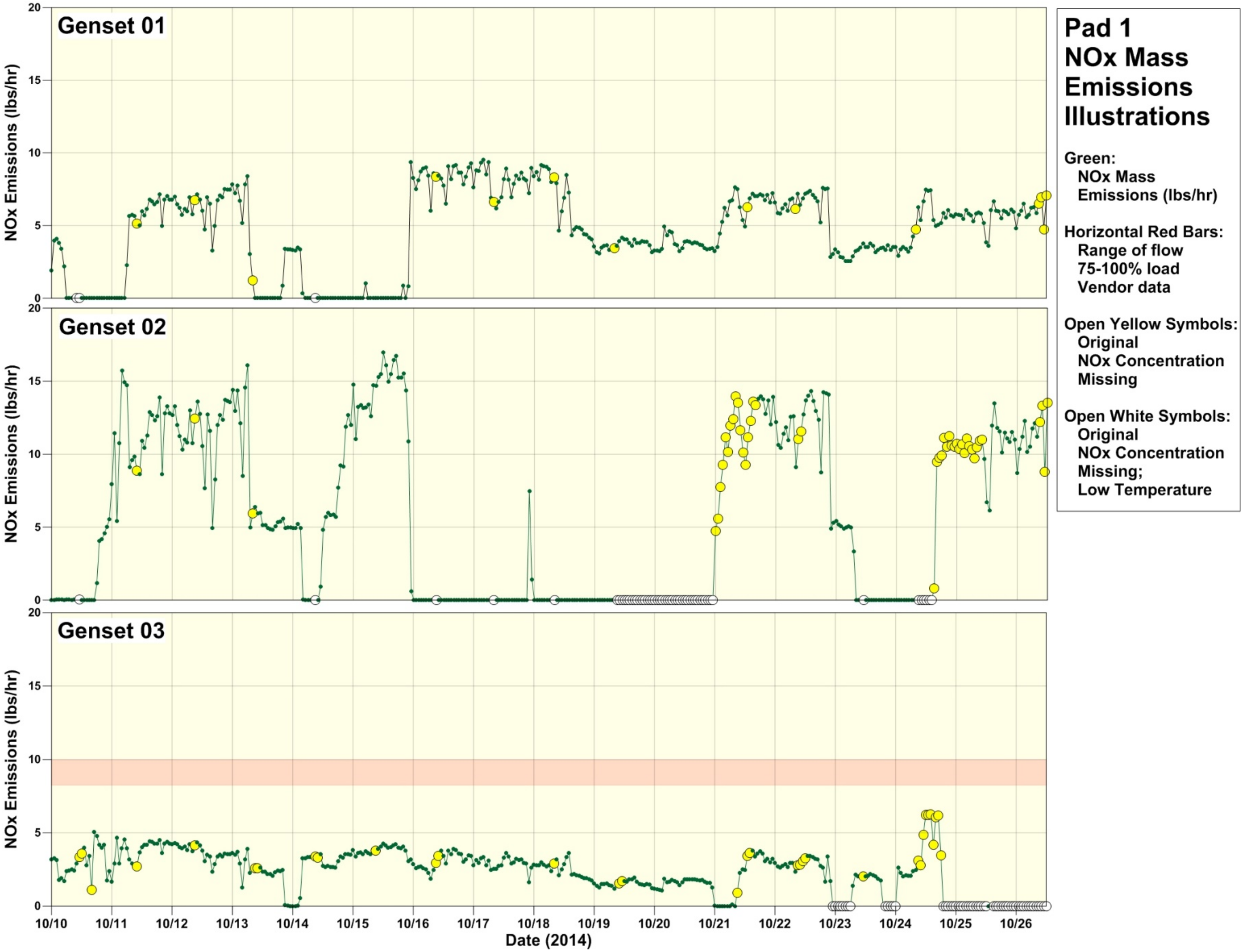


Figure A.15: Pad 2 NOx Mass Emissions Illustrations.

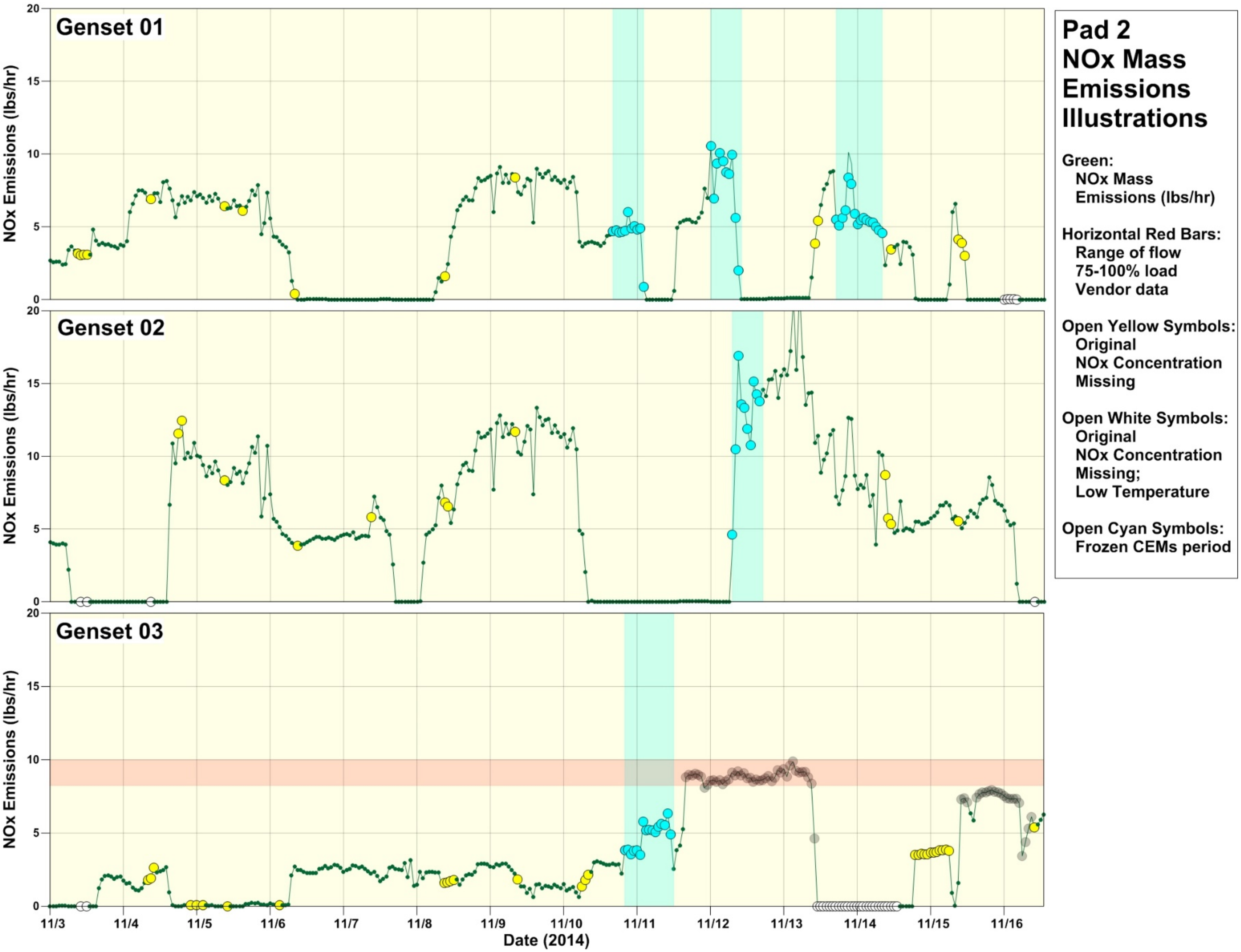


Figure A.16: Ambient NO_2/NOx Ratios.

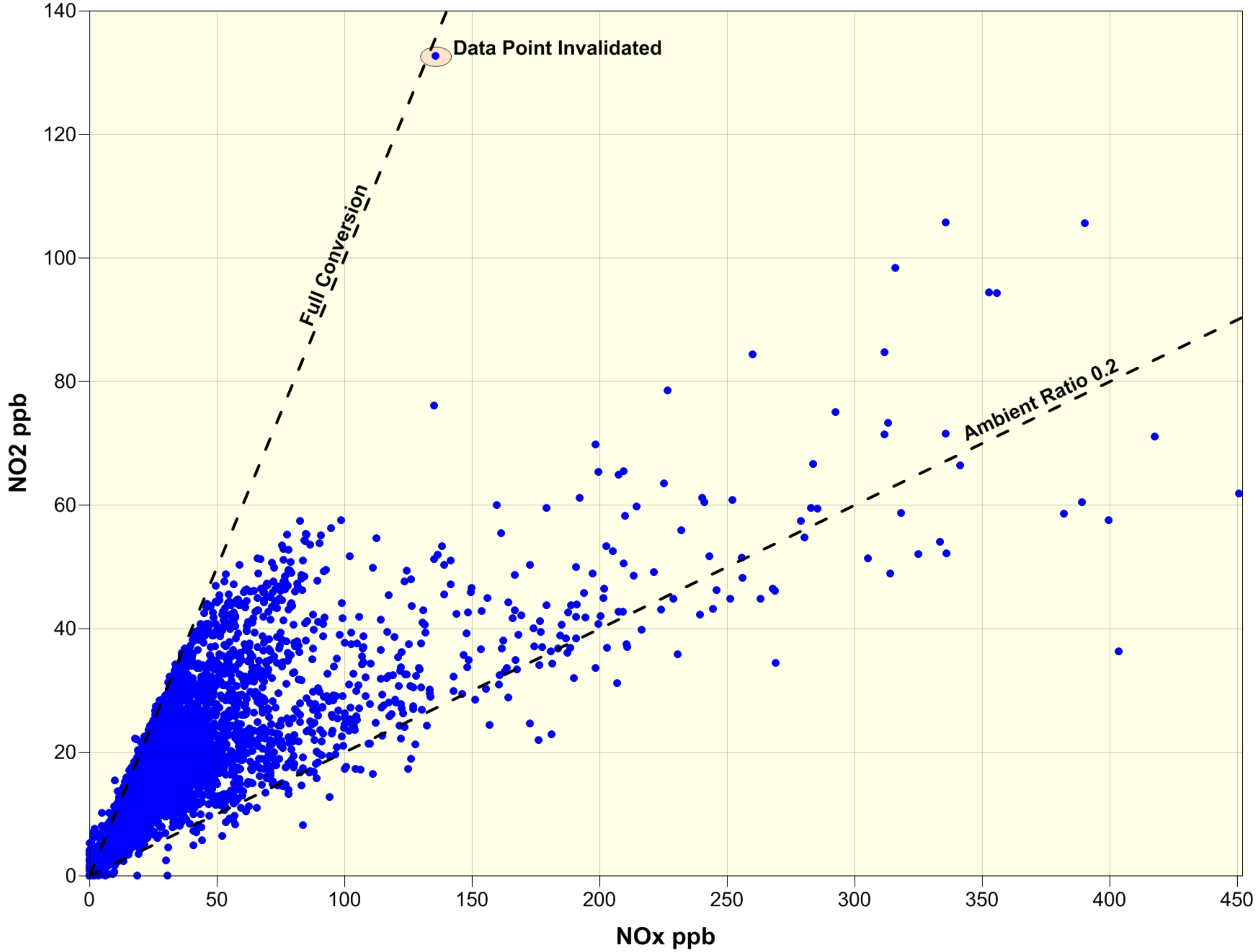


Figure A.17: NOx and NO_2 Background Concentrations.

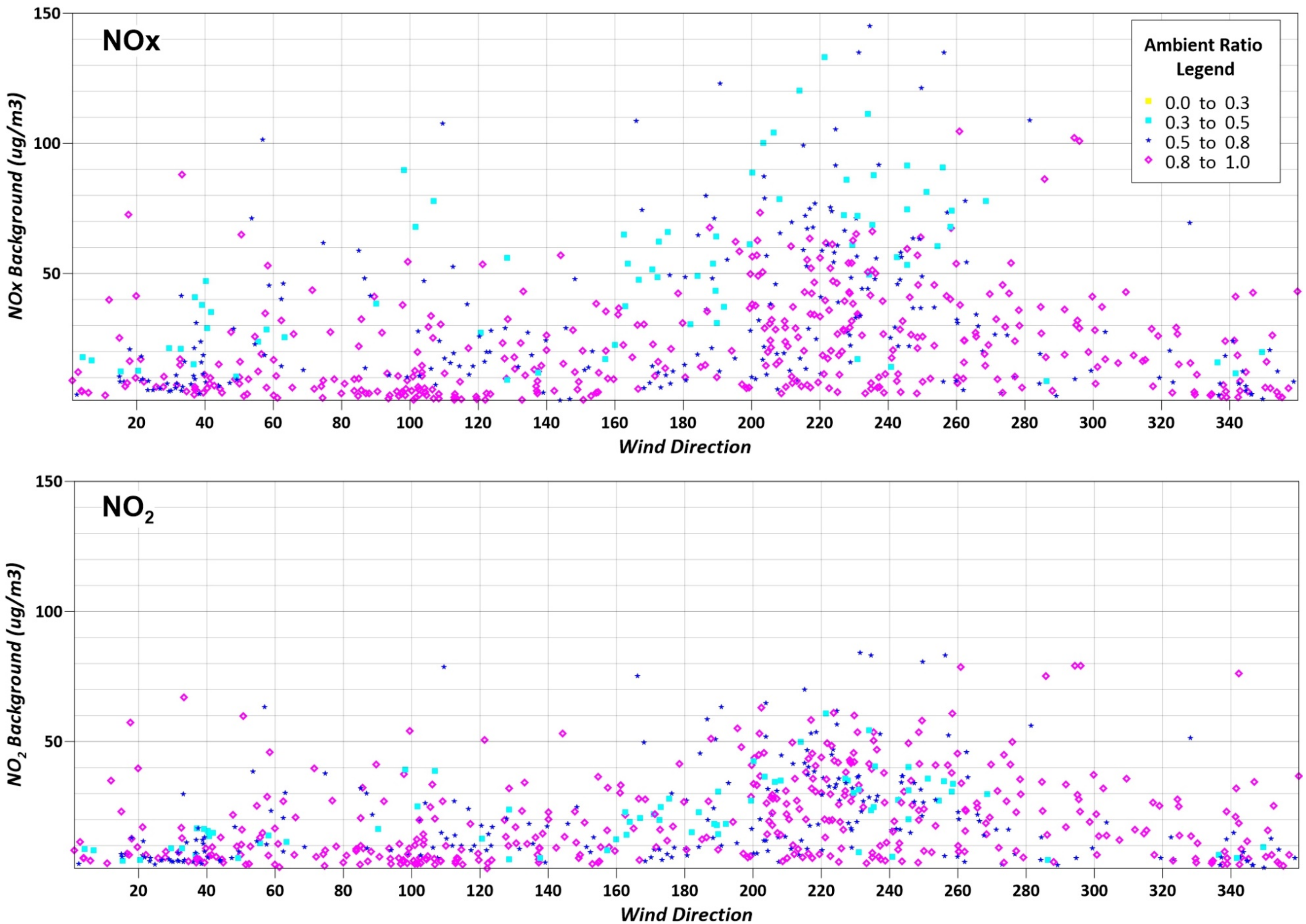


Figure A.18: Ambient Ozone Time Series.

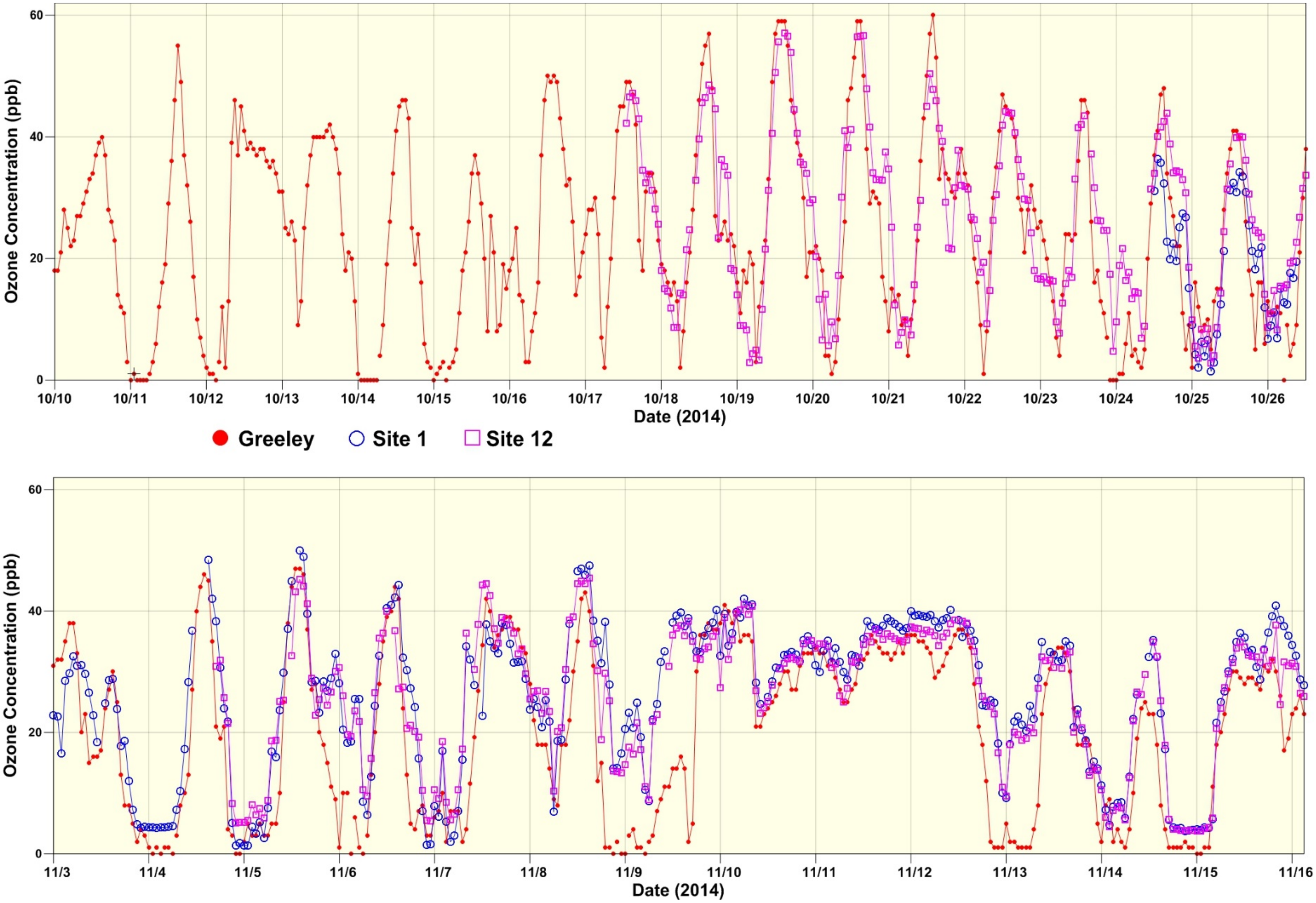


Figure A.19: Ambient Ozone Upwind/Downwind Analysis.