THESIS

LONG DURATION MEASUREMENTS OF PNEUMATIC CONTROLLER EMISSIONS ON ONSHORE NATURAL GAS GATHERING STATIONS

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ABSTRACT

LONG DURATION MEASUREMENTS OF PNEUMATIC CONTROLLER EMISSIONS ON ONSHORE NATURAL GAS GATHERING STATIONS

Over the last 15 years, advances in hydraulic fracturing have led to a boom of natural gas production the United States and abroad. The combustion of natural gas produces less carbon dioxide (CO_2) than the combustion of other fossil fuels per unit of energy released, making it an attractive option for reducing emissions from power generation and transportation industries. Uncombusted methane (CH_4) has a global warming potential (GWP) of 86 times that of CO_2 on 20 year time scales and a GWP of global warming potential 32 times greater than CO_2 on a 100 year time scale [1]. The increase in supply chain throughput has led to concerns regarding the greenhouse gas contributions of CH_4 from accidental or operational leaks from natural gas infrastructure.

Automated, pneumatic actuated valves are used to control process variables on stations in all sectors of the natural gas industry. Pneumatic valve controllers (PCs) vent natural gas to the atmosphere during their normal operation and are a significant source of fugitive emissions from the natural gas supply chain. This paper outlines the work that was done to improve the characterization of emissions from PCs using long duration measurements. This work was performed as part of the Department of Energy funded Gathering Emission Factor (GEF) study.

A thermal mass flow meter based emission measurement system was developed to perform direct measurements of pneumatic controller emissions over multiday periods. This measurement system was developed based on methods used in previous studies, with design modifications made to meet site safety regulations, power supply constraints and measure-

ment duration targets. Emissions were measured from 72 PCs at 16 gathering compressor stations between June, 2017 and May, 2018.

The average emission rate of 72 PCs was 10.86 scfh [+4.31/-3.60], which is 91.2% of the EPA's current emission factor for PCs on gathering compressor stations. The mean measurement duration of these 72 samples was 76.8 hours. Due to potential biases associated with flow meter errors, updates to EPA emission factors based on these data are not proposed. However, because all previous studies to quantify PC emissions used short sampling times (typically $\leq$15 minutes) the long duration measurements provided insight into previously unobserved PC emissions behavior.

A panel of industry experts assessed the emissions recordings and found that 30 PCs (42% of measured devices) had emissions patterns or rates that were inconsistent with their design. 73% of emissions measured during this study were attributed to these 30 PCs that were malfunctioning from an emissions perspective. It was also found that PC emission rates are more variable over time than previously thought. Due to this high temporal variability, the short duration observations currently used by leak detection programs to identify malfunctioning equipment have a low probability of providing accurate characterizations of PC emissions.

Many natural gas companies are investigating ways to improve the efficiency of their operations and reduce rates of natural gas leakage in their systems. The data presented in this paper improves the characterization of emissions behavior from a significant emission source in the production, processing and transmission sectors of the natural gas supply chain and has implications for organizations with an interest in reducing emissions from PCs.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1

INTRODUCTION

1.1 Motivation for Methane Emission Estimates

Between 2000 and 2017, annual production of dry natural gas in the U.S. increased by 40% from 19,181,980 to 26,863,432 million standard ft^3 (scf) [3], largely due to the gradual displacement of coal by natural gas as the nation's primary energy source for electricity generation. This shift has been driven by improvements in extraction techniques leading to low gas prices (market forces) and increasingly strict environmental regulations on power generation (regulatory forces) [4]. Combusted natural gas emits fewer greenhouse gases than coal on a unit of energy basis (53.2 kg of CO_2 per million BTU for natural gas compared to 93.5 kg of CO_2 per million BTU for bituminous coal [5]), the displacement of coal by natural has the potential to greatly decrease the greenhouse gas contributions of the power generation sector. However, the potential climate benefits of this transition are dependent on the total leakage rate of uncombusted natural gas through the supply chain between extraction and delivery to end use [6, 7]. Although the combustion of natural gas emits less greenhouse gases per unit of energy than all other fossil fuels, methane (CH_4), which is the primary component of natural gas, is a powerful greenhouse gas with a global warming potential 32 times greater than CO_2 on a 100 year time scale and 86 times greater than CO_2 on a 20 year time-scale. The higher GWP over shorter time scales is due to the shorter atmospheric lifetime of CH_4 compared to CO_2; the half life of atmospheric CH_4 is 8.6 years. Therefore, the majority of CH_4 climate impacts are attributed to the 20 years after emissions occur, significant short term climate benefits can be achieved by curbing emissions from such sources with short lifetimes and high radiative forcing values [1].

There are numerous points for pressurized natural gas to vent to the atmosphere along the supply chain, either through unintentional leaks or venting that takes place during normal process operations. Previous studies have estimated that a leakage rate of 3-4% of supply chain throughput would fully negate the climate benefits of transitioning from coal to natural gas for electrical generation [6,8]. Alvarez *et al* estimated that in 2015, the total natural gas leak rate was 2.3% of total US natural gas production [9]. Therefore, complete assessment of life-cycle greenhouse gas contributions by the natural gas industry is largely dependent on an accurate estimate of total natural gas emissions between extraction and delivery.

1.2 Methane Emissions in the Natural Gas Industry

1.2.1 Emissions Estimates

Methane emissions from natural gas infrastructure can be estimated using either bottom up or top down methods. Bottom up, or component level, methods involve identifying and measuring leaks on individual pieces of equipment. These measurements are then used to calculate emission factors at the component or equipment level for all equipment that operates in a given sector. Estimates of emissions from an entire sector are then made by scaling up these emission factors by equipment counts in the sector. Top down, or facility level, methods involve measuring the aggregate emissions from an entire facility through tracer flux or aircraft mass balance measurements. Top down studies have consistently reported higher emission estimates than bottom up studies [10]. Numerous studies have been undertaken to quantify emissions from all sectors of the NG supply chain with the intention of identifying high impact areas of emissions reduction, informing policy or regulatory action and estimating total anthropogenic contribution of methane emissions [7,11–13]. The results of these studies, coupled with updated reports of industry activity data, form the basis for the annual estimates of methane emissions from the natural gas industry which are included in the EPA's annual *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, which publishes estimates of all anthropogenic greenhouse gas emissions by industry [2].

1.2.2 Emissions by Sector

When publishing emission estimates in the natural gas industry, the Environmental Protection Agency (EPA) stratifies the operations of the natural gas supply chain into four sectors: production, processing, transmission and storage, and distribution. Each sector has a unique set of emission sources related to the sector's functions.

- Production (65% of estimated annual supply chain emissions [14])

  Activities in the production sector include exploration of underground geologic formations, drilling and extraction of raw natural gas, and initial separation and treatment of produced gas and liquids. Emissions from gathering and boosting stations (also referred to as *gathering* compressor stations) are also included in production sector estimates. These stations act as central nodes where natural gas produced from drilling is collected, treated, compressed and sent to downstream sectors via high pressure gathering pipelines. Emission sources include completion flowbacks from hydraulic fractured well sites, pneumatic controllers (PCs), fugitive leaks, liquid unloadings, well workovers, and compressor engine exhaust.

- Processing (21% of estimated annual supply chain emissions [14])

  In the processing sector, gas received from gathering pipelines is treated to remove liquids, CO_2 and H_2S and refined to at least 95% CH_4 content to meet "pipeline quality" specifications. Treated gas is again compressed and transported in pipelines to downstream sectors. The primary emission sources in the processing sector are fugitive emissions from leaking station equipment and seals on reciprocating and centrifugal compressors [15].

- Transmission & Storage (7% of estimated annual supply chain emissions [14])

  The transmission and storage sector consists of high pressure pipelines, compressor stations, underground storage fields, and supporting infrastructure that transports natural gas from gathering and processing stations to industrial users and distribution systems. The primary emission sources in the transmission and storage sector are PCs, compressor engine exhaust, station equipment and compressor fugitive leaks, and station or equipment blow-down events.

- Distribution (7% of estimated annual supply chain emissions [14])

  The natural gas distribution sector consists of the network of low pressure pipelines that deliver gas from custody transfer points at the termination of transmission pipelines (city gates) to end residential or industrial users. The primary emission source in the distribution sector is fugitive leaks from underground pipelines.

Total emissions from the natural gas supply gain were estimated to be 163.5 million metric tonnes (MMT) CO_2 equivalent in 2016 [14].

1.3 Gathering Emission Factor (GEF) Study

In 2016, the US Department of Energy's (DOE) Office of Fossil Energy issued a funding opportunity announcement titled "Methane Emissions Mitigation and Quantification from Natural gas Infrastructure" in an effort to act on the President's 2014 Climate Action Plan,

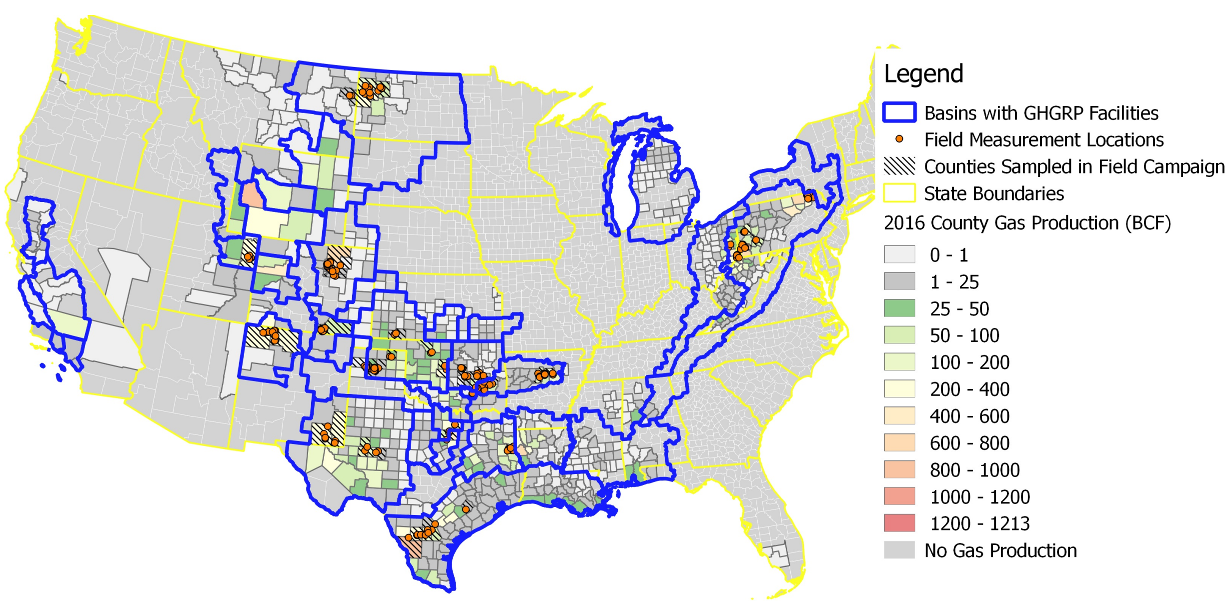

Figure 1.1: Location of gathering compressor stations where field measurements were performed during the DOE funded Gathering Emission Factor study.

which included a strategy to reduce methane emissions [16] [17]. This FOA offered funding for research aimed at developing leak mitigation-focused technologies and improving estimates of methane emissions from midstream natural gas operations, with a focus on better characterizing regional variations in emissions. Researchers at the Colorado State University's Energy Institute were awarded funding under Area of Interest A0I 2A of this grant to perform direct emission measurements at the device level to develop methane emission factors for all classes of equipment found on gathering compressor stations. To accomplish this, CSU partnered with the engineering firm AECOM to assist with planning, logistics, field work and analysis. Nine midstream natural gas companies also acted as partners in the study and offered access to their sites and input on the methods used in the study. The primary objectives of the GEF study were to collect data on the operating characteristics (activity data) and perform component level leak measurements on a nationally representative sample of gathering compressor stations and use these data to develop activity emission factors for equipment used on these stations. In addition to developing emission factors, the secondary goals of the study were to develop and field-test methods for improving emission measurements from two emission sources that are currently not well characterized and have large uncertainty in their emission estimates. These two sources are: Methane slip in compressor engine exhaust on classes of engines not subject to testing for air quality permit requirements and emissions from PCs.

This thesis will concentrate on the second source - emissions from PCs - using work done during the GEF project to improve the characterization of emissions from PCs using long duration measurements. This report includes an overview of PC operation and classification and a summary of current EPA estimates of PC emissions and results of previous PC emission studies. The design and construction of a measurement system to perform long duration field measurements of PC emissions on gathering compressor stations is outlined. The planning and execution of this measurement system's field deployment, including site and device selection methods and measurement protocols are presented. An analysis of the results of long duration emission measurements and comparisons to current characterizations of PC emissions is performed. Finally, the shortcomings of this study's methods and recommendations for future studies are also discussed.

Chapter 2

PNEUMATIC VALVE CONTROLLERS

2.1 Principle of Operation

The engineering discipline of process control is defined as the analysis, design and implementation of control systems for maintaining the output of an industrial process within a given tolerance [18]. On stations in all sectors of the natural gas supply chain, automated pneumatically-powered valves and actuators are used in to control process variables. These control systems are ubiquitous in the industry because these stations have a constant source of high pressure natural gas than can be used to power actuators, eliminating the needs for electrical power on remote sites or separate compression equipment to compress and dry ambient air to power actuators. Pneumatic process control systems are also robust, maintainable and relatively inexpensive. The three predominant process variables that PCs control on gathering compressor stations are liquid level, pressure and temperature [19]. Isolation valves, emergency shutdown (ESD) valves in safety systems, and liquid or chemical injection pumps may also be controlled and actuated pneumatically. Figure 2.1 shows a

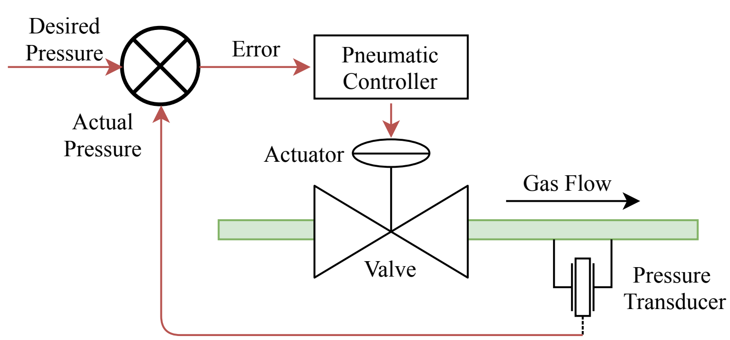

Figure 2.1: Closed loop control schematic of pneumatic pressure controller. A pressure transducer monitors the pressure downstream of the process valve. When the pressure falls out of the desired range, the PC sends pressurized gas to the actuator which adjusts the valve setting and the downstream pressure.

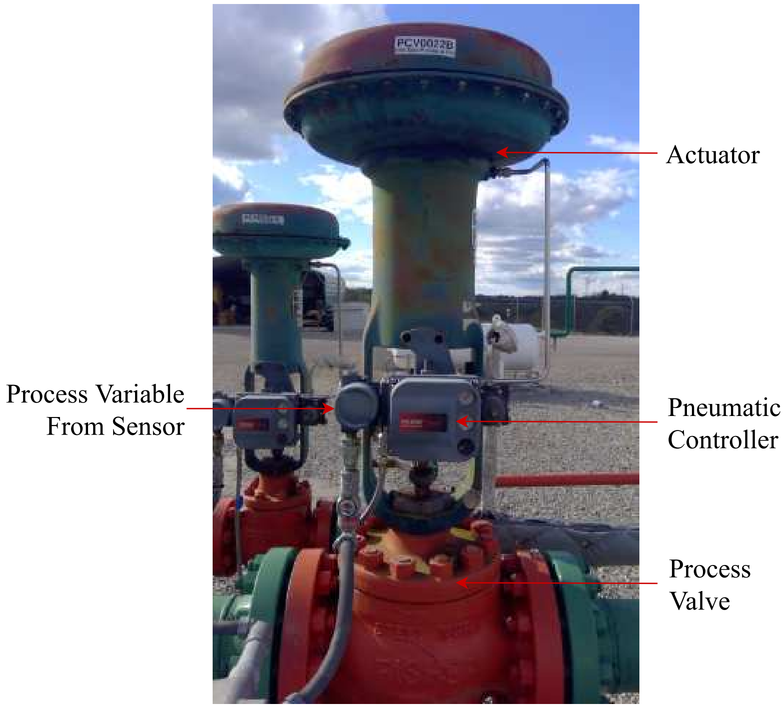

Figure 2.2: Typical assembly of a PC, actuator and valve in pressure control service on a natural gas gathering station.

common configuration of a pneumatic control loop in pressure control service, and Figure 2.2 shows a photograph of a common configuration of PC, actuator and valve.

A pneumatic control loop consists of a controller, a process sensor, process valve and a source of high pressure supply gas. On gathering compressor stations, high-pressure gas is typically drawn from the discharge side of station compressors and any treatment equipment (such as dehydrators and liquid separators) and is typically regulated to 20-40 psig. Each process valve has a dedicated controller that monitors a process variable and generates a signal to operate the valve when the variable falls out of its desired range. PCs monitor processes variables through mechanical, electrical or pneumatic sensors. Mechanical inputs include liquid level float-switches (Figure 2.3) or bimetallic thermometers. Electrical inputs are generally analog electrical signals from process transducers (Figure 2.1). Pneumatic inputs sense gas pressure signals from the controlled process directly [19]. PCs can be configured to control “snap acting” or “throttling” process valves depending on specific service requirements. Snap acting valves only operate in fully open or fully closed states while

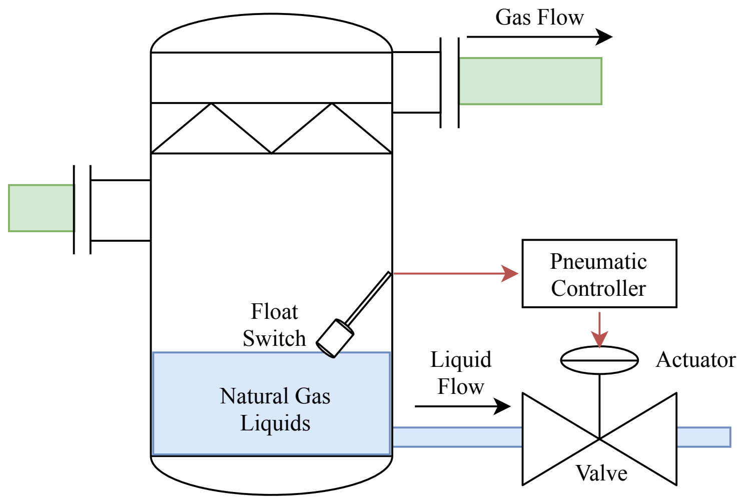

Figure 2.3: Closed loop control schematic of pneumatic level controller. When the liquid level in the pressure vessel reaches its "high" setting as indicated by the float switch, the PC sends pressurized gas to the actuator which opens the process valve and drains the liquids to an on site storage tank.

throttling valves can operate in any state between fully open and fully closed. Although each valve type can be used to control any process variable, snap acting valves are most commonly used in level control applications (Figure 2.3) and throttling valves are most commonly used in pressure control applications (Figure 2.1). The operation, classification and emissions behavior of PCs has been well documented in previous works [14, 19–23].

The majority of PCs vent a portion of supply gas to the atmosphere by design while pressurizing or depressurizing valve actuators. These emissions occur either continuously between control events (continuous bleed PC) or in intermittent bursts, depending on the design and specific application of the PC. In addition to emissions from venting during normal process control operation, PCs can also emit gas through leaking tube fittings, valve stems, and damaged or malfunctioning controller components. The U.S. Environmental Protection Agency (EPA) classifies PCs according to their normally operating vent behavior as intermittent or continuous bleed [22]. Continuous bleed devices are further classified as as low-bleed or high-bleed based on their steady state (inactive) emissions [19]. PCs that vent <6 scfh of gas are classified as low-bleed and those that vent ≥ 6 scfh of gas are classified as high-bleed.

2.2 Measurement Methods

2.2.1 Direct Measurements

Three methods have been used to perform direct measurements of emissions from PCs. Because all gas that flows through the pressurized supply gas line to the PC is eventually exhausted to atmosphere, a flow meter installed on this supply line provides a very accurate measurement of the device's emissions. Measurements made on the supply gas line capture emissions due to normal operation of the device as well as any other leaks in the pressurized control loop (Figure 2.4). However, connecting a flow meter to a PC's supply line can be problematic as the PC is unable to control its process valve while the supply line is disconnected. If PCs can not be taken offline to install meters on supply gas lines for safety or operations reasons, meters can also be installed on a controller's exhaust port (2.5). This configuration simplifies installation but does not capture leaks from the device's pressurized control loop. Also because the housings of most PCs are weatherproof enclosures and are not gas tight, emissions can escape from other points in a PC's housing other than its exhaust port. For these reasons, measurements made on exhaust ports are less reliable than supply line measurements.

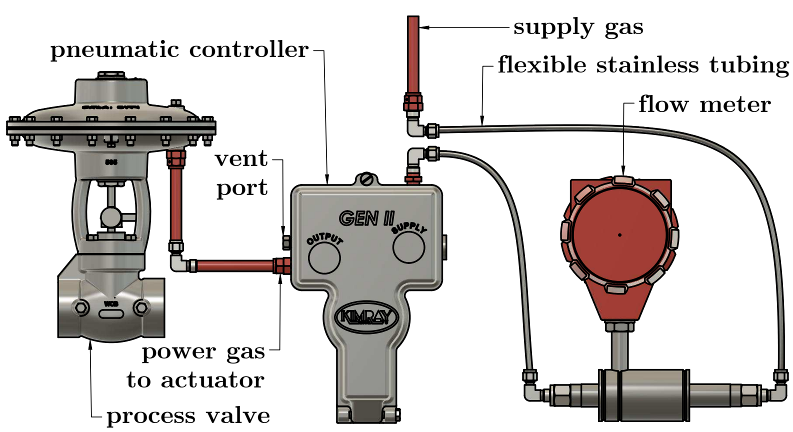

Figure 2.4: Configuration of a thermal mass flow meter used to measure PC emissions on the supply gas lines to the PC. Meters inserted in-line with supply gas lines as shown capture all emissions in the control loop occurring at or downstream of the meter.

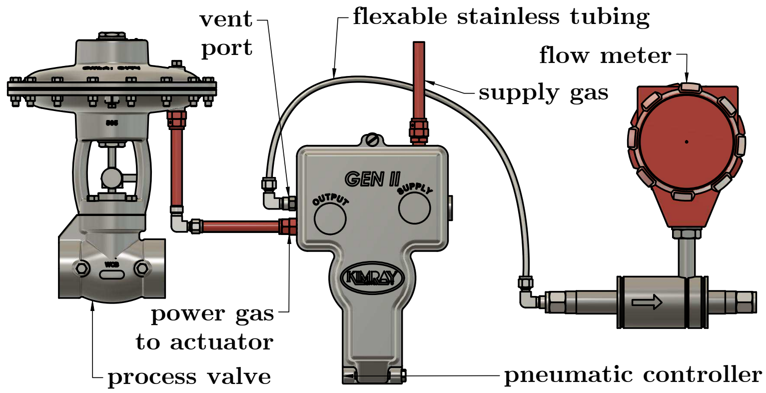

Figure 2.5: Configuration of a thermal mass flow meter used to measure PC emissions at a PC's exhaust port. Most PCs have a dedicated, threaded exhaust port that can be used to route exhaust gases out of buildings or away from ignition sources. Meters connected to PC exhaust ports only capture emissions venting from the port.

The Bacharach HI FLOW® sampler is a portable instrument designed to measure natural gas emission rates from leaking equipment that has also been used in several studies to measure emissions from PCs. The HI FLOW® sampler uses a high volume blower to draw natural gas leaks and a quantity of ambient air into a catalytic detector that measures the concentration of CH_4 in the air/natural gas mixture. The CH_4 concentration of the mixture is coupled with the measured flow rate of the sample stream to calculate the mass flow rate of the gas leak [24]. Because this instrument is designed to measure steady state leaks and only provides instantaneous emissions readings, it is not well suited for measuring the variable emissions from PCs.

2.2.2 Calculation Based Estimates

Several previous studies have pointed out significant logistical and technical challenges in attempting to perform these direct measurements on PCs. These challenges include the constraints on selecting an appropriate flow meter and the feasibility of deploying flow meters for a long enough duration across a large enough sample to capture the diversity of PC makes, models and applications [19,21,25]. An alternative approach to direct measurements is to calculate the theoretical emissions from PCs in different services. Estimates can be made for expected emissions per actuation event for intermittent vent PCs based on the typical displacement volume of actuators. Estimates can be made for expected emission rates for continuous bleed PCs using orifice geometries and typical supply pressures. These engineering calculations are then coupled with field observations of actuation frequencies to develop emission factors for each class of controller.

2.3 Pneumatic Controller Emission Estimates

Emissions from PCs make a significant contribution to total emissions from the natural gas supply chain. PC activity data and annual emissions from all onshore natural gas operations are shown in Table 2.1. To put the annual estimated PC emissions (1260 Gg CH_4/year) into appropriate context, consider that the average passenger vehicle in the United States emits 4600 kg of CO_2 per year [26]. On a 20 year time-scales, the global warming potential of CH_4 is approximately 86 times that of CO_2 [27], so the annual equivalent CH_4 emissions from an average passenger vehicle are 53.5 kg CH_4. From a greenhouse gas emissions standpoint, in 2016 the emissions from PCs in the natural gas industry were equivalent to the emissions from approximately 23.6 million passenger vehicles ($\approx$ 8% of number of registered vehicles in the United States during the same year [28]).

Table 2.1: Summary of activity data and annual emissions from all PCs in onshore production, gathering and boosting, transmission and storage sectors [2] and comparison to annual GHG emissions from US passenger vehicles.

EPA Classification	Count of Devices	Average Hours of Operation[1]	Annual Emissions (Gg)[2]
Low Bleed Devices	177061	7502	34.9
High Bleed Devices	23295	7220	118.6
Intermittent Vent Devices	573759	7450	1090.6
Total (Whole Gas)			1531
Total (Methane)[3]			1257

[1] Reported to the Greenhouse Gas Reporting Program (GHGRP) [29]
[2] Calculated using emission factors for low bleed, high bleed and intermittent vent devices shown in Table 2.2 and a natural gas density of 0.668 kg/m^3 under standard conditions (1 atm, 70° F).
[3] Calculated using an average CH_4 content of produced natural gas of 82.1% [2].

2.3.1 Previous Studies

The EPA's current PC emission factors used to calculate the annual PC emissions in Table 2.1 are generated from the results of a 1996 EPA/GRI study [23] which compiled direct measurements and survey data provided by upstream natural gas companies and results from a Canadian Petroleum Association PC emission rate study. A relatively small data set was used to calculate these emission factors (41 continuous bleed controllers and 19 intermittent vent controllers). This single set of PC emission factors is used to estimate PC emissions from all sectors of onshore natural gas production. Table 2.2 summaries mean emission factors utilized by the EPA and results of studies undertaken since the 1996 EPA/GRI study. Substantial variability exists between reported average emission rates.

Observations:

- The majority of these studies rely on sampling times of $\leq$ 15 minutes when performing direct measurements. During the University of Texas study, 62% of the measured devices did not actuate or had average recorded emissions of <0.01 scfh during the 15 minute sampling period. Other studies reported similar results. These short measurement times forced authors to make assumptions regarding actuation frequency and emission rates for controllers that do not actuate while being observed. Because these assumptions were applied to a large percentile of total measurements, average emission rates are often driven by estimations of PC behavior and not results of direct measurements. The only study that reported longer measurement times was the EPA Uinta study, that took measurements of ~1 hour for their 14 mass flow meter measurements. Average emission rates during 1 hour duration samples did not differ significantly from average emissions measured during shorter samples in this study.

- All of the studies reviewed were performed on production sites and no data were collected on emissions from PCs on the gathering compressor stations that were the focus of the GEF project. Although there is some overlap in the make, models and applications of PCs used on production sites and compressor stations, some PCs are

Table 2.2: Summary of results of previous studies focused on quantifying emission rates from PCs and current EPA emission factors.

Study	Geographic Area	Number of PCs Evaluated	Emission Estimation Strategy[5]
Univ. of Texas [20]	United States[1]	377	DM[6]
D. T. Allen, et. al [11]	United States[2]	305	DM
Prasino [30]	BC, Canada[3]	480	DM
EPA Uinta [31]	UT, Uinta Basin	80	DM&EC[7]
Greenpath Energy [25]	AB, Canada	1688	EC
OIPA [21]	OK, United States[4]	680	EC

Study	Average Emissions (scfh)[8]	Average Emissions (IV)[9]	Average Emissions (CB)[9]
Univ. of Texas	5.5	24.1	2.2
D. T. Allen, et. al	11.2	5.1	17.4
Prasino	8.9	8.4	9.1
EPA Uinta	0.36	0.33	1.1
Greenpath Energy	14.1	na[10]	na[10]
OIPA	1.03	0.04	21.5
Current EPA Emission Factors [2, 23][11]	11.5[12]	13.5	5.9[13]

[1] Appalachian, Mid-Continent and Rocky Mountain NEMS regions.
[2] Gulf Coast, Midcontinent, Rocky Mountain and Appalachian NEMS Regions.
[3] Measurements were made at sites in Dawson Creek, Fort St. John, Grand Prairie, Hanna (Alberta) and Brooks (Alberta) production basins.
[4] Granite Wash, Mississippian, Woodford, South Central OK Oil Play, Arkoma and Marmaton production areas.
[5] Direct Measurements (DM) and/or Engineering Calculations (EC)
[6] Engineering calculations used to estimate emissions from the
[7] Direct measurements performed on 20 PCs, engineering calculations used to estimate emissions from remaining 60 PCs.
[8] Whole gas emission rate
[9] Intermittent Vent controller (IV) or Continuous Bleed controller (CB).
[10] Study does not report distinct emission rates for IV and CB controllers.
[11] From 2016 GHGI
[12] Average of emission factors for IV, LB and HB PCs weighted by national device count from subpart W reporting data (667,785 IV devices, 206,825 LB devices, and 29,405 HB devices)
[13] Average of emission factors for LB and HB PCs weighted by national device count

unique to each sector. For PCs that do overlap, it is unknown how the emission behaviors of the controllers compare.

- Two studies made an effort to distinguish between PCs that were operating correctly or malfunctioning from an emissions perspective [20, 31]. The University of Texas study consulted with an independent industry expert to identify PCs that may have been having malfunctioning based on the comparison of the device's recorded behavior with its expected behavior; 29 of the top 40 emitters in the study were identified as having "equipment issues" by the consultant. This study reported 19% of the devices with emission rates >6 scfh accounted for 95% of total emissions. Although other studies relying on direct measurements did not attempt to classify PCs as normally operating or malfunctioning, they did report similar observations of small subsets of PCs contributing a large percentage of emissions [11, 13, 30]. The EPA's assessment of PC emissions on well pads in the Uinta Basin identified intermittent vent PCs as malfunctioning if the device showed sustained, continuous emissions exceeding 0.2 scfh [31]. 14% of the intermittent vent PCs observed during the study were identified as malfunctioning. The majority of emissions recorded during this study were attributed three normally operating continuous bleed PCs and the subset of 11 malfunctioning intermittent vent PCs.

- Studies relying on combined direct measurements and engineering calculation methods or engineering calculations alone report much lower average emission rates than studies relying entirely on direct measurements. Because the engineering calculation approach does not take into account the impact of malfunctioning PCs, this discrepancy is possibly indicative of the driving effect malfunctioning PCs have on average emission rates.

- There is some inconsistency across the studies on PC classification (intermittent vs continuous vent) and on whether all pneumatic devices (pumps, ESD valves) should be included in tallies or whether emission factors should focus exclusively process control valves. For example, 40% of the controllers observed during the the OIPA study [21] were back-pressure regulators, which are not included in this or other studies; and 13% of the PCs measured in the University of Texas study were emergency shut down (ESD) controllers which are not included in this or other studies. Some studies include emissions from pneumatic pumps in their emission estimates and some do not. Because each study has a unique sample of equipment lumped together as PCs, the emission rates reported by the studies are not always directly comparable.

The emission factors used for PCs today are based on a relativity small dataset from 1996 that may be outdated, as all measurements were made before advances in hydraulic fracturing that enabled the current shale gas boom. There is room to improve the accuracy of PC emission estimates published in previous studies, either due to engineering calculations not accounting for high emitting, malfunctioning controllers or short duration measurements leading to high uncertainty of emission rates for PCs that do not actuate or have measurable emissions during sampling times.

Chapter 3

EMISSION MEASUREMENT SYSTEM

3.1 System Requirements & Constraints

The challenges of envisioning a measurement to accurately measure the emissions from a diverse population of PCs and the causes of uncertainties in previous PC emission estimates are documented in previous works and are summarized in Section 2.3.1 of this report. Because no measurements longer than one hour had previously been recorded, the primary objective for the measurement system was to record time series emission data over a multi day period. These measurements would allow emission factors to be calculated directly from the data, without needing to make assumptions about the PC's behavior over longer time periods. The following requirements and constraints were established for the proposed measurement system in collaboration with industry partners.

3.1.1 Safety

Participating industry partners cited safety concerns as the greatest barrier in securing approval for deploying a given measurement system. Because the proposed measurement system would need to be connected to operating equipment and left on site for multiple days without supervision, each partner required the system be evaluated through a Measurement of Change (MOC) process for each site where measurements were proposed. This process assessed the compliance of the measurement system with the operator's safety protocols. Natural gas compressor sites are categorized as Class I, Div I-II, according to National Fire Protection Association's hazardous location classification system, meaning that flammable vapors and gases may be present in combustible concentrations under normal conditions [32]. The National Electric Code (NEC) defines requirements for equipment used to eliminate electrical ignition sources through isolation in explosion-proof enclosures or intrinsically safe design. Any electronics were required to be certified as intrinsically safe according to NEC standards or be housed in gas tight, explosion proof housings.

Another safety concern relates to physically connecting to a PC. PCs operate to keep compressor stations running at steady state. Connecting meters to supply gas lines requires depressurizing and taking the controlled equipment offline, meaning the PC is no longer controlling its process valve. Depending on the design of the valve's actuator, this can cause the valve to snap shut or to remain at the setting it was at when supply gas was disconnected. In both cases, the valve, and therefore the process the valve controls, is no longer being actively adjusted. This can trigger automatic shutdowns on downstream equipment, disrupting station operation. The measurement system also needed to be passive in design, and have no possible way to create back-pressure at any point in the PC's control loop or obstruct its vent port to atmosphere.

3.1.2 Measurement Duration & Power Supply

All previous studies have relied on short duration measurements, forcing scientists to make assumptions about the long duration behavior of PCs that had no emissions or actuations during measurement times. To address this knowledge gap, a minimum measurement duration of 72 continuous hours was assigned as a target. This target duration was based on anecdotal evidence from industry experts serving on the project's Technical Review Committee (TRC). Several TRC members who collaborated on previous PC emission studies hypothesized that due to the potential for high variability of PC operation over time and long periods separating actuation events, multi-day measurements would be necessary to collect high confidence data. This measurement duration would require a trade-off with the number of PCs that could be sampled during the study and ultimately result in a smaller sample set. However, it was preferable to focus on gathering high confidence data even if the overall sample size would be reduced.

Many compressor stations, especially older or geographically remote stations, do not have electrical power on site. To avoid limiting sampled stations to those with power supply, the measurement system also needed to be independently powered for the entire target measurement duration.

3.1.3 Flow Meter

An ideal meter for the study would be able to measure very low, steady flow rates from low bleed PCs as well as very, short duration high emission spikes from intermittent vent controllers. Low bleed controllers have average emission rates of <6 scfh and previous studies recored short duration emission spikes of up to 300 scfh [20]. The selected meter needed to have an adequate span and turndown ratio to capture low, continuous emissions as well has high emission intermittent events to avoid clipping data. The meter also needed to have a fast enough response time to capture the rapid changes in emission rates expected from intermittent vent PCs. Selecting a meter with this wide a range can result in substantial error at the low end of the meter's range. Because it was anticipated that a small subset of high emitting PCs would drive the emission factors, it was preferable to select a meter that could capture the maximum emissions recorded in the literature, even at the expense of accuracy at lower flow rates. Because it was anticipated that long duration measurements would eliminate much of the uncertainty from previous studies, using a flow meter accurate to ±5% of measured value was acceptable.

The flow meter would also be required to measure natural gas of varying compositions (between 65-100% CH_4). Because it was expected the meters would be connected to PC exhaust ports (measuring at atmospheric pressure) as well as supply gas lines (measuring at pressures between 25-50 psia), the meter needed to be able to measure gases of varying densities. The flow meter would also need to conform to all safety requirements, particularly intrinsic safety for electrical components and open flow paths to eliminate any possibility of creating blockages or back-pressure in the supply gas or exhaust port lines.

3.1.4 Data Logging

All data collected by the measurement system needed to be logged and timestamped in an easily retrievable location in a format conducive to loading into software for post-processing. Due to the transient nature of emissions during valve actuation events, data needed to be logged at a minimum frequency of 1 Hz to capture transient events. The resolution of recorded data needed to match the resolution of the flow meter's output. Finally, the data logger needed to conform to all safety requirements for electrical equipment, as defined in Section 3.1.1.

3.1.5 Versatility & Usability

It was anticipated that the study team would encounter a wide variety of make, model and configurations of PCs so the measurement system needed to be able to connect to a diverse range of equipment. To minimize PC downtime when connecting the measurement system to supply gas lines, the system needed to be fast to install. The system would travel with the measurement team in a van full of other measurement equipment between sites so the system needed to be relatively compact and packable. Because the system would be left on-site for up to five days during each deployment with as many as 20 deployments planned, it needed to be physically robust and able to withstand exposure to the elements over the course of all field work.

3.2 Component Selection

Based on input from the GEF project's technical review committee, the decision was made to model the measurement system for this project off the approach taken by Allen et al. [20], with design modifications to meet site safety regulations, power supply constraints and measurement duration targets.

3.2.1 Flow Meter

Six Sierra 740i thermal dispersion mass flow meters were selected to quantify emission rates from pneumatic devices. Thermal dispersion mass flow meters measure the heat transfered from an electrically heated velocity sensor element in the meter's flow path to the boundary layer of the gas flowing past the sensor element to determine gas velocity. Measurements of gas properties (temperature and pressure) and the cross-sectional area of the meter's flow body can then be used to determine the mass flow rate of the gas [33]. The boundary layer heat transfer calculations used to correlate heat loss from the sensor element are a function of a gas's physical properties (viscosity, heat capacity and thermal conductivity for a given temperature and pressure). Therefore, if a gas different than the meter's calibration gas is being measured, a correction factor can be applied to correct for the differences in the gas's properties. Meters were factory calibrated to a full scale flow of 300 scfh with a precision of $\pm 0.5\%$ plus 0.5% of flow at readings below 50% of full scale, and $\pm 0.5\%$ of flow at readings above 50% of full scale. The meters were calibrated on ambient air at a pressure of 50 psig. These meters are certified for use in Class I/Div I locations and satisfy all safety requirements for operating on natural gas stations.

During deployment the meters monitored three variables: Gas flow rate, temperature, and pressure. The magnitude of each reading was displayed on a user interface screen and output via a dedicated 4-20 mA analog channel. 4 mA output corresponds to the lower limit of the variable's span (32° F for temperature, 0 psia for pressure and 0 scfh for flow) and 20 mA output corresponds to the upper calibrated limit of the variable's span (212° F for temperature 100 psia for pressure and 300 scfh for flow).

3.2.2 Power Supply

The power drawn by the meter is proportional to the flow through the meter because at higher flow rates, a higher current is needed to heat the active sensor element to maintain a temperature differential between the active and passive sensor probes. The manufacturer stated a maximum current draw of 0.2 amps at flows at or above the meter's full scale value of 300 scfh. The meters run on a 24 VDC supply, so to achieve the measurement duration target of 72 hrs a battery with at least 350 watt-hours of storage was needed. A 25.6 V, 384 watt-hour LiFePO4 battery was selected which would provide the meters with 80 hours of battery life at their maximum current draw. This gave the power supply a capacity buffer to satisfy power requirement for the data logger and account for losses in the 24-24 V DC-DC converter used to provide consistent output voltage to the flow meters. These batteries and DC-DC converters were housed in an aluminum explosion proof housing with power cables passing through gas tight cable glands to satisfy safety requirements (Section 3.1.1).

3.2.3 Data Logger

Because the meters are designed to interface with industrial control or SCADA systems, there was no integrated data logging capability available with the meters from the manufacturer. Therefore, each meter was fitted with a custom data logger mounted on the meters electronics inside their explosion proof housing to record flow. The data logger recorded temperature and pressure data at a 1 Hz sampling rate for the duration of deployment. The logger's electronics convert three 4-20 mA analog output current signals into digital voltage values that were recored on a micro-SD card. A real time clock was integrated with the data logger so each recorded data point written to the SD card was time and date stamped.

The Sierra flow meters selected for the study output flow, temperature and pressure data via three analog 4-20 mA channels. The following operating requirements were identified to select an appropriate data logger:

- Powered from same 24 DC power supply as flow meter
- Low power consumption
- Contained in Class I/Div enclosure, either with power supply or within flow meter housing.

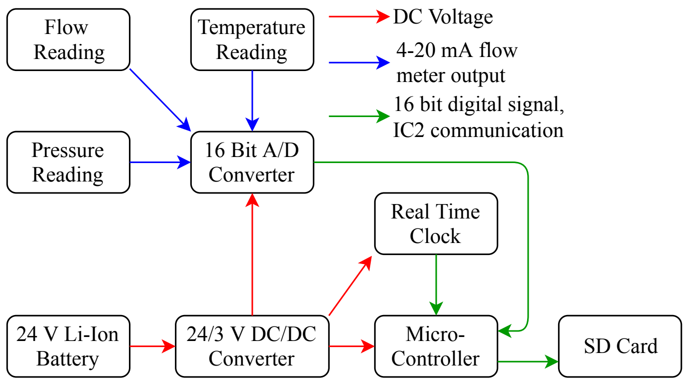

Figure 3.1: Schematic of hardware interactions for data logger developed to record 4-20 mA output signals from Sierra 780i flow meters.

- Able to write to SD card, easily extractable, well organized data.

Modern programmable microcontrollers such as those manufactured by Ardunio, Adafruit or SparkFun, are compact, can accept digital or analog inputs, support multiple communication protocols, consume little power relative to the requirements of the flow meter, and are offered with integrated SD card slots for reading and writing data. These microcontrollers satisfy all operating requirements better than off the shelf products. The compact size of these microcontrollers also would allow the data logger to be integrated with the flow meter's electronics and mounted in the meter's explosion proof housing 3.3. The Adafruit Adalogger M0 microcontroller was selected for is low cost, low power demands, integrated micro-SD card slot and support of I2C communication. To ensure high signal resolution, two 16 bit analog to digital converters (ADCs) were used to measure voltage drop across 150 Ω resistors as a surrogate for current measurement for each of the flow meter outputs. A high accuracy real time clock (RTC) was selected to provide time and date stamps for each recording.

3.3 System Integration

Based on project budget, project sampling goals and available space in the mobile research vehicle, components were purchased to assemble six of the measurement systems described above. The flow meter, power supply and power converters were used as "off the shelf" products and did not require additional development or modifications. The data logger required several breadboard prototypes and iterations of code development to ensure output channels from the flow meters were written to the logger's removable microSD card and that the loggers components (analog to digital converters, DC-DC converter and RTC) were addressed and communicating correctly. The completed data loggers were built on perma-proto boards and piggy-backed onto the flow meter's electronics using custom 3D printed mounts (Figure 3.2).

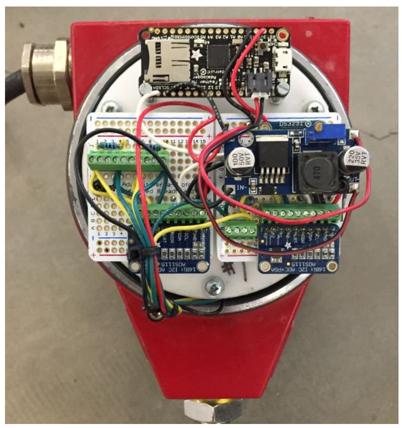

Figure 3.2: Custom microcontroller based datalogger integrated with Sierra 708i thermal mass flow meter.

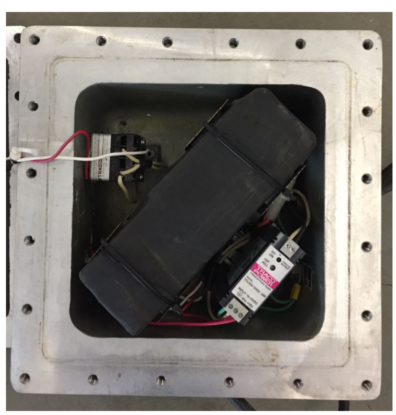

Figure 3.3: Measurement system power supply and DC-DC converters secured in explosion proof, gas tight housing to conform to Class I Div I hazardous area requirements.

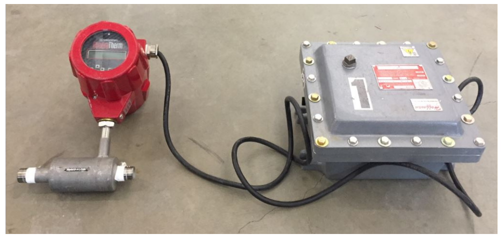

Figure 3.4: Fully assembled thermal mass flow meter based measurement system and power supply.

Chapter 4

FIELD DEPLOYMENT

4.1 Site & Device Selection

The accuracy of the emissions factors and scalability of the collected data depend on sampling a selection of standard pneumatic devices that operate across representative sample of gathering stations. The number of PCs that could be instrumented during this study was constrained by the desired duration of measurements and logistical issues due to measurements taking place in parallel with other objectives during the GEF project. The following sections outline how stations and specific devices were selected for measurement to best utilize the the six flow meters available for deployment during each week teams were in the field.

4.1.1 Preliminary Site Selection

A nationally representative sample of sites was generated from partner company assets using a randomized, clustered sampling strategy. First, basins were selected to be representative of a national sample, with two constraints: (1) at least 2 partner companies had operating gathering station assets in the basin (for internal anonymization reasons), and (2) at least one basin was selected for each production type (wet/dry gas). Basins were arranged in order to minimize travel time for the team using a mobile measurement unit.

After basin selection, measurement weeks were allocated to each basin. For each week, one company was selected to host measurements, except for two weeks where basin size and station count necessitated measurements on two companies during one week. Once the company-weeks were confirmed, site selection proceeded as described below. Each company was assigned at least two weeks of measurement, and two companies hosted three full weeks each. Long-duration PC measurements were scheduled for 11 field-weeks; however, during campaign planning (after sample weeks were locked in), the study team discovered that the pneumatic controls at a high percentage of partner sites had been converted to run on compressed air. From an emissions perspective, this is a positive development, as it eliminates vented and leaked emissions from PCs entirely. Consequently, long-duration measurements could only be made during 8 of 11 field-weeks, during which time 44 devices were instrumented at eight stations between June and November 2017. Sites visited during this portion of the campaign are classified as "Class I' in following data summaries.

4.1.2 Secondary Site Selection

Due to the prevalence of stations where PCs were powered by compressed air, the study team decided to continue PC measurements after the end of the GEF field campaign to increase the same size and diversity of sites. Partners were requested to provide basin locations for sampling. The extended sampling included 11 additional gathering stations in four basins. These stations were selected in collaboration with industry partners in areas not visited during the field campaign. These stations *were not* randomly selected during the original site selection. CSU personnel were present for meter installation, at a minimum, in the first station in each basin, and reviewed the installation locations for subsequent measurements with the operator's personnel. At the end of the measurement period, the operator uploaded the data, recharged the meter, moved the meter to the next designated location, and photographed the installation. During the additional sampling period, CSU was present for meter installation at five stations (stations classified as "Class II"), and measurement instruments were installed by parter company operators without CSU study team members present at six stations (stations classified as "Class III).

Therefore, the data presented here is a combination of randomly selected and guided site selection, both done in cooperation with industry partners. While selection was not entirely random, the addition of measurements after the field campaign improved the geographic diversity of the dataset, more than doubled the total number of measurements made, and extended data collection across nine elapsed months, increasing the variability in weather conditions. Including all measurements, PC measurements were made at stations owned by eight of nine partner companies that participated in the GEF study; all stations operated by the last partner utilized compressed air to operate pneumatic devices.

4.1.3 Device Selection

Measurement of specific controllers on each station was limited by the ability to temporarily disconnect the supply gas line during meter installation. This was not an issue for on/off type controllers that could be taken out of service without disturbing a process; however, to measure controllers designed to continuously throttle or maintain sensitive pressures, some station equipment needed to be taken off-line briefly for meter installation. For example, fuel gas pressure controllers or station inlet pressure controllers were isolated and depressurized prior to meter installation. Therefore, measured controllers were selected on an opportunistic basis subject to these constraints.

Emergency shut-down (ESD) and other station safety or isolation controllers were not instrumented in this study. These devices rarely actuate, and therefore would not represent emissions from PCs that were actively controlling process variables. In addition, other measurements during the field campaign screened for, and measured, PCs that were emitting, and leaking ESD controllers would have been identified in this way. Due to these constraints, the study team utilized engineering judgment to select controllers for measurement. During the measurement campaign the mix of PC types and controlled applications was monitored, and subsequent meter deployments were guided to increase the diversity of resulting measurements.

4.2 Measurement Protocol

Because the measurement system was installed unattended on sites for several days at a time and involved connections to process control loops, partner companies mandated that the meter installation follow formal management of change (MOC) review. This review involved evaluating the operation of the measurement system to ensure all components conformed to station safety protocols for electrical equipment and that installation of the system would not adversely affect station operations. The CSU measurement team coordinated directly with the site operations supervisors and engineers during the MOC review in the weeks leading up to each station visit to tentatively identify PCs to measure and any station specific requirements.

Each station visit began with a site safety briefing and a hands on introduction to the measurement system with station operators. After the site safety briefing, operations staff will performed a quick walk through of the site with the CSU measurement team to identify PCs for measurement. If operations staff decided there were no acceptable options for isolating devices of a certain process and installing the meters on supply gas lines, the meters were connected via threaded exhaust ports. When devices were identified for measurement, the measurement team and operations staff coordinated on the meter installation. If a meter was being installed in the supply gas line, the protocol was as follows.

- Measurement team connected flow meter to independent power supply and configured data collection. Location of independent power supply was be determined by site operator to minimize footprint and impact of measurement device at each location.
- Site operator or technician isolated valve/controller
- Site operator or technician parted supply line and installed and secured meter
- Measurement team turned on the device and begin data collection
- If possible, site operator manually actuated device and measurement team ensured meter was operating correctly and data was being recorded
- Site operator performed final safety assessment and leak check of installed meters and independent power supply boxes

- Measurement team performed leak scan of entire pressurized control loop with FLIR camera to ensure the installation did not result in leaks in the control loop.

Figure 4.1: Emission measurement system installed on supply gas line to PC controlling liquid level in a secondary liquids storage tank.

If the meter is being installed at a controller exhaust port, the protocol is as follows.

- Measurement team connected flow meter to independent power supply and configure data collection. Location of independent power supply was determined by site operator to minimize footprint and impact of measurement device at each location.
- Site operator or technician connected flow meter inlet to controller exhaust port
- Measurement team turned on the device and began data collection
- If possible, site operator manually actuated device and measurement team ensured meter was operating correctly and data was being recorded
- Site operator will perform final safety assessment and leak check of installed meters and independent power supply boxes.

Figure 4.2: Three emission measurement systems installed on exhaust ports to PCs controlling liquid levels on compressor interstage knockout tanks.

After installation the measurement systems were left in place unattended for a minimum of three days. The CSU measurement team would return to retrieve the meters after four to five days, which typically exceeded the battery life of the measurement system and maximized the amount of data collected.

Chapter 5

POST-CAMPAIGN DATA MANAGEMENT

The following sections outline the corrections that were made to raw data prior to analysis.

5.1 Signal Filtering

Raw voltage values recorded to secure digital (SD) memory cards were converted to temperature, pressure and flow magnitudes during post processing. The recording system for the meters exhibited a low signal to noise ratio at the lower ends of the flow reading (0-10 scfh, 0-3% of span). Because many of the emissions recordings were in this flow range, a filter was applied to the raw data to reduce this noise prior to analysis. Flow data was filtered using a low-pass filter (Matlab *lowpass()* function) with a cutoff wavelength of 60 seconds and a -60 dB stop-band. To prevent overshooting or ringing, a filter with a low steepness was used. Figure 5.1 shows signal noise reduction at zero flow.

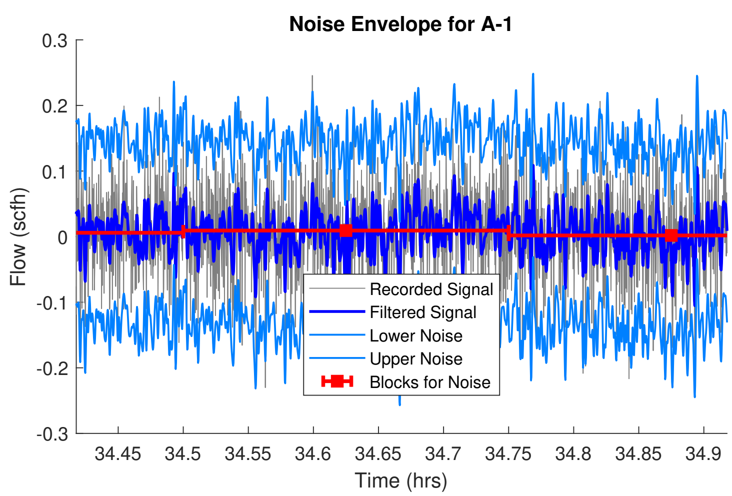

Figure 5.1: Attenuation of signal noise in flow meter recording under zero flow conditions after the application of lowpass filter.

5.2 Gas Composition Corrections

Because the thermal mass flow meters used in this study rely on thermal properties of the gas being measured to correlate heat transfer between the gas and sensor elements and gas velocity, the raw flow data collected needed to be corrected based on the specific gas composition at each station. Gas used to power PCs is most commonly drawn from a station fuel gas line, so recent fuel gas analysis were provided for each station where PC measurements were made. Film coefficient correction factors were generated using software provided by meter the manufacturer (user interface shown in Figure 5.2). This software computes a correction coefficient between a reference gas (air) and a known gas composition based on the density, thermal conductivity, heat capacity, and viscosity of the known gas composition at a given temperature and pressure. The average supply gas temperature

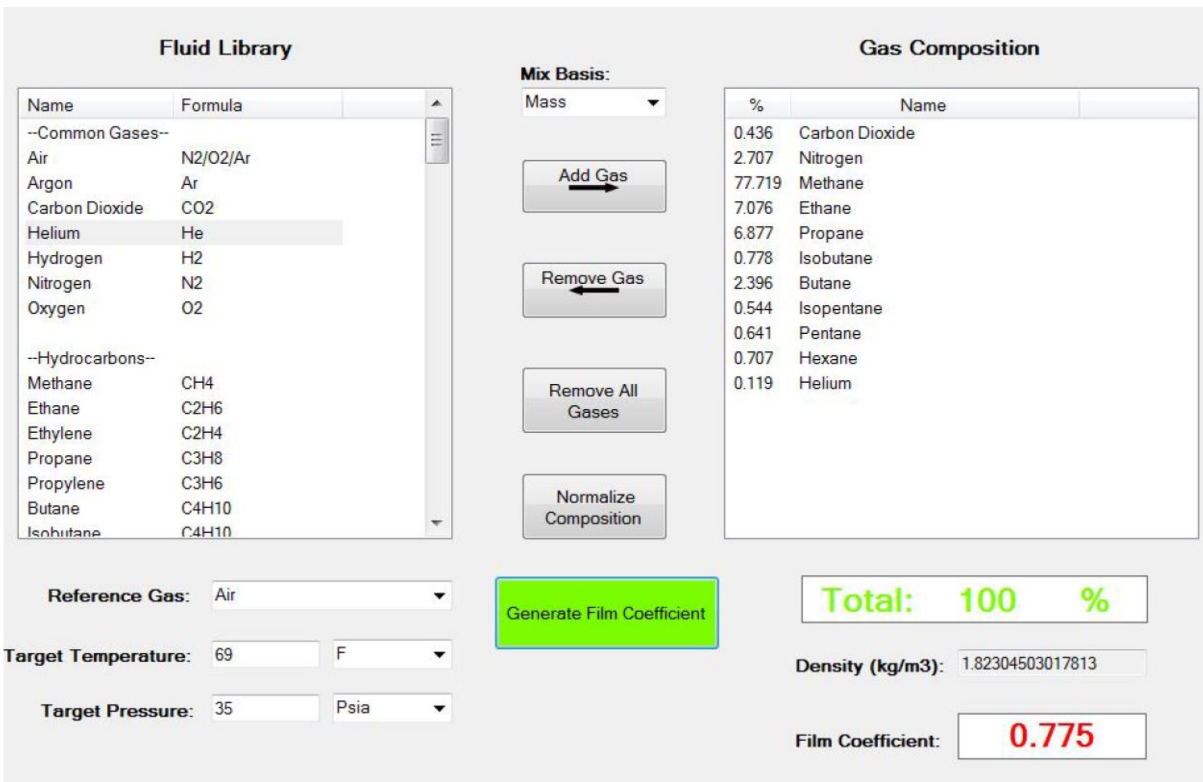

Figure 5.2: User interface for software provided by Sierra instruments to calculate correction factors for flow meter readings between flow meter calibration gas (air) and site specific natural gas compositions. Gas composition shown is from site N.

and pressure readings for each recording were used to generate these correction factors. Correction factors between 0.775 and 0.81 were applied to raw data. The error introduced by performing these gas composition corrections are not explicitly published by the meter manufacturer and challenging to estimate analytically. However, these corrections were included in validation tests performed on the measurement system to estimate absolute meter error (discussed in Section 5.5).

5.3 Non-Zero Flow Readings

The Sierra meters that were utilized for the study exhibit a behavior where they indicate a non-zero flow through the meter when the meter is pressurized and no flow is occurring. This issue was discovered when a steady reading of ≈10 scfh was observed on the user interface of a meter installed on the supply gas line of a PCs with very high supply gas pressure (≈ 60 psia) but the study team was unable to find any evidence of gas leaking at any point on the controller's pressurized control loop. The magnitude of this non-zero value was observed to increase with increase at higher supply gas pressure and decrease at lower supply gas values, eventually falling to zero below a supply pressure of 30-35 psia. This suggested measurements made on the supply gas lines of controllers at pressures above this threshold value were prone to showing a non-zero baseline. Emissions data collected by meters connected to controller exhaust ports were not prone to this error because measurements were made at atmospheric pressure, below this pressure threshold. A review of data collected during the field campaign and a series of lab tests confirmed that a substantial number of recordings made during this study were impacted by this meter effect. Henceforth this error is referred to as *NZ flow*: "NZ" indicates times when no gas is flowing through the meter, but the meter indicates non-zero flow.

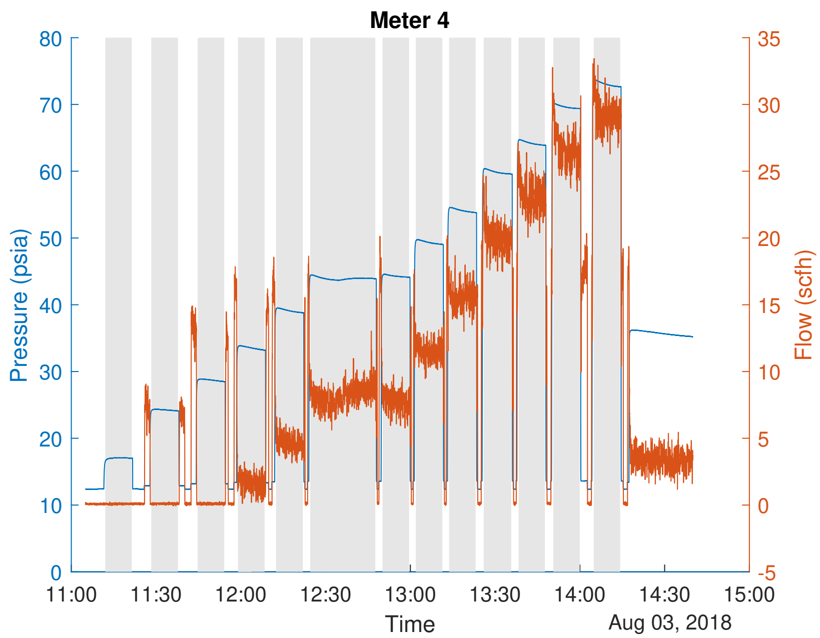

Figure 5.3: Example data recording for flow meter testing and characterization of NZ meter error as a function of operating pressure. Gray shading indicates times when indicated flow had stabilized sufficiently to be utilized for evaluating the indicated flow rates.

5.3.1 Pressure to NZ Correlation

In field conditions when NZ flow *may have* occurred, it is impossible to distinguish between true flow and a false, non-zero flow rate indicated by the meter. Therefore, samples where NZ conditions occur must be treated differently from samples where it could not occur. A series of lab tests were performed to analyze the NZ behavior and develop a correction factor to apply to data impacted by this problem. The meters were connected to a pressure regulated supply of natural gas at the *Methane Emissions Technology Evaluation Center* (METEC) and tested at a range of pressures. Meters were connected in parallel and lines through the meters were purged. The pressure in the lines was then increased between 13 and 70 psia with the meter outlets closed. After each successive increase in gas pressure, the meter reading was allowed to stabilize and meter parameters were recorded for a period of several minutes. An example of one of these pressure tests is shown in Figure 5.3. There was no gas moving through the meters during this test so in this case, all indicated flow measurements are attributed to the NZ effect.

The mean and standard deviation of the indicated flow was extracted for each stable period and a linear or parabolic trend with pressure was fit to the resulting data. Periods with high variability, as represented by standard deviation, were eliminated from the fit. Figure 5.4 provides an example for a meter with a linear fit, while Figure 5.5 illustrates the one meter (meter 6) that utilized a parabolic fit.

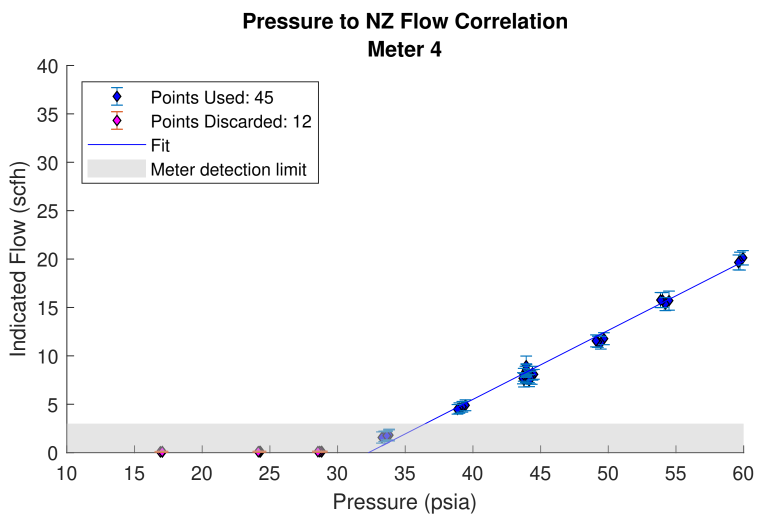

Figure 5.4: Example of a linear fit correlating NZ flow meter readings to operating pressure during measurement. Linear fits were applied to flow meters 1-5.

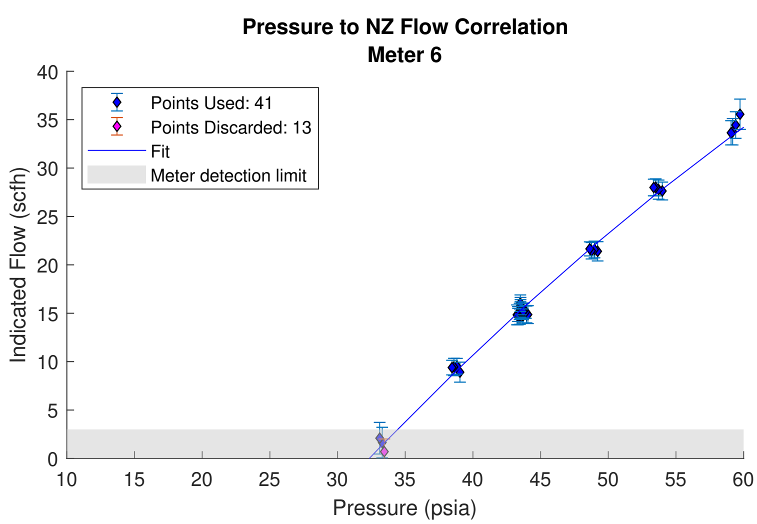

Figure 5.5: Example of parabolic fit correlating NZ flow meter readings to operating pressure during measurement. A parabolic fit was only applied to meter 6.

The gray shaded area in figure indicates the manufacturer's stated detection limit of the meter during normal (i.e. non-zero) flow conditions, based on the meter's 100:1 turn-down ratio and calibrated flow range. The rise of the correlated points above the grey shaded area indicates pressures at which the meter can exhibit non-zero readings. For example, when there is no gas flow, meter 4 begins to indicate a false NZ reading at pressures above ≈35 psia. When supply gas pressures reach 50 psia, any recorded flow at or below ≈10 scfh (whole gas) could represent a false NZ reading.

The resulting fits for all meters are shown in Figure 5.6. These pressure-NZ correlations are used to determine points in each data set where recorded flow rates could have been due to NZ meter error (based on supply gas pressure) and are ultimately applied to set false NZ readings to zero.

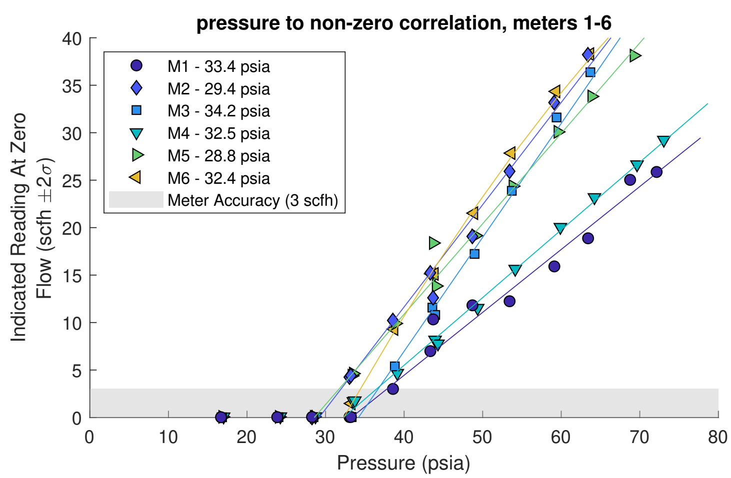

Figure 5.6: Correction curves for all flow meters correlating NZ flow meter readings to operating pressure during measurement. The pressure at which NZ behavior starts is indicated in the legend for each meter.

5.3.2 Long Duration Tests

Two additional long duration tests were performed on the meters in a field setting to evaluate the stability of the NZ flow baseline over multiple days and quantify uncertainty in the correlations developed in Section 5.3.1. For each of these tests, meters were connected in

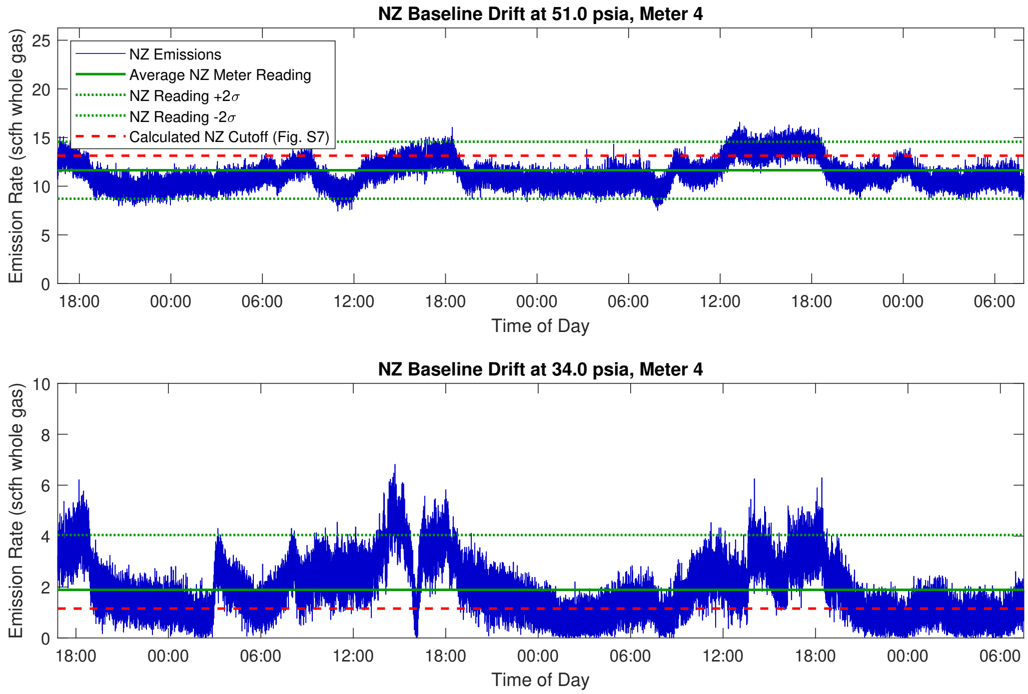

Figure 5.7: Drift of NZ baseline over 2.5 day tests. These tests were performed on each meter at two pressures: Once at the pressure where the NZ effect was present in all meters (34 psia) and once at the maximum pressure recorded in the field (54 psia). The standard deviations ($\pm 2\sigma$) plotted in Figures 5.6, 5.8 and 5.5 and used to zero NZ flow rates (Figures 5.9 and 5.10) are based on a linear fit between the standard deviations of meter readings from the long duration tests at 34 and 50 psia.

parallel to a regulated, high pressure tank of natural gas. Outlets of all meters were capped and checked for leaks. The meters were then pressurized with natural gas and left to record indicated flow (i.e. the NZ baseline), gas temperature and pressure data over a 3 day period. Testing was performed outside to provide diurnal variation in ambient temperatures the meters similar to what was experienced in the field. The motivation behind these tests was to determine the degree to which the NZ baseline would drift over a multi day test period.

The average baseline meter reading was observed to deviate from the value calculated using the correction correlations from Figure 5.6. This demonstrates the level of uncertainty associated with differentiating between actual flow and meter error. Although visual inspection of the drift in the NZ baseline suggests that the value varies with gas temperature, no reliable or repeatable temperature correlation could be identified. Since the meter's

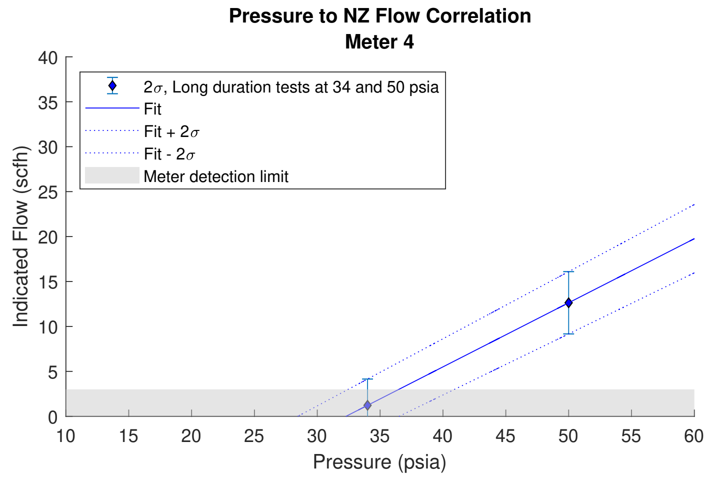

Figure 5.8: Example of a linear fit correlating NZ flow meter readings to operating pressure, with standard deviations from long duration tests (Figure 5.7)

response to changes in gas composition, pressure and temperature is non-linear and dependent on proprietary algorithms and heat transfer correlations programmed into the meter's micro-controllers, this likely made a simple correlation impossible.

To account for the variability in the meter's NZ reading, the standard deviation of NZ data from the low and high pressure long duration tests were used to assign the NZ cutoff value for each data set. In Figure 5.8, the solid line shows the fit from Figure 5.6, the error

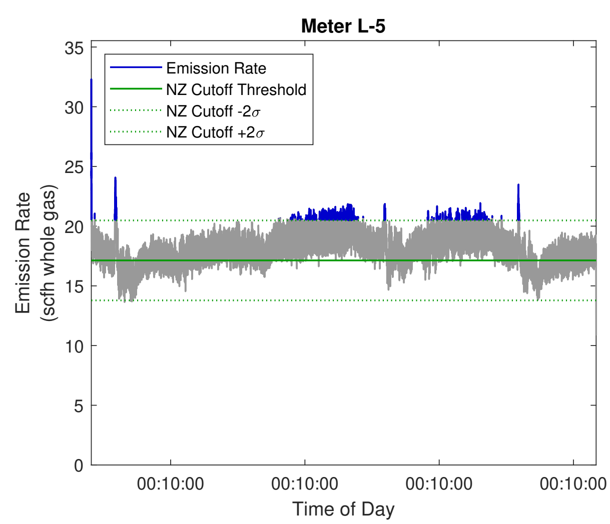

Figure 5.9: Example of an emissions recording impacted by NZ flow meter error. Because the majority of the measurements of this recording are within $+2\sigma$ of the mean NZ cutoff threshold, it is likely that this entire recording can be attributed to the NZ meter effect.

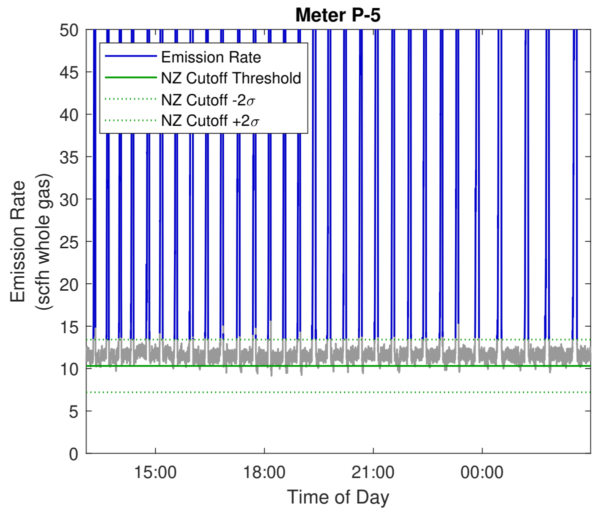

Figure 5.10: Another example of emissions recording heavily impacted by NZ flow meter error. In this recording, the NZ cutoff threshold calculated using Figure 5.6 curves did not capture the actual NZ baseline. To account for measurement noise and drift, all readings less than the calculated NZ cutoff $+2\sigma$ were set to zero.

bars show two standard deviations from the low and high pressure tests plotted in Figure 5.7. Henceforth, all references to standard deviations used in NZ corrections refer to those calculated from long duration tests. The dashed lines are the fit between the error bars at 34 and 50 psia, which represent the uncertainty in identifying a NZ baseline for a given pressure.

The uncertainty limits identified by this process impact the evaluation of emissions data effected by the NZ meter error. In Figure 5.9, the PC being measured has an NZ cutoff of 17.1 scfh, calculated using its supply gas pressure of 46.6 psia and the curves in Figure 5.6. Based on the results of the long duration tests that show disagreement between calculated NZ cutoffs values and actual NZ readings (Figure 5.7), and the fact that >80% of the flow readings fall within $\pm 2\sigma$ of the NZ cutoff, it is very likely that all of the meter recordings for this test were a product of the NZ meter effect. However, due to noise in the signal and drift of the NZ baseline, zeroing meter readings below the calculated NZ cutoff threshold would only succeed in filtering 19% of the data points, and 83% of the emissions would remain. A similar issue can be seen in Figure 5.10, where the actual NZ baseline is slightly greater

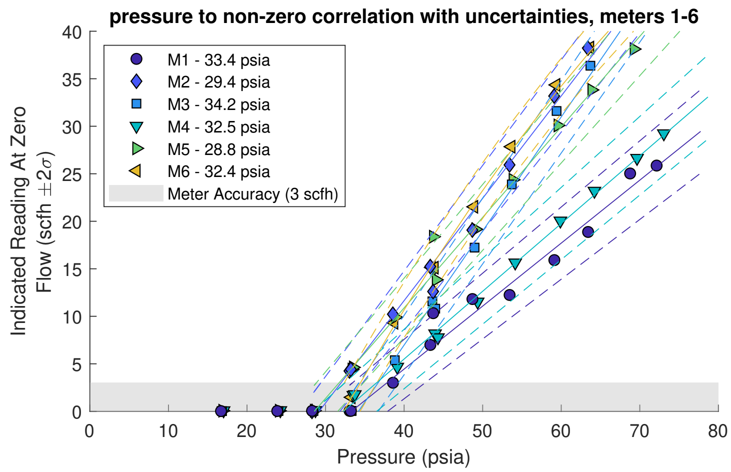

Figure 5.11: Correction curves and uncertainty bounds for all flow meters correlating NZ flow meter readings to operating pressure during measurement. The pressure at which NZ behavior starts is indicated in the legend for each meter.

than the calculated NZ cutoff threshold. Because the calculated NZ threshold is less than the actual observed baseline, zeroing flows below the threshold would have no effect on the emission rate, even though there is a clear NZ baseline.

Table 5.1: Correction curves fits for top uncertainty bounds used to assign NZ cutoff values

Linear Fits				
Meter	Slope	Intercept	NZ Threshold	
Meter 1	0.7	-20.27	33.43	
Meter 2	1.11	-29.64	29.4	
Meter 3	1.23	-39.25	34.24	
Meter 4	0.75	-21.24	32.46	
Meter 5	0.99	-25.43	28.83	
Parabolic Fit				
Meter	C1	C2	Intercept	NZ Threshold
Meter 6	-0.01	1.97	-52.54	32.38

Many recordings exhibited the characteristic shown in Figures 5.9 and 5.10 where there is a clear NZ baseline that was not fully captured by the NZ cutoff threshold. To account for the uncertainty in calculating an NZ cutoff threshold for a data set with a given supply gas pressure due to meter noise and NZ baseline drift, all flows below the NZ cutoff $+2\sigma$ were set to zero. This increase in the NZ cutoff threshold was applied to all datasets that were identified as potentially having an NZ reading based on their supply pressure.

5.4 Data Correction Summary

The specific process followed to apply corrections using correction curves shown in 5.11 was:

1. Correct gas flow for gas composition and apply noise filter.

2. Compute mean gas flow rate before NZ correction.

3. Compute the mean pressure for each recording. In all cases, supply gas pressure was stable and varied $< \pm 2$ psia during test duration.

4. Using the mean pressure, compute the flow rate at which the meter *may* be in NZ conditions, as per Figure 5.11.

5. Set all samples with indicated flow below the calculated NZ cutoff threshold $+2\sigma$ to zero (5.1).

6. Recompute mean gas flow rate and compare with flow rate computed before the NZ correction.

5.5 Validation of Data Correction Methods

A series of controlled tests were performed on the flow meters that simulated the supply pressures and gas flow rates encountered in the field. Data collected during these test were corrected using the methods outlined in Sections 5.1-5.3 and compared to the actual flow through the meters to validate the correction methodology presented in the above sections.

Experimental Set Up

Validation tests were performed at the CSU Methane and Testing Evaluation Center (METEC). A similar set up to that described in Section 5.3 was used. The six Sierra flow meters were connected in series between a pressure regulated supply of 87.0% CH_4 natural gas and a manifold of automated valves that were operated to simulate leaks (Figure 5.12a). An Omega FMA 1700A series flow meter ($\pm 1\%$ of span, or 1.59 scfh) monitored flow through the Sierra meters and provided timestamped flow rates for comparison (Figure 5.12a).

(a) Six Sierra flow meters connected in series at the CSU Methane Testing and Evaluation Center.

(b) Pressure regulators and Omega flowmeter used for Sierra meter verification

Figure 5.12: Experimental setup for validation tests to check accuracy of flow meters and data correction method.

Results

The setup described above was used to simulate a series of natural gas leaks at six supply pressures. These tests were performed on the range of pressure the meters were exposed to during field tests using a similar natural gas composition. The Sierra meters collected data on a three stepped flow rates pressures between 24 and 60 psia. The flow through the meters was returned to zero for at least 120 seconds between each test and each consecutive flow rate was maintained for at least 60 seconds to allow meter readings to stabilize (Figure 5.13).

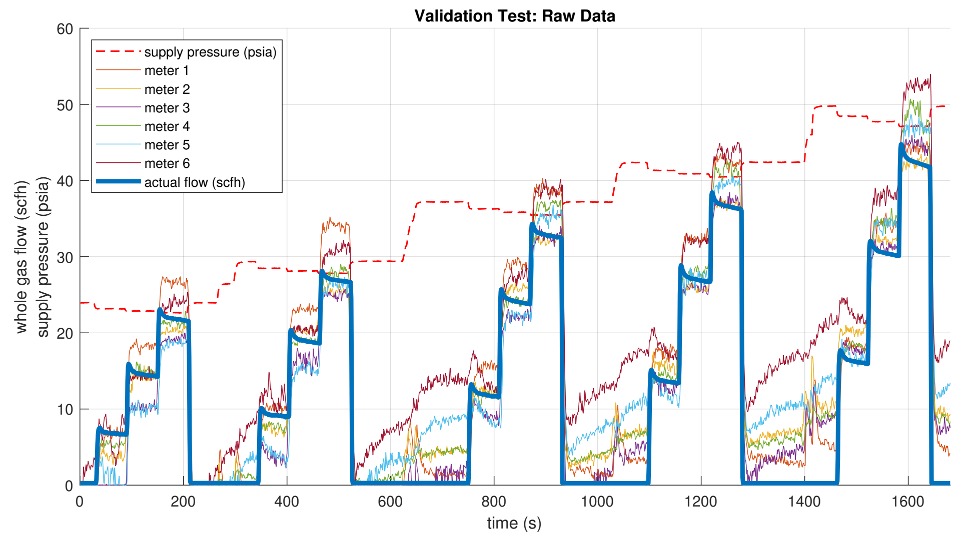

Figure 5.13: Comparison of Sierra meter recording to actual flow rates for measurements taken between 24-60 psia. Gas composition correction has been applied, filtering or NZ correction has not been applied. The tendency of flow meters to record non-zero flow rates under zero flow conditions under higher pressures is clear.

When pressure increases, the meters show a significant non-zero baseline when there is no flow through the meters and there is variability in the magnitude of this baseline between

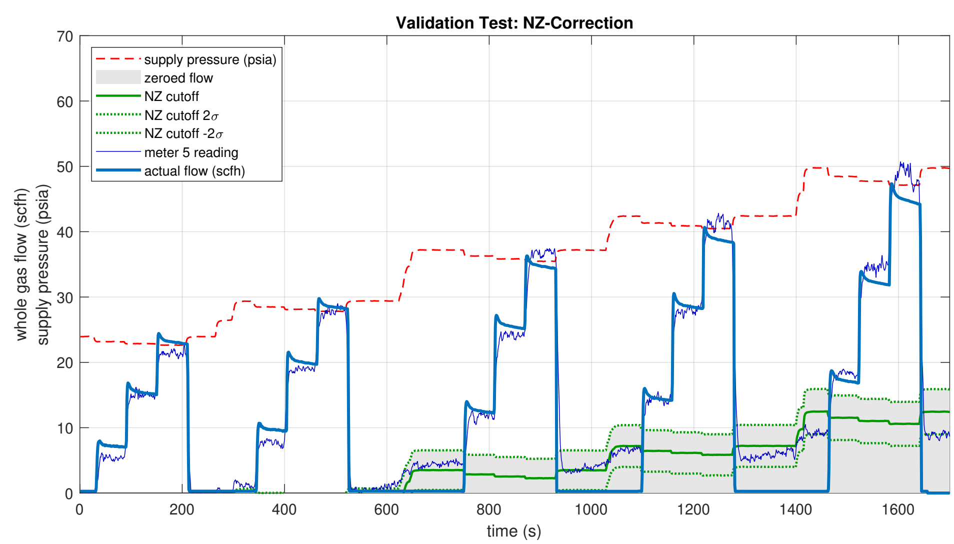

Figure 5.14: Comparison of Sierra meter number 5 recording to actual flow rates for measurements taken between 24-60 psia. Corrections for the NZ meter error, gas composition and signal filtering have been applied. After data correction methods are used, the recordings by Sierra flow meters used in the field agree reasonably well with the comparison flow meter, with an RMS deviation of 1.34 scfh.

the six meters. Data in Figure 5.13 is corrected for gas composition but noise filter and NZ corrections have not been applied. Without the NZ correction over this range of pressures, the Sierra flow meters over-estimate the actual flow by between 1% (meter 3) and 58% (meter 6). On average, the meters over-estimate the actual flow by 22%.

The NZ flow correction methodology was then applied using the correction curves shown in Figure 5.11. Figure 5.14 shows the calculated NZ baseline for meter number 4 during this test. The shaded area represents the NZ baseline as a function of pressure. To apply the NZ correction to the meter's flow readings, all flow values that lie within this shaded region are set to zero. For meter 4, this correction reduces the overestimation of actual flow rates from 13% to 3%. Applying this correction reduces the average disagreement between the Sierra meters and the actual flow rate from 22% to 2%.

The most significant implication of this meter error is the effective increase of the meter's detection limit that occurs at higher measurement pressures. At pressures where a meter can show a false NZ reading, any actual flows below the NZ baseline calculated using the correlations in Table 5.1 are indistinguishable from meter noise.

Chapter 6

RESULTS & DISCUSSION

6.1 Measured Data and Relevant Meta-data

Long duration measurements were made on 98 PCs at 17 natural gas gathering compressor stations and one production site between June 2017 and May 2018. Each station visited was assigned a randomly generated letter. Each PC measured on that site was given a number 1-6 corresponding to the number of the flow meter that was connected to that device. All measured devices were then identified using this naming scheme. The flow meter recordings made on site 'D' using meter #1 (PC D-1) are shown in Figure 6.1

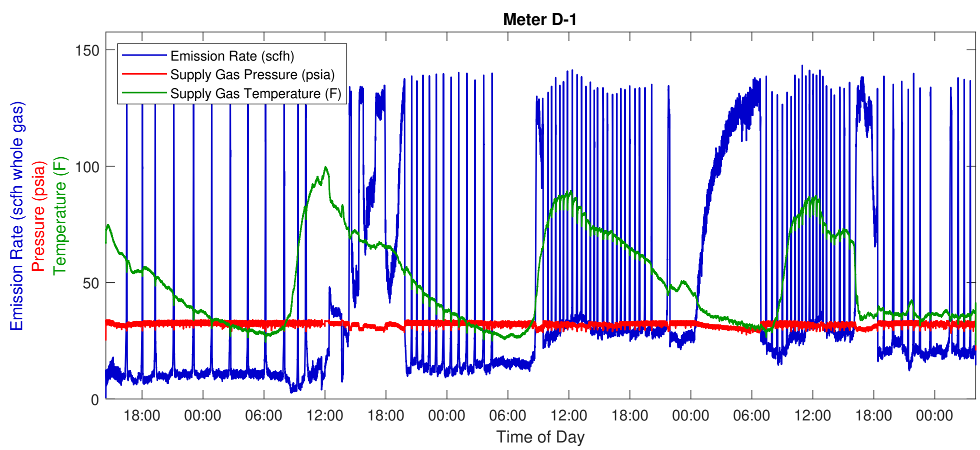

Figure 6.1: Example of flow meter recordings of PC emissions, supply gas temperature and supply gas pressure for Site D, meter 1, recorded over an 85 hour period.

Table 6.1: Summary of meta-data relevant to device operation collected for PC D-1

PC Specific Data	Valve Operation[1]	EPA Type[2]	Major Equipment[3]	Process Variable	PC Make Model
PC D-1	Snap Acting	IV	Compressor	Liquid Level	Murphy L1200N

[1] 'Snap acting' or 'throttling' designation provided by station operator.
[2] Intermittent vent, low bleed or high bleed designation originally provided by station operator. Inconsistencies in EPA type identification were clarified and resolved by independent panel (Section 6.2)
[3] Major equipment category where PC is operating. Compressor, dehydrator, separator, yard piping or acid gas removal unit.

Comprehensive metadata was also collected specific to each station visited and PC measured on that station. Meta-data for device D-1 is shown in Table 6.1. A compilation of all data sets collected are included in Appendix A of this document.

6.1.1 Impact of NZ Meter Error

The complete data correction methodology summarized in Section 5.4 was applied to 86 emissions recordings collected during the field campaign. Based on the distribution of supply gas pressures measured in the field (Figure 6.2), it was anticipated a large number of measurements would be impacted by the NZ meter error. The data corrections applied to correct for the NZ meter error had a non-trivial impact on the population of collected data. Data sets were classified as *zero impact*, *low impact*, *high impact* or *discarded* based on the percentage of emissions recorded that were attributed to the NZ meter error. The distribution of impacts on average emission rates after the application of the NZ corrections is shown in Figure 6.3.

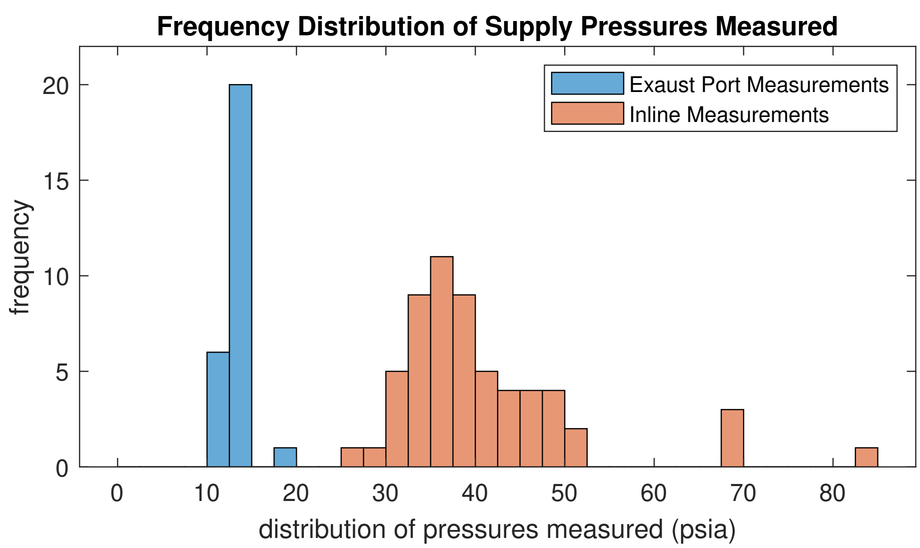

Figure 6.2: Distribution of supply gas pressures measured during the field campaign.

Zero Impact: Recordings that were installed on PC exhaust ports or had low enough supply gas pressures that their average emission rates were impacted by $< 1\%$ by the NZ correction (42 measurements or approximately $\frac{1}{2}$ of the measurements).

Low Impact: Recordings where the average emission rate changed by less than 20% after the NZ correction was applied (7 measurements).

High Impact: Recordings where the average emission rate changed by more than 20% after the NZ correction was applied. Recordings in this category include cases where nearly all data points were zeroed and/or a very small percentage of samples remain after the correction, but there were clearly emission or actuation events that were *not* impacted by the NZ error (see recording G-5 as an example). (23 measurements)

Discarded: Recordings where the average emission rate was effectively zeroed after applying the NZ correction ($>$ 80% change in emissions) *and* there were *not* distinct actuations or emission events above the NZ baseline (14 measurements). Recordings meeting these criteria were discarded from the data set before analysis because there were no emissions recordings distinguishable from meter noise. The implications of discarding these samples is discussed in Section 6.5.1

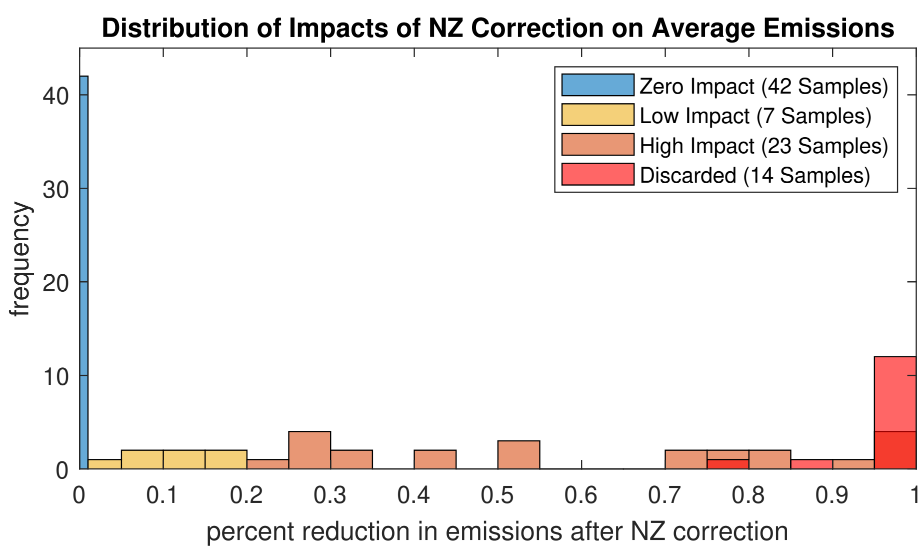

Figure 6.3: Distribution of NZ meter error corrections impacts on average emission rates from all PCs measured

6.2 Industry Panel and Controller Classification

While in the field, it was often challenging for the measurement team to identify specific attributes of controllers. To identify controllers by EPA classification (high, low or intermittent vent), the measurement team relied on site operator input, which was often inconsistent with other observations on site. This resulted in conflicting classifications of controllers by the end of the study. Due to the wide variety of emission patterns observed, there was also interest in using the emission data and controller meta data to estimate whether controllers were operating as designed. To accomplish this, a panel of four industry experts and three study team members were assembled to review data for each controller recording. Based on the controller data the review panel classified each controller according to EPA subpart W venting categories (high, low or intermittent vent), determined if the controller was operating as designed or was malfunctioning, identified possible common failure modes across the sample of malfunctioning controllers, and provide perspectives on possible causes of the irregular emissions patterns observed. Controllers were assigned as malfunctioning strictly based on the emissions behavior of the device. By this definition, a device identified as malfunctioning from an emissions perspective could still be performing its intended function and operating correctly from a process control perspective. The flowchart in Figure 6.4 illustrates the panel's selection process for classifying controllers (Section 6.2.2) and bucketing controllers by EPA classification type (Section 6.2.1).

6.2.1 Classification by EPA Type

The panel's criteria for classifying each controller by EPA type was based on specifications given in manufacturer's literature. The highest level of classification (intermittent vs. continuous vent) is straightforward to assign based on device specifications. The secondary classification for continuous controllers (high vs low bleed) is not as straightforward, as continuous bleed rates can be a function of supply gas pressure to the controller. For devices where emissions were measured in supply gas lines, supply pressure was recored over the

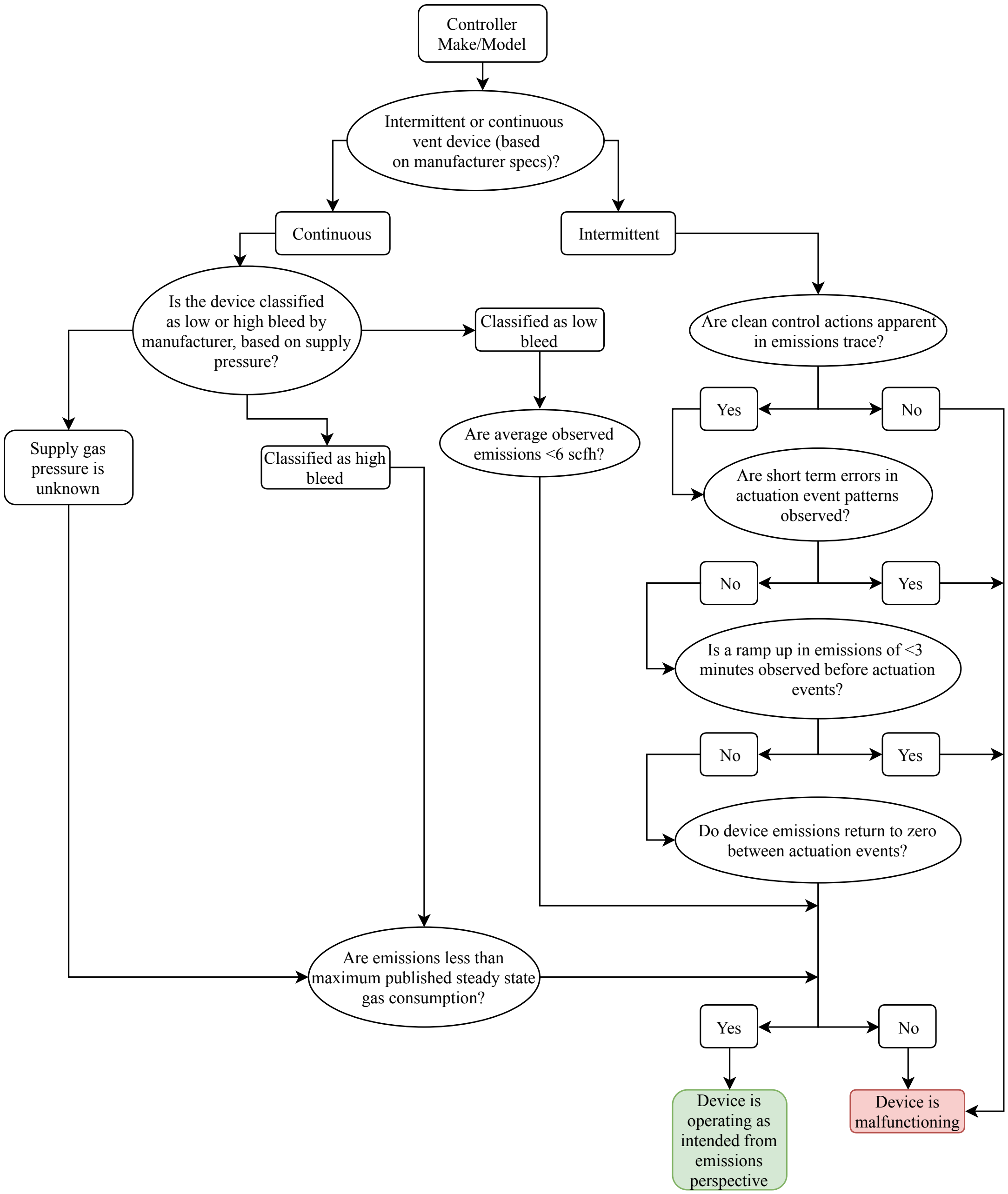

Figure 6.4: Flowchart summarizing the industry panel's criteria for classifying PCs according to their vent behavior and identifying PCs as normally operating or malfunctioning from an emissions perspective

test run and bleed rate classifications were based on steady state gas consumption rates for recorded supply pressure. If emissions were measured at controller exhaust ports, supply pressures were unknown and low vs high bleed classifications were assigned by consulting additional manufacturer literature or based on field experience of panel members. There are also several common models of electro-pneumatic controllers whose classification as low vs high bleed is dependent on the internal relay installed in the device; because the relay types were not noted during field work, classifications were assigned for these devices by consulting station operators.

6.2.2 Classification as Normally Operating or Malfunctioning

Continuous Bleed Controllers: Devices classified as low bleed were identified as normally operating if their average emission rates were $\leq$6 scfh. Devices classified as high bleed were identified as normally operating if their average emission rates were consistent with their published steady state gas consumption values.

Intermittent Vent Controllers: Four criteria were assigned to classify intermittent vent controllers as normally operating or malfunctioning. If the emissions trace for an intermittent vent device was observed to violate any of these criteria, the controller was identified as malfunctioning. PC classification was performed by evaluating emission traces that were filtered for noise, corrected for gas composition, and had NZ correction algorithm applied. These criteria are:

1. **Continuous Emissions**: Emissions recording of an intermittent vent PC that does not show control actuations and emits gas continuously (Figure 6.5).

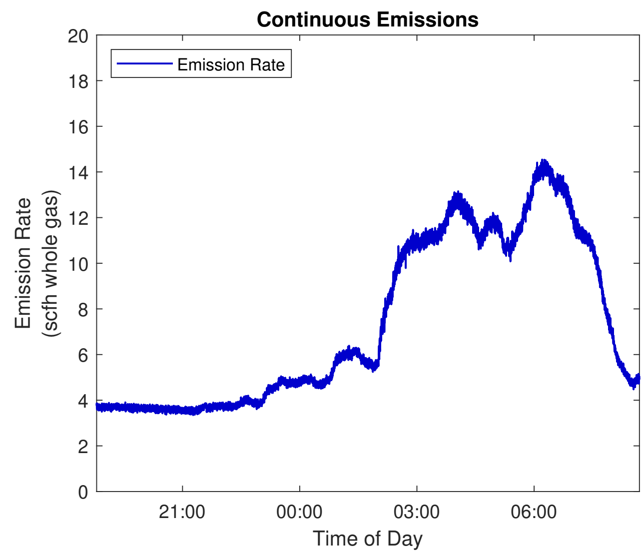

Figure 6.5: Intermittent vent PC that does not show distinct actuations and vents gas continuously.

2. **Extended Ramp**: PC shows an emission ramp longer than three minutes in duration leading up to an actuation event (Figure 6.6).

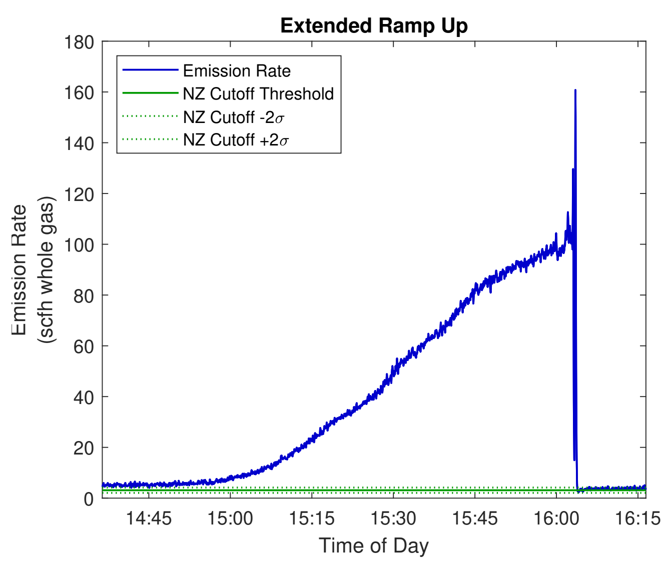

Figure 6.6: PC emissions gradually increase for 45 minutes leading to actuation event. This behavior is inconsistent with the design of the device and controllers exhibiting this behavior were identified as malfunctioning.

3. **Does Not Return to Zero**: PC shows control actuations but emission rates do not return to zero between actuation events (Figure 6.7)

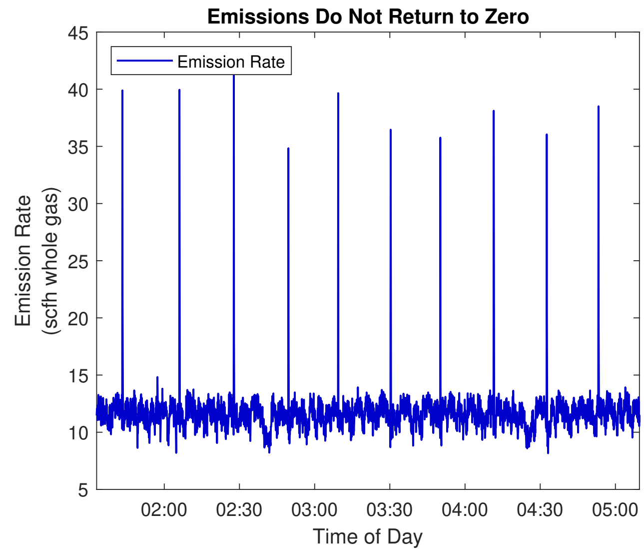

Figure 6.7: PC emissions do not return to zero between actuation events. Since NZ corrections have already been applied, this malfunction is visible *only* if emissions between actuations exceed the NZ threshold.

4. **Irregular Behavior**: Intermittent vent PC shows some combination of the the previous three behaviors or generally irregular emissions patterns (Figure 6.8).

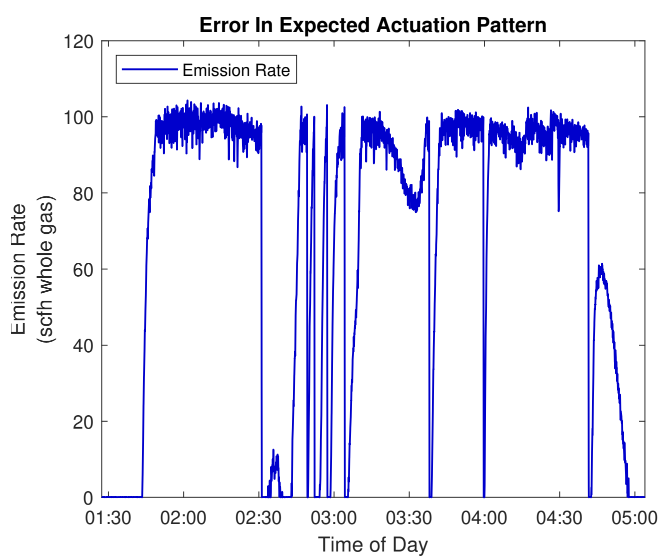

Figure 6.8: PC demonstrating irregular emissions behavior over the majority of the data collection period. The device was identified as malfunctioning.

Table 6.2 shows which of the above criteria were exhibited by each intermittent vent PC that was identified as malfunctioning.

Table 6.2: Classification of malfunctions for intermittent PCs

Recording ID	Continuous Emissions	Extended Ramp	Does Not Return to Zero Between Actuations	Irregular Behavior	Total Malfunction Classifications
A-3			✓		1
A-4	✓				1
D-1	✓	✓	✓	✓	4
D-4	✓		✓	✓	3
D-6			✓	✓	2
G-5	✓			✓	2
H-1		✓			1
H-6			✓	✓	2
I-5	✓			✓	2
N-1	✓				1
N-2	✓			✓	2
N-3				✓	1
N-4	✓				1
O-6		✓		✓	2
P-1				✓	1
P-5		✓			1
S-2	✓			✓	2
S-4	✓			✓	2
T-4		✓			1
T-5		✓			1
T-6		✓		✓	2
U-5		✓			1
U-6		✓			1
V-2	✓			✓	2
V-6	✓	✓	✓		3
Fraction Impacted	48%	40%	24%	58%	

6.3 Malfunctioning PC Emissions

The long duration measurements allowed for a more accurate analysis of the impact that malfunctioning PCs have on average emission rates. Using the criteria established in Section 6.2, 30 PCs (42% of the sampled population) were classified as malfunctioning. Table 6.3 shows the average emission rates for normally operating and malfunctioning PCs for each EPA classification type.

Table 6.3: Average emission rates for normally operating and malfunctioning PCs.

PC Type	Number of Samples	Number of Malfunctioning	Average Emissions (scfh, normally operating PCs)	Average Emissions (scfh, malfunct. PCs)
IV	40	25	2.82 [+3.23/-2.41]	16.11 [+7.88/-6.35]
LB	24	5	0.68 [+0.50/-0.42]	34 [+20.81/-19.78]
HB	8	0	19.25 [+13.55/-10.26]	-[3]
Totals	72	30	4.98 [+3.49/-2.95]	19.09 [+7.61/-6.80]

[1] No high bleed PCs were assigned as malfunctioning

The cumulative distribution function in Figure 6.9 illustrates the impact that malfunctioning controllers have on the average emission rates in this study. 25 PCs (35% of samples) had emissions greater than the mean. Of these PCs, five were high bleed PCs, 18 were malfunctioning PCs (14 intermittent and 4 low bleed), and only one was a normally operating intermittent vent controller with a very high actuation rate. Several previous studies [11] [20]

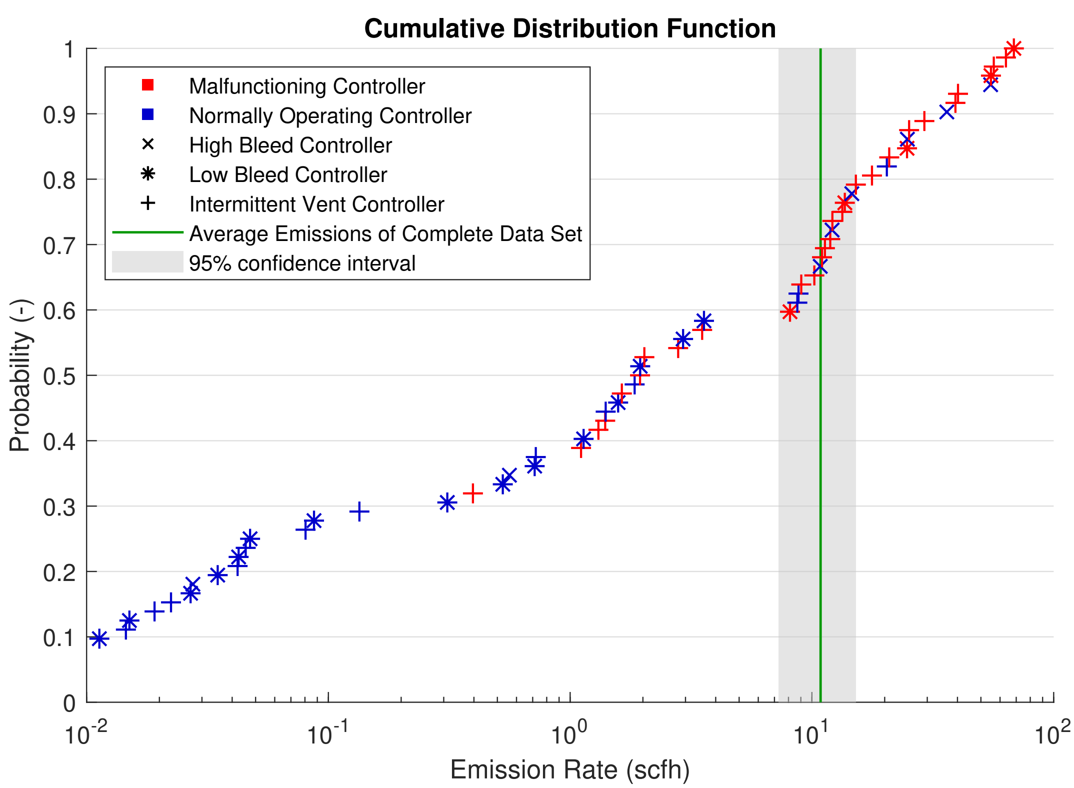

Figure 6.9: Cumulative distribution function showing contribution of malfunctioning and normally operating PCs of each EPA type toward total measured emissions.

reported a ”long-tailed” distribution where the majority of total emissions are attributed to a small subset of devices. This distribution was observed in this study but was not as pronounced as in other studies. 95% of the emissions can be attributed to the top 42% of devices. In comparison, Allen et. al reported the top 19% of devices accounted for 95% of total emissions. This difference is likely due to the long measurement duration, as many of the devices measured during previous studies did not have emissions during the observation period. This is discussed further in Section 6.4.

6.3.1 Low Bleed PCs

Figures 6.10 shows the distribution of emission rates for normally operating and malfunctioning low bleed PCs. All of the low bleed PCs classified as malfunctioning had emissions continually exceeding the 6 scfh threshold for the entire duration of their measurement. This

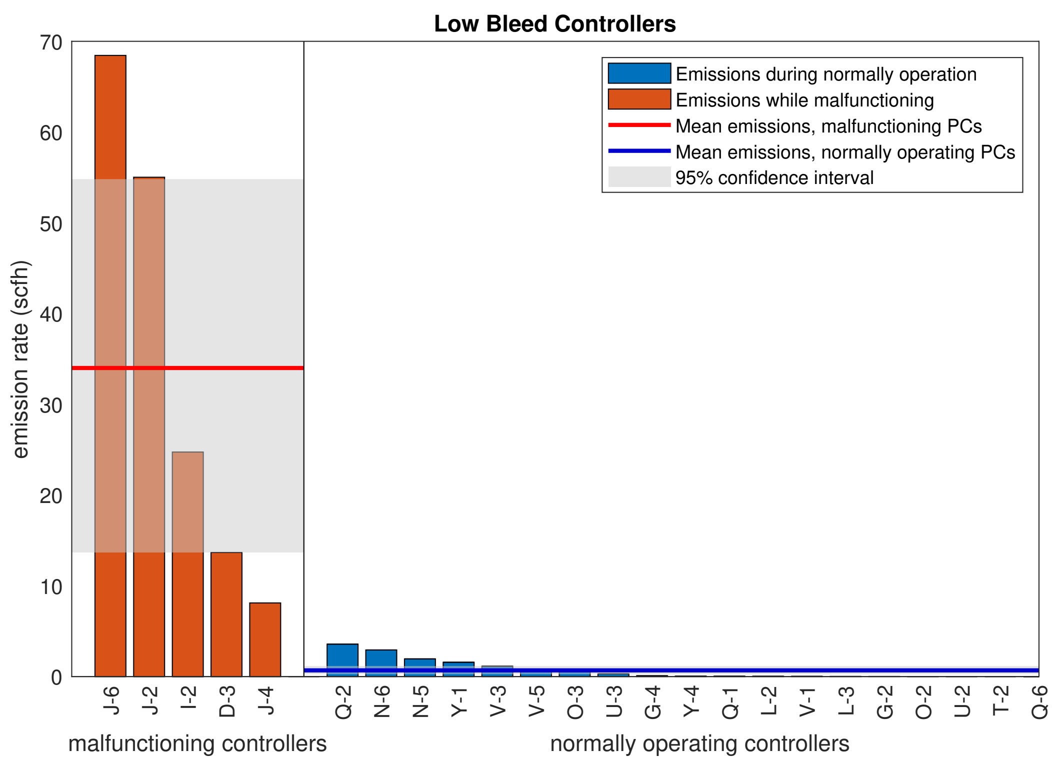

Figure 6.10: Emission contribution from malfunctioning and normally operating low bleed type controllers.

is distinct from the behaviors of intermittent vent PCs where 64% of the malfunctioning population had periods of time during their operation where they were operating correctly 6.3.2.

High supply gas pressure to low bleed controllers may explain the high emissions shown by the five malfunctioning low bleed PCs. Because the internal mechanism of continuous low bleed controllers offers an open path to atmosphere, higher supply pressures result in higher continuous emission rates. Four of these malfunctioning low bleed PCs (J-6, J-2, D-3 and J-4) had supply pressures of between 43 and 46 psia, which make up four of the five highest supply gas pressures recorded on low bleed controllers. The controllers in question (the Fisher C1 and Dyna-flo 4000LBR) can be configured to output two control pressure ranges: 17-29 psia (low pressure output) and 20-44 psia (high pressure output). The manufacturer stated normally operating supply pressures for these two configurations is 34 and 49 psia for the low and high pressure outputs respectively [34] [35]. The output pressure configuration for these PCs is unknown, but *if* they were configured for low pressure output, their high emissions rates could be attributed to the fact they are operating at pressures outside of their design specifications.

6.3.2 Intermittent Vent PCs

50% of the intermittent vent PCs classified as malfunctioning had periods during their observation time when they were operating correctly. For each of these PCs, the emissions during normal operation and emissions due to malfunctioning behavior were isolated. Normally operating emission states were determined by identifying peaks in emission traces and zeroing all emissions in the recording *except* for three minutes leading up to and the five seconds following each peak. This was based on the expert panel's metrics of actuation times for normally operating devices (Section 6.2). The emissions for each of these states are plotted in Figure 6.12.

The average emission rate for the 25 malfunctioning controllers is 16.11 [+7.88/-6.35] scfh. If the emissions during malfunctioning states are removed, the average emissions for

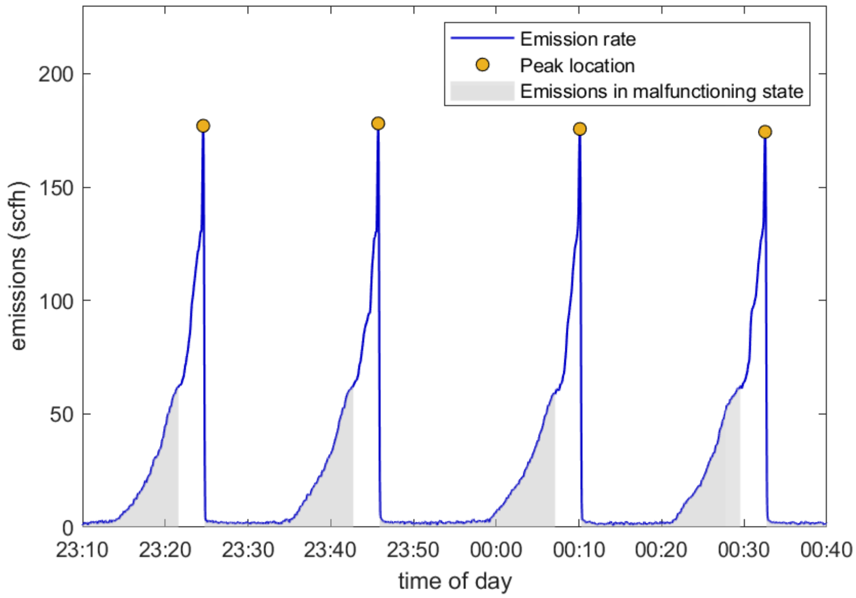

Figure 6.11: Device H-1 was identified as malfunctioning because of its extended ramp in emissions leading to actuation events. Emissions from device's malfunction states were assigned as all emissions *except* those during three minutes preceding and 5 seconds after peaks.

these controllers is 2.15 [+1.89/-1.38] scfh. This is of similar magnitude to the average emissions from the 15 normally operating intermittent vent PCs (2.82 [+3.23/-2.41] scfh). However, the mean actuation rate for malfunctioning controllers (0.83 actuation events per hour) is over twice that of normally operating PCs (0.36 actuation events per hour). These frequencies are in the range of estimates made by Allen et al. for devices that did not actuate during 15 minute sampling times [20], and are less frequent than assumed actuation rates used in the OIPA study [21]. These frequencies are also on the scale (>1 hr between events) of frequencies recorded by long duration actuation counters installed on actuators during the EPA's Uinta Basin study [31].

The actuation rate of a given intermittent vent PC is mainly determined by how the controller is tuned and calibrated, the appropriate selection of controller make/model for its application, the latency and accuracy of its input signal and the stability of the process variable it is controlling. Several of these factors (calibration and tuning, appropriate application and signal quality) can be adversely impacted by poor operating procedures, such

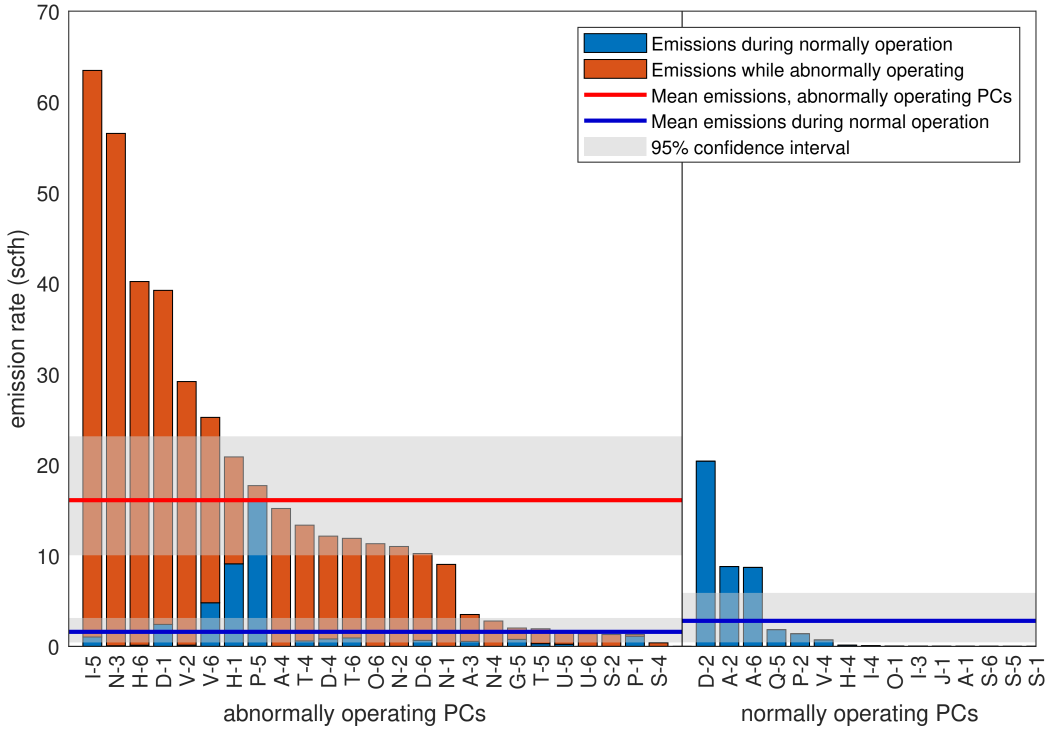

Figure 6.12: Emission contributions from malfunctioning and normally operating intermittent vent type controllers.

as re-purposing PCs for applications outside their intended use or long gaps in controller recalibrating and tuning. The higher actuation rate of malfunctioning PCs suggests that some of the malfunctioning behavior observed in this study is due to operational practices, and is not solely attributed to mechanical failures.

6.4 Simulating Shorter Sampling Times

All previous studies with the objective of measuring emissions from PCs (Section 2.3.1) have relied on sampling times of between 15 minutes to 1 hour. Several of these studies acknowledged that due to the expected high temporal variability in the operation and emission rates of PCs, it is unlikely that such short duration measurements can be used to accurately characterize average emission rates. A simulated short duration sampling strategy was generated to compare the results of the long duration measurements collected in this study to the results that would have been collected using the methods of previous studies. For each data set, 1000 random, 15 minute samples between 8 am and 5 pm were drawn with replacement and the average emissions were calculated for each sample. By plotting the distribution of these sampled emission averages, it was possible to calculate the probability that a 15 minute sample will yield an accurate characterization of a PC's average emission rate.

Simulated emissions are shown in Figure 6.13 for examples of intermittent vent and high bleed PCs. For intermittent PCs that are operating correctly or malfunctioning, emissions and actuation frequency can vary widely over time. If a measurement is made during any randomly-selected 15-minute period, there is a low probability that the number of actuations occurring during that sample will be representative of the actuation rate over an extended period. For device P-5, a 15 minute emission measurement had a 30% chance of not capturing an actuation event and measuring zero emissions, even though the average emission rate over a 68 hour period was 18 scfh.

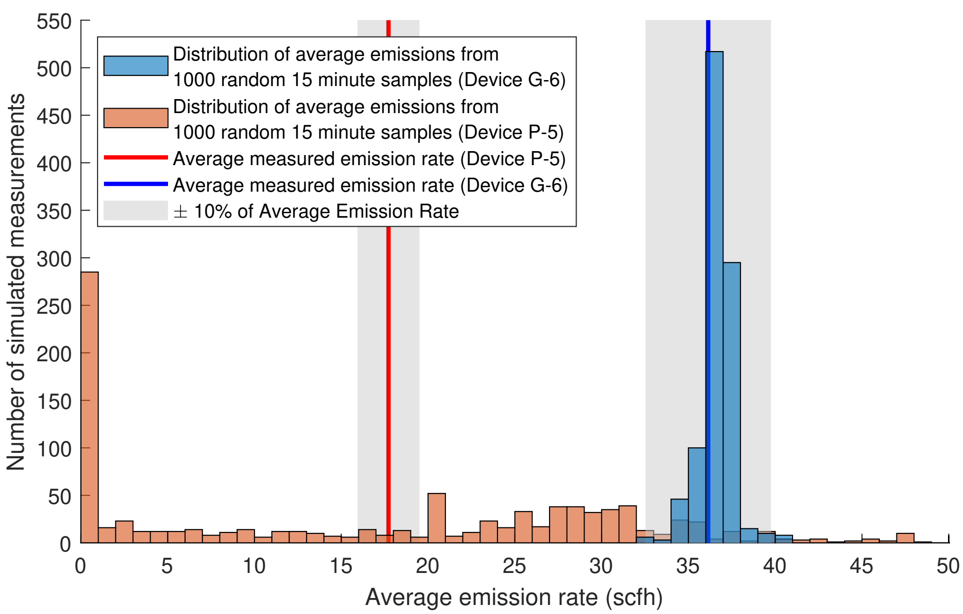

Figure 6.13: Distribution of 1000, 15 minute averages for device P-5. Due to the high variations in emission rates, here is a low probability that a 15 minute measurement will provide an accurate characterization of the PC's long term average emissions.

For both normally operating and malfunctioning continuous vent PCs (both high and low bleed), emissions rates are more consistent over time than those from intermittent vent devices. Therefore, the accuracy of a 15-minute duration measurements are more likely to be representative of long term averages. 100% of malfunctioning low bleed devices could have been identified as malfunctioning during their first 15 minutes of observation. Figure 6.13 shows the distribution of 1000 randomly selected 15 minute averages for a high bleed device. Nearly all of these simulated measurements are within ±10% of the average emissions over its 50 hour measurement duration.

Measurement duration also impacts the probability that malfunctioning behavior will be captured during observation. 48% of malfunctioning controllers could have been identified as malfunctioning during their first 15 minutes of observation,

Analysis was also performed to determine a minimum length of time required to accurately characterize average emissions for each device. Across all devices, the average emissions during the first 24 hours of measurement were 94.5% of the average emission rate for the entire duration of all measurements (Figure 6.15). This indicates that a measurement of

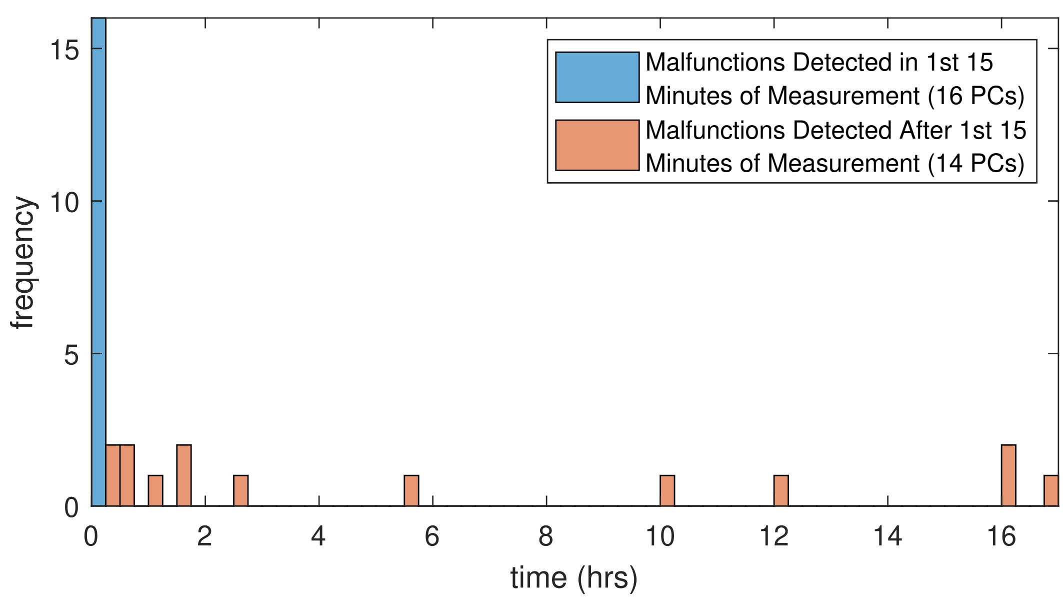

Figure 6.14: Minimum times to ID malfunctions

24 hours is adequate to make accurate estimations of device emissions. As the measurement time is reduced from 24 hours, the probability of capturing an accurate characterization of average emissions decreases.

The Monte Carlo methods used to generate Figure 6.13 were applied to each measured device. The distributions of probabilities that a 15 minute, three hour, six hour, 12 hour or 24 hour sample would give a measurement within ±10% of the device's long term average are plotted in Figure 6.16.

The results of this simulation provide insight into the results that would be expected from short duration observations. The group of devices that have a high probability ($> 75\%$) of a short duration sample giving an accurate characterization (±10%) of the device's long term emissions are: normally operating low bleed PCs with very low emission rates, intermittent vent PCs with infrequent actuations and low emission rates, and high bleed PCs with medium to high emission rates. The two outliers in this group are a malfunctioning intermittent vent PC with very low emissions and two malfunctioning low bleed PCs with high emissions. 50%

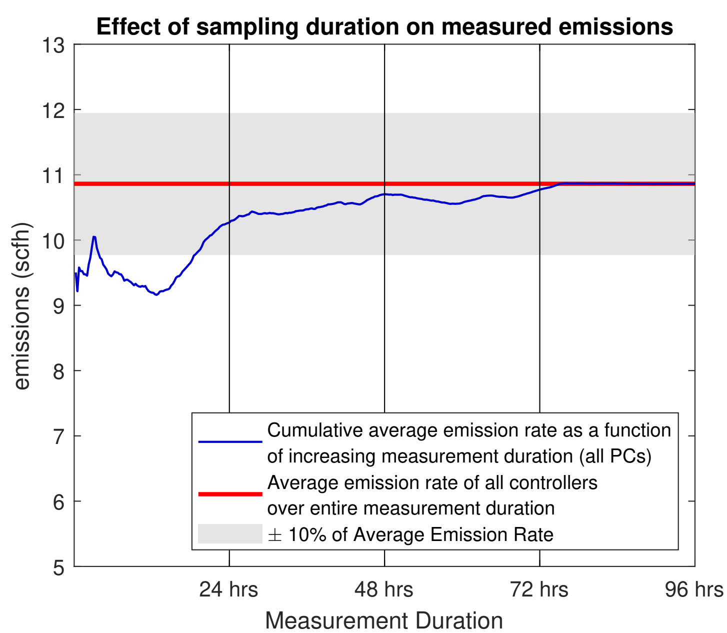

Figure 6.15: Cumulative average emissions of all PCs measured over a four day period, converging to the long-term average of 10.86 scfh. This indicates the tendency for underestimation of averages for shorter duration measurements.

of the measured PCs have a low probability (< 20%) of a 15 minute sample giving an accurate characterization (±10%) of the device's long term emissions. This population is responsible for the majority (60%) of all measured emissions. All but two of the 25 malfunctioning intermittent vent controllers evaluated during this study are part of this population.

Current emission factors for PCs and previous PC emission studies all have relied on short duration measurements. Natural gas company's leak detection and measurement (LDAM) or lead detection and repair (LDAR) programs which are responsible for identifying leaking or malfunctioning equipment largely involve scanning equipment with optical gas imaging cameras. Using this practice, individual PCs are often evaluated for less than 10 seconds. Obviously, deploying long term or continuous emission measurements systems to monitor emissions from large populations of PCs is cost and resource prohibitive for natural gas companies. However, the data presented here clearly shows the serious limitations of current methods in identifying the malfunctioning PCs that are responsible for the bulk of emissions from this class of equipment.

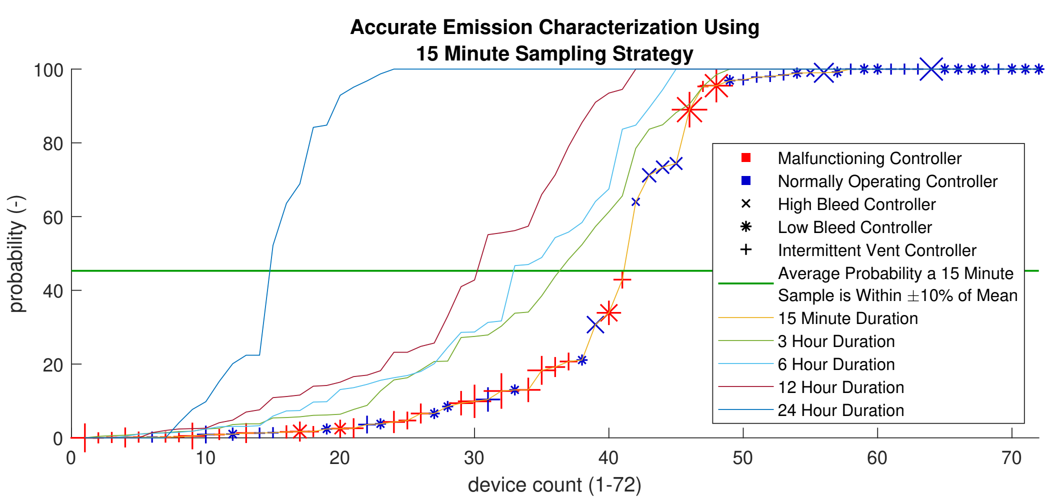

Figure 6.16: Probability that PC emission measurements of increasing duration have of measuring within ±10% of long term average. The size of the markers for the 15 minute duration curve correspond to the emission rate from that device (larger markers=higher relative emissions)

6.5 Comparisons of Average Emissions

6.5.1 Study Bias

The data presented in this thesis suffers from two potential biases: First, 14 measurements (16% of samples) were discarded due to the non-zero flow meter errors that effected measurements taken at higher supply pressures (Section 5.3). These samples were discarded because $>$ 80% of the recording was attributed to meter error, and there were no emissions during the recording that could be distinguished from meter noise. The non-zero baseline of these meter recordings were between 4 and 25 scfh. For each of these recordings, emissions *could* have been present at any flow rate between zero and the recording's non-zero baseline. Therefore, this set of discarded data represents a loss of information that could have a non-trivial affect on the calculation of emission factors.

The average emission rates for all measured PCs (included discarded sets) are plotted in figure 6.17, with emissions from discard sets simulated between 0-100% of their NZ baselines. If it assumed that emissions from all discarded sets are actually zeros, the average emissions for the 86 controllers is 9.09 [+4.31/-3.60] scfh. If it assumed that all discarded sets are

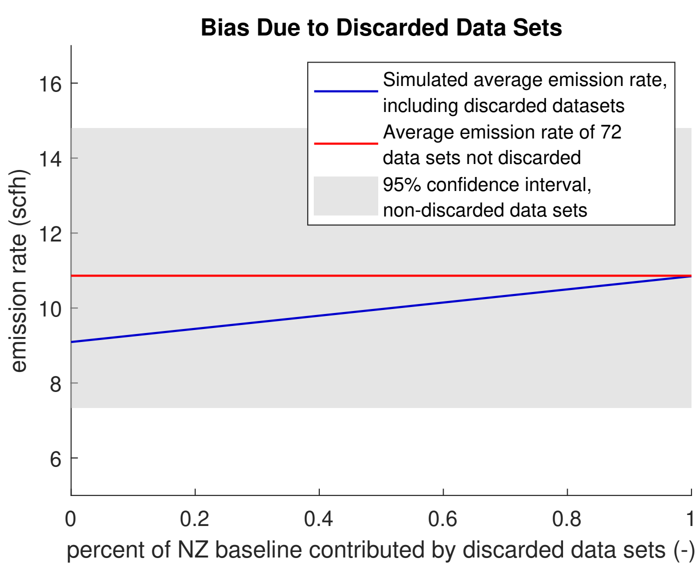

Figure 6.17: Potential bias introduced in average calculated emission rates due to discarding the 14 data sets heavily impacted by non-zero flow meter error.

equal to their NZ baselines, the average emissions for the 86 controllers is 10.85 [+4.31/-3.60] scfh, which is almost exactly the mean emissions from non-discarded samples. Because it is highly improbable that *all* discarded samples were emitting at rates slightly less than their NZ baselines, the average emission rates presented in this study are likely biased high. Due to his potential bias and the level of data manipulation needed to correct for flow meter errors, the average emission rates presented in this study are not suitable for developing new emission factors for PCs.

However, the aggregate, average emission rates across all devices measured in this study are similar to the emission factors utilized in the EPA's Greenhouse Gas Inventory (GHGI) [2]. If GHGI estimates are weighted by gathering station controller counts in each category, the average emission rate per controllfer is 11.84 scfh. The average emission rate per controller in this study (10.86 [+4.31/-3.60] scfh), is 91.2% the GHGI estimate. The GHGI estimates average emission rates from gathering station pneumatic devices as 1.39, 37.3, and 13.5 scfh for low bleed, high bleed and intermittent vent controllers respectively. These values are 548%, 51.6% and 82.4% of the average low-bleed, high-bleed and intermittent vent emissions measured in this study. While aggregate emissions from all PCs measured and emissions from intermittent vent controllers agree with GHGI estimates, measurements of low-bleed PCs were much higher and measurements of high-bleed PCs were much lower than GHGI estimates.

6.6 Recommendations for Future Studies

- The most significant shortcoming in this study was the non-zero flow meter error that necessitated significant corrections to data sets and rendered some data unfit for analysis. A higher precision, non-intrinsically safe flow meter could be contained in an explosion proof housing with logger and power supply, with gas tight through fittings threaded into the housing. This would eliminate the need to use an industrial, Class I Div I certified instrument to measure emissions and would give researchers greater flexibility in flow meter choice. Meters could also be calibrated on a tighter flow range than the meters in this study. 99% of the emissions measured in this study were between 0-200 scfh. If meters were calibrated on this range, high emission peaks from intermittent vent controllers would occasionally be clipped, but lower flow rates between 0-50 scfh (the majority of emissions) could be measured with higher accuracy.

- This study presents PC emissions data specific to gathering compressor stations. There is overlap between the makes, models and applications of PCs on gathering compressor stations and those found in other sectors of the oil and gas industry but there is also equipment that is specific to each sector. The behavior of the PCs at the single gas production site where measurements were made was distinct from behavior observed from PCs on gathering stations. Future studies would need incorporate long duration measurements from PCs across sectors to confirm that the results presented here apply to equipment on stations other than gathering compressor stations.

- Measurements of longer than 24 hours provide diminishing returns in terms of accurate characterization of emissions and identification of malfunctioning PCs. If possible, future studies should focus on shorter duration measurements than those in the data presented here in favor of a larger sample size.

- This study did not attempt to identify common mechanical failure modes of PCs. Future studies could include a tear-down analysis component to determine the root causes of high emissions from malfunctioning PCs. This would aid in identifying preventative maintence and repair practices or design changes that could be implemented to best reduce PC emissions.

Bibliography

[1] T. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. Allen, J. Boschung, Y. X. A. Nauels, V. Bex, and P. Midgley, *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2013.

[2] U.S. Environmental Protection Agency. Greenhouse gas customized search, petroleum and natural gas systems. Reporting Year 2016, Accessed: April 28, 2018. [Online]. Available: https://goo.gl/D1Md4L

[3] U.S. Energy Information Administration. (2017) Natural Gas: U.S. Dry Natural Gas Production. Accessed: April 20, 2018. [Online]. Available: https://goo.gl/LZjk22

[4] ——. (2016) Natural gas expected to surpass coal in mix of fuel used for U.S. power generation in 2016. Accessed: Sept 9, 2018. [Online]. Available: https://goo.gl/T7aHoS

[5] ——. (2017) Carbon Dioxide Emissions Coefficients. Accessed: Sept 9, 2018. [Online]. Available: https://goo.gl/LZjk22

[6] R. A. Alvarez, S. W. Pacala, J. J. Winebrake, W. L. Chameides, and S. P. Hamburg, "Greater focus needed on methane leakage from natural gas infrastructure," *Proceedings of the National Academy of Sciences*, vol. 109, no. 17, pp. 6435–6440, 2012. [Online]. Available: http://www.pnas.org/content/109/17/6435

[7] A. J. Marchese, T. L. Vaughn, D. J. Zimmerle, D. M. Martinez, L. L. Williams, A. L. Robinson, A. L. Mitchell, R. Subramanian, D. S. Tkacik, J. R. Roscioli, and S. C. Herndon, "Methane emissions from united states natural gas gathering and processing," *Environmental Science & Technology*, vol. 49, no. 17, pp. 10 718–10 727, 2015, pMID: 26281719.

[8] S. Schweitzke, W. M. Griffin, H. S. Sullivan, Matthews, and L. M. Bruhwiler, "Natural gas fugitive emissions rates constrained by global atmospheric methane and ethane," *Environmental Science & Technology*, vol. 48, no. 14, p. 77147722, 2014.

[9] R. A. Alvarez, D. Zavala-Araiza, D. R. Lyon, D. T. Allen, Z. R. Barkley, A. R. Brandt, K. J. Davis, S. C. Herndon, D. J. Jacob, A. Karion, E. A. Kort, B. K. Lamb, T. Lauvaux, J. D. Maasakkers, A. J. Marchese, M. Omara, S. W. Pacala, J. Peischl, A. L. Robinson, P. B. Shepson, C. Sweeney, A. Townsend-Small, S. C. Wofsy, and S. P. Hamburg, "Assessment of methane emissions from the u.s. oil and gas supply chain," *Science*, vol. 361, no. 6398, pp. 186–188, 2018. [Online]. Available: http://science.sciencemag.org/content/361/6398/186

[10] T. L. Vaughn, C. S. Bell, C. K. Pickering, S. Schwietzke, G. A. Heath, G. Pétron, D. J. Zimmerle, R. C. Schnell, and D. Nummedal, "Temporal variability largely explains top-down/bottom-up difference in methane emission estimates from a natural gas production region," *Proceedings of the National Academy of Sciences*, vol. 115, no. 46, pp. 11 712–11 717, 2018. [Online]. Available: https://www.pnas.org/content/115/46/11712

[11] D. T. Allen, V. M. Torres, J. Thomas, D. W. Sullivan, M. Harrison, A. Hendler, S. C. Herndon, C. E. Kolb, M. P. Fraser, A. D. Hill, B. K. Lamb, J. Miskimins, R. F. Sawyer, and J. H. Seinfeld, "Measurements of methane emissions at natural gas production sites in the united states," *Proceedings of the National Academy of Sciences*, vol. 110, no. 44, pp. 17 768–17 773, 2013. [Online]. Available: http://www.pnas.org/content/110/44/17768

[12] D. J. Zimmerle, L. L. Williams, T. L. Vaughn, C. Quinn, R. Subramanian, G. P. Duggan, B. Willson, J. D. Opsomer, A. J. Marchese, D. M. Martinez, and A. L. Robinson, "Methane emissions from the natural gas transmission and storage system in

the united states," *Environmental Science & Technology*, vol. 49, no. 15, pp. 9374–9383, 2015, pMID: 26195284. [Online]. Available: https://doi.org/10.1021/acs.est.5b01669

[13] B. K. Lamb, S. L. Edburg, T. W. Ferrara, T. Howard, M. R. Harrison, C. E. Kolb, A. Townsend-Small, W. Dyck, A. Possolo, and J. R. Whetstone, "Direct measurements show decreasing methane emissions from natural gas local distribution systems in the united states," *Environmental Science & Technology*, vol. 49, no. 8, pp. 5161–5169, 2015, pMID: 25826444. [Online]. Available: https://doi.org/10.1021/es505116p

[14] U.S. Environmental Protection Agency, "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016," Washington, DC, 2017, EPA 430-R-18-003.

[15] A. L. Mitchell, D. S. Tkacik, J. R. Roscioli, S. C. Herndon, T. I. Yacovitch, D. M. Martinez, T. L. Vaughn, L. L. Williams, M. R. Sullivan, C. Floerchinger, M. Omara, R. Subramanian, D. Zimmerle, A. J. Marchese, and A. L. Robinson, "Measurements of methane emissions from natural gas gathering facilities and processing plants: Measurement results," *Environmental Science & Technology*, vol. 49, no. 5, pp. 3219–3227, 2015, pMID: 25668106. [Online]. Available: https://doi.org/10.1021/es5052809

[16] D. Utech. (02/28/2014) A strategy to cut methane emissions. Accessed: September 1, 2018. [Online]. Available: https://goo.gl/E7nxXB

[17] United States Department of Energy, Office of Fossil Energy U.S. Environmental Protection Agency. (04/13/2016) Methane emissions mitigation and quantification from natural gas infrastructure. Accessed: September 1, 2018. [Online]. Available: https://goo.gl/4CmTCr

[18] J. Smuts, *Process Control for Practitioners*, 1st ed. Houston, TX: OptiControls Inc, 2011.

[19] D. A. Simpson, “Pneumatic controllers in upstream oil and gas,” *Society of Petrolium Engineers*, October 2014.

[20] D. T. Allen, A. P. Pacsi, D. W. Sullivan, D. Zavala-Araiza, M. Harrison, K. Keen, M. P. Fraser, A. Daniel Hill, R. F. Sawyer, and J. H. Seinfeld, “Methane emissions from process equipment at natural gas production sites in the united states: Pneumatic controllers,” *Environmental Science & Technology*, vol. 49, no. 1, pp. 633–640, 2015.

[21] “Pneumatic controller emissions from a sample of 172 facilities,” Oklahoma Independent Petroleum Association, Tech. Rep., November 2014.

[22] U.S. Environmental Protection Agency, “Oil and natural gas sector pneumatic devices,” Washington, DC, April 2014, EPA 430-R-18-003.

[23] U.S. Environmental Protection Agency & Gas Research Institute, “Methane emissions from the natural gas industry, volume 12: Pneumatic devices,” June 1996, EPA-600/R-96-0801, GRI-94-0257.29.

[24] Bacharach INC., “Hi flow® sampler for natural gas leak rate measurement,” 2015, instruction 0055-9017 Operation and Maintenance.

[25] Greenpath Energy, “Alberta fugitive and vented emissions inventory study,” Prepared for Alberta Energy Regulator, Tech. Rep., 2016.

[26] U.S. Environmental Protection Agency. Greenhouse gas emissions from a typical passenger vehicle. Accessed: Oct 20, 2018. [Online]. Available: https://goo.gl/sM3NRv

[27] United States Environmental Protection Agency, “Understanding global warming potentials,” Tech. Rep., 2018. [Online]. Available: https://goo.gl/2RfMjp

[28] Statista. (2016) Number of motor vehicles registered in the United States from 1990 to 2016. Accessed: Dec 4, 2018. [Online]. Available: https://www.statista.com/statistics/183505/number-of-vehicles-in-the-united-states-since-1990/

[29] U.S. Environmental Protection Agency. Greenhouse gas reporting program: Petroleum and natural gas systems. Accessed: Oct 21, 2018. [Online]. Available: https://goo.gl/VugfLm

[30] Prasino Group, "Final Report for determining bleed rates for pneumatic devices in British Columbia," Report to British Columbia Ministry of Environment, Tech. Rep., December 2013.

[31] E. D. Thoma, P. Deshmukh, R. Logan, M. Stovern, C. Dresser, and H. L., "Assessment of uinta basin oil and natural gas well pad pneumatic controller emissions," *Journal of Environmental Protection*, vol. 8, no. 4, April 2017.

[32] Rockwell Automation, "Class/Division Hazardous Location," 2018, EPA 430-R-18-003. [Online]. Available: https://goo.gl/qJCJEA

[33] J. G. Olin, "New developments in thermal dispersion mass flow meters," Tech. Rep., 2014. [Online]. Available: https://goo.gl/YZFssM

[34] Fisher Controls International, "Fisher c1 pneumatic controllers and transmitters," August 2017, product Bulletin 34.3:C1.

[35] Dyna-flo Control Valve Services Ltd., "Model 4000lb pressure controllers," 2017, Technical sales bulletin P-40LBB0815A.

Appendix A

DATA SUMMARY

Data on each PC measured is summarized on one page, grouped into sections as described above. Each page starts with a listing of relevant parameters about the PC, with the following variables:

Site Class: *Class I*: Station was selected during original site selection exercise using randomized clustered sampling method. Meta-data was collected and instruments were installed by CSU personnel. *Class II*: Station was selected by hand from list of volunteered industry partner resources to improve geographic diversity and total number of measured PCs. Meta-data was collected and instruments were installed by CSU personnel. *Class III*: Station was selected by hand from list of volunteered industry partner resources to improve geographic diversity and total number of measured PCs. Meta-data was collected and instruments were installed by industry partner personnel, under the same protocols used by CSU personnel for site Classes I and II.

NEMS Region: National Energy Model region in which measurement was made.

Install Location: Location where measurement meter was installed. *Inline* indicates the meter was installed in the supply gas to the controller. *Exhaust* indicates the meter was installed on the exhaust port of the controller.

Controller Location: Major equipment category where PC was installed.

Process Controlled: The process variable controlled by the PC. Values include:] liquid level, temperature, and pressure.

Controller Model: Make and model of the PC

EPA Bleed Type: PC classification in accordance with the EPA classification method or intermittent, low- and high-bleed devices. Continuous bleed PCs are listed as *contin-*

uous is the intended bleed rate is unknown, *low bleed* if the intended bleed rate was $\leq 6scfh$, or *high bleed* if intended bleed rate is $> 6scfh$.

Gas Methane Fraction: Mole faction of methane in gas composition used to power the PC

Measurement Duration: Time measured on the PC

Avg. Gas Temperature: Temperature of the supply gas, as reported by the installed meter.

Avg. Supply Pressure: Pressure of the supply gas, as reported by the installed meter.

Corrected for Gas Comp.: Indicates whether flow rates are corrected for gas composition.

NZ Cutoff: For recordings impacted by the NZ correction, any flow below this cutoff level (in scfh whole gas) could represent erroneous readings from the meter, rather than real gas flows.

Emission Rate: Whole gas emission rate, with 95% confidence interval.

Samples Remaining The fraction of samples in the recording that *were not* impacted by the NZ correction.

Emissions Remaining The fraction of total indicated emissions in the recording that *were not* impacted by the NZ correction. Note that these emissions were *slightly* impacted by filtering noise from the flow recordings.

Evaluation The opinion of the expert panel on whether the PC is working correctly *from an emissions perspective*; a PC may be effectively completing its assigned function but emitting more gas than it is designed to emit.

Notes: Additional notes made by the field team or clarification on classifications.

A.1 Zero Impact

This section contains recordings made on PCs where average emission rates were unaffected by the NZ meter error. This includes all recordings where meter was connected to a PC's exhaust port, as measurements were made at atmospheric pressure well below the NZ baseline pressure thresholds. This section also includes recordings where either supply gas pressures were low enough that no NZ baseline was observable, or the NZ correction had a minor (<1%) effect on average emissions.

Device A-1

Site Class: II	NEMS Region: Southwest
Install Location: Exhaust	Measurement Duration: 69.3 hrs
Controller Location: Glycol Dehydrator	Avg. Gas Temperature: 48.8 $^\circ F$
Process Controlled: Temperature	Avg. Supply Pressure: 13.2 psia
Controller Model: Kimray T12	Gas Methane Fraction: 92%
EPA Bleed Type: Intermittent	Emission Factor: 0.019 [0.0065 to 0.044]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Normally Operating	

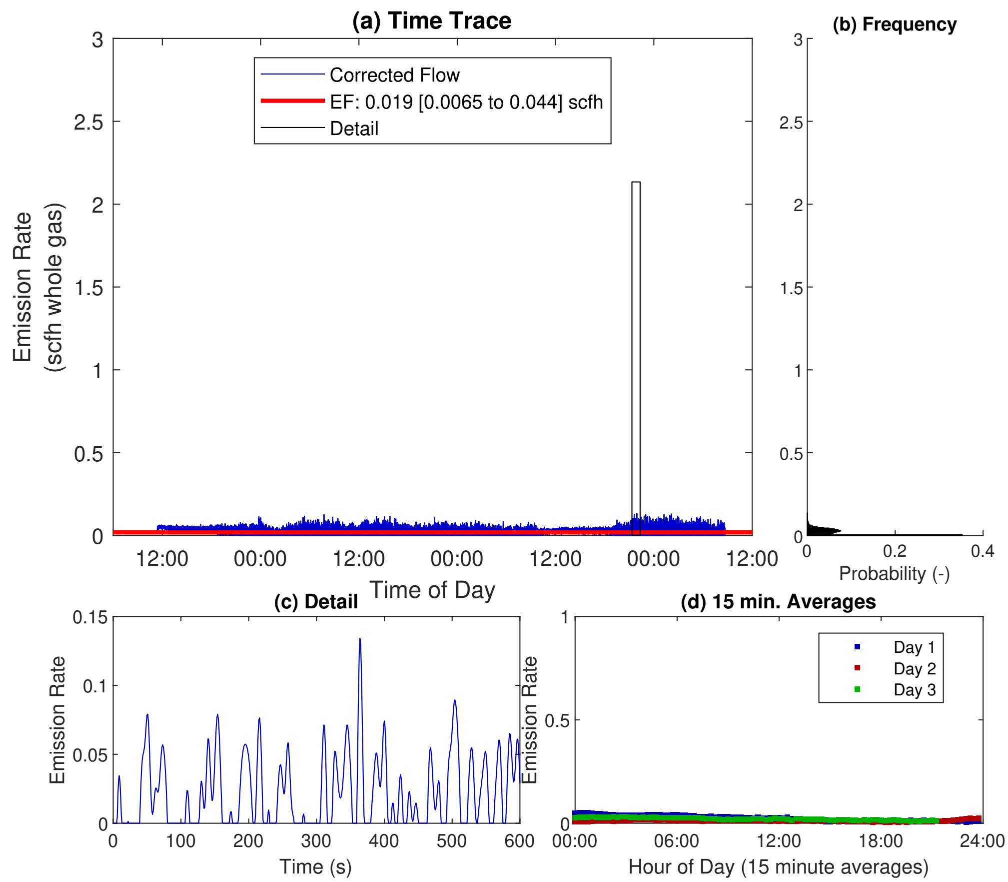

Figure A.1: Device A-1

Device D-1

Site Class: I	NEMS Region: Rocky Mountain
Install Location: Inline	Measurement Duration: 85.6 hrs
Controller Location: Compressor	Avg. Gas Temperature: 50.6 $^\circ F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 32.4 psia
Controller Model: Murphy, L1200N	Gas Methane Fraction: 99.2%
EPA Bleed Type: Intermittent	Emission Factor: 39 [8.6 to 1.3e+02]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Abnormally Operating	

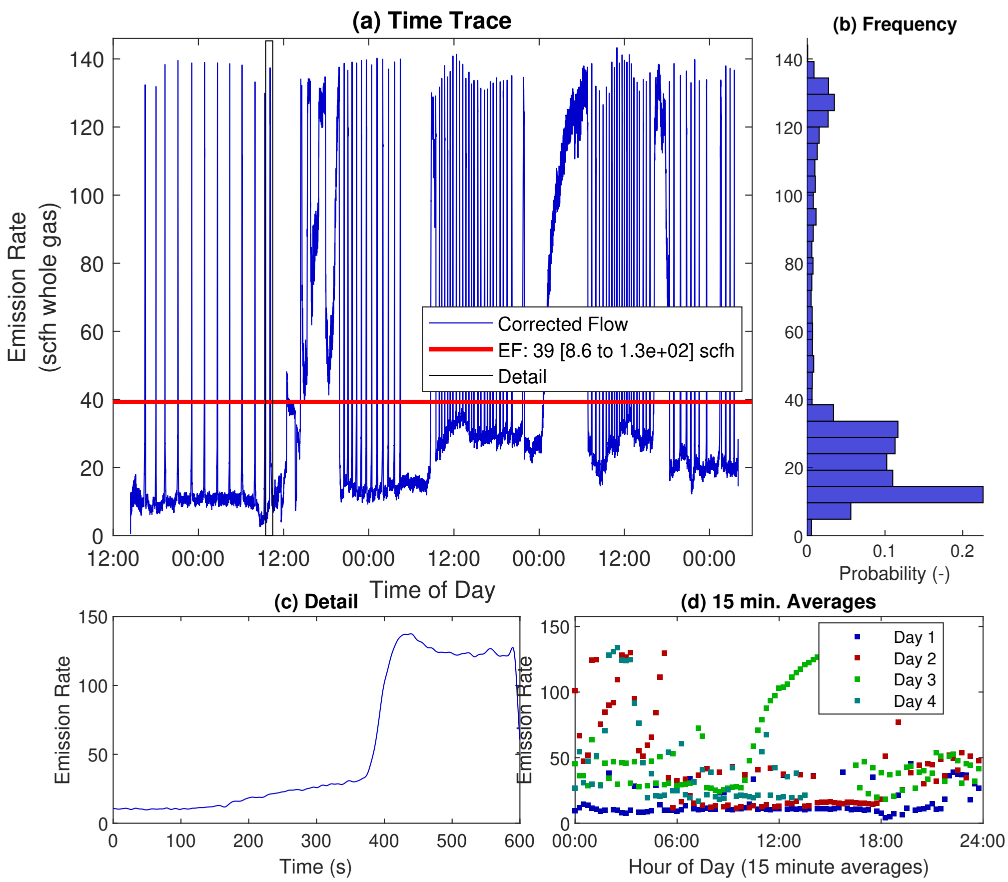

Figure A.2: Device D-1

Device D-4

Site Class: I	NEMS Region: Rocky Mountain
Install Location: Inline	Measurement Duration: 90.8 hrs
Controller Location: Compressor	Avg. Gas Temperature: 41.8 °F
Process Controlled: Liquid Level	Avg. Supply Pressure: 33 psia
Controller Model: Mallard, 3100-P1	Gas Methane Fraction: 99.2%
EPA Bleed Type: Intermittent	Emission Factor: 12 [0 to 51]
Non-zero Correction:	NZ Cutoff: 0.485 scfh
Samples Remaining: 40%	Emissions Remaining: 99%
Evaluation: Abnormally Operating	

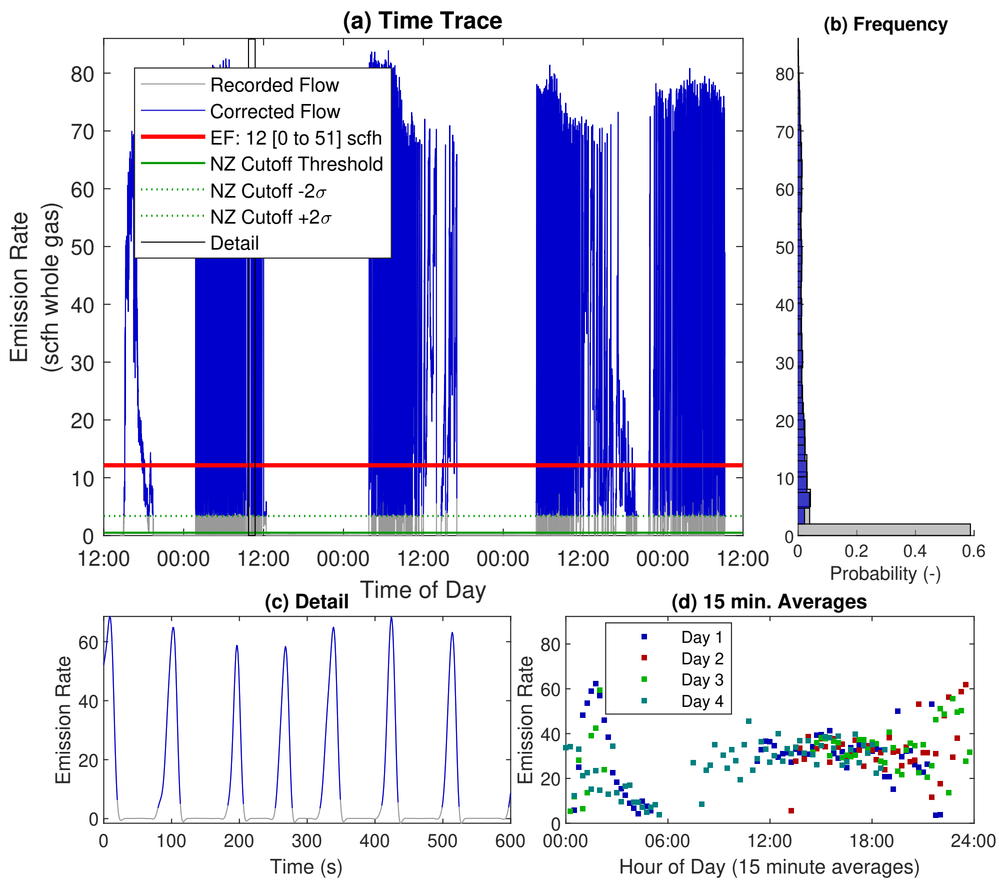

Figure A.3: Device D-4

Device D-6

Site Class: I	NEMS Region: Rocky Mountain
Install Location: Inline	Measurement Duration: 72.3 hrs
Controller Location: Compressor	Avg. Gas Temperature: 59.7 °F
Process Controlled: Liquid Level	Avg. Supply Pressure: 32.7 psia
Controller Model: Mallard, 3100-P1	Gas Methane Fraction: 99.2%
EPA Bleed Type: Intermittent	Emission Factor: 10 [7.1 to 14]
Non-zero Correction:	NZ Cutoff: 0.466 scfh
Samples Remaining: 96%	Emissions Remaining: 100%
Evaluation: Abnormally Operating	

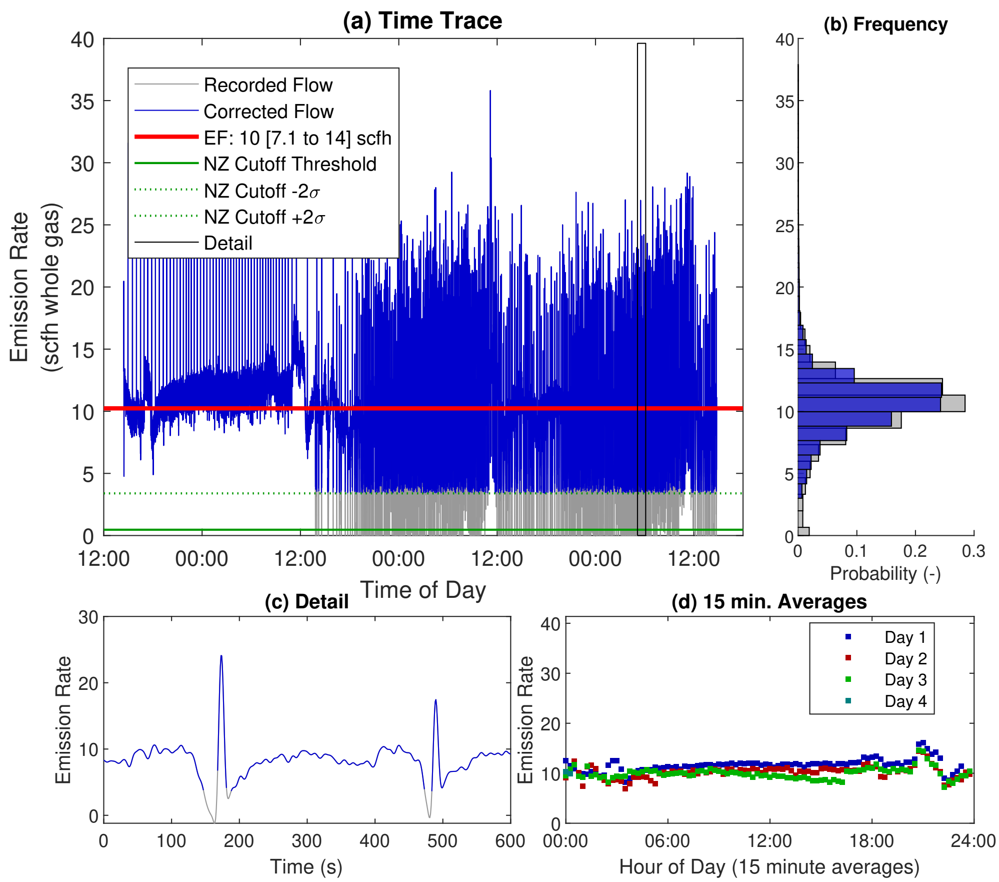

Figure A.4: Device D-6

Device G-2

Site Class: II	NEMS Region: Gulf Coast
Install Location: Exhaust	Measurement Duration: 50.9 hrs
Controller Location: Compressor	Avg. Gas Temperature: 37.8 $^\circ F$
Process Controlled: Pressure	Avg. Supply Pressure: 14.4 psia
Controller Model: Control Air Inc 950XP	Gas Methane Fraction: 94.5%
EPA Bleed Type: Low Bleed	Emission Factor: 0.011 [0.0058 to 0.018]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Normally Operating	

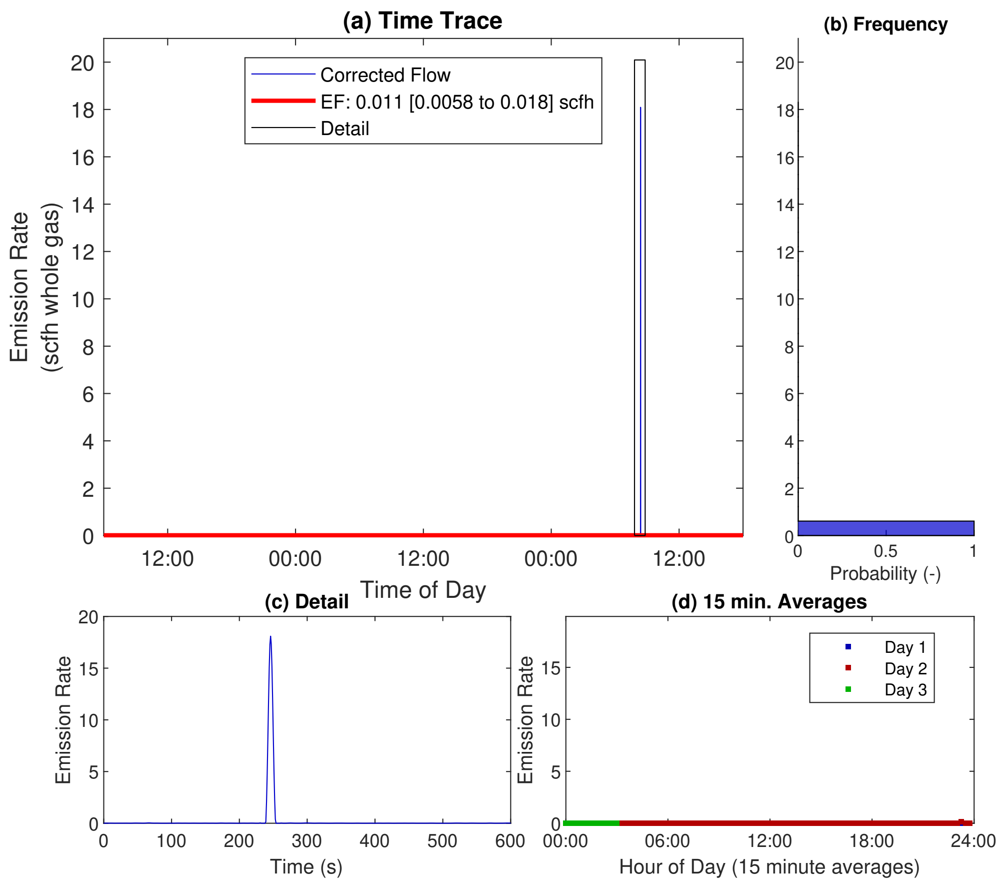

Figure A.5: Device G-2

Device G-3

Site Class: II	NEMS Region: Gulf Coast
Install Location: Exhaust	Measurement Duration: 50.4 hrs
Controller Location: Yard Piping	Avg. Gas Temperature: 50.4 °F
Process Controlled: Pressure	Avg. Supply Pressure: 14.6 psia
Controller Model: Fisher 582i	Gas Methane Fraction: 94.5%
EPA Bleed Type: High Bleed	Emission Factor: 0.028 [0.0046 to 0.044]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Normally Operating	

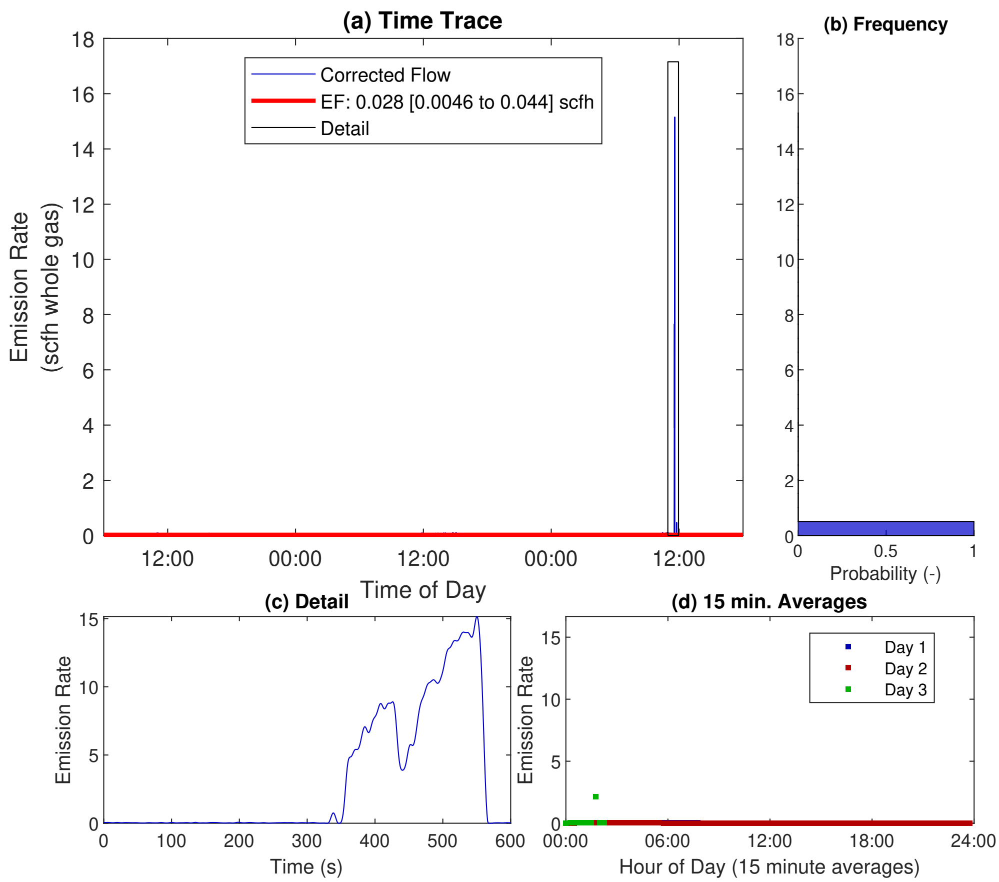

Figure A.6: Device G-3

Device G-4

Site Class: II	NEMS Region: Gulf Coast
Install Location: Exhaust	Measurement Duration: 50.2 hrs
Controller Location: Compressor	Avg. Gas Temperature: 33.8 $^{\circ}F$
Process Controlled: Pressure	Avg. Supply Pressure: 14.7 psia
Controller Model: Control Air Inc 950XP	Gas Methane Fraction: 94.5%
EPA Bleed Type: Low Bleed	Emission Factor: 0.087 [0.038 to 0.27]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Normally Operating	

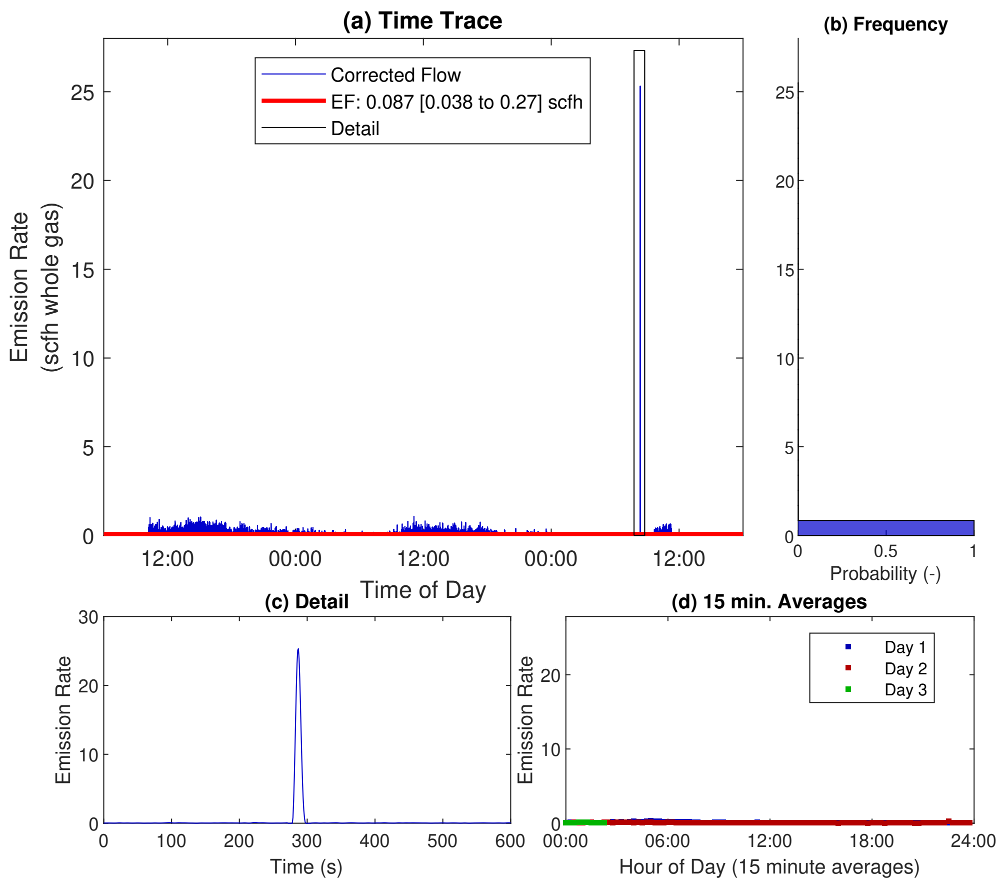

Figure A.7: Device G-4

Device G-6

Site Class: II	NEMS Region: Gulf Coast
Install Location: Inline	Measurement Duration: 49.4 hrs
Controller Location: Yard Piping	Avg. Gas Temperature: 33.5 $^{\circ}F$
Process Controlled: Pressure	Avg. Supply Pressure: 34.6 psia
Controller Model: Fisher 546	Gas Methane Fraction: 94.5%
EPA Bleed Type: High Bleed	Emission Factor: 36 [32 to 38]
Non-zero Correction:	NZ Cutoff: 3.31 scfh
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Normally Operating	

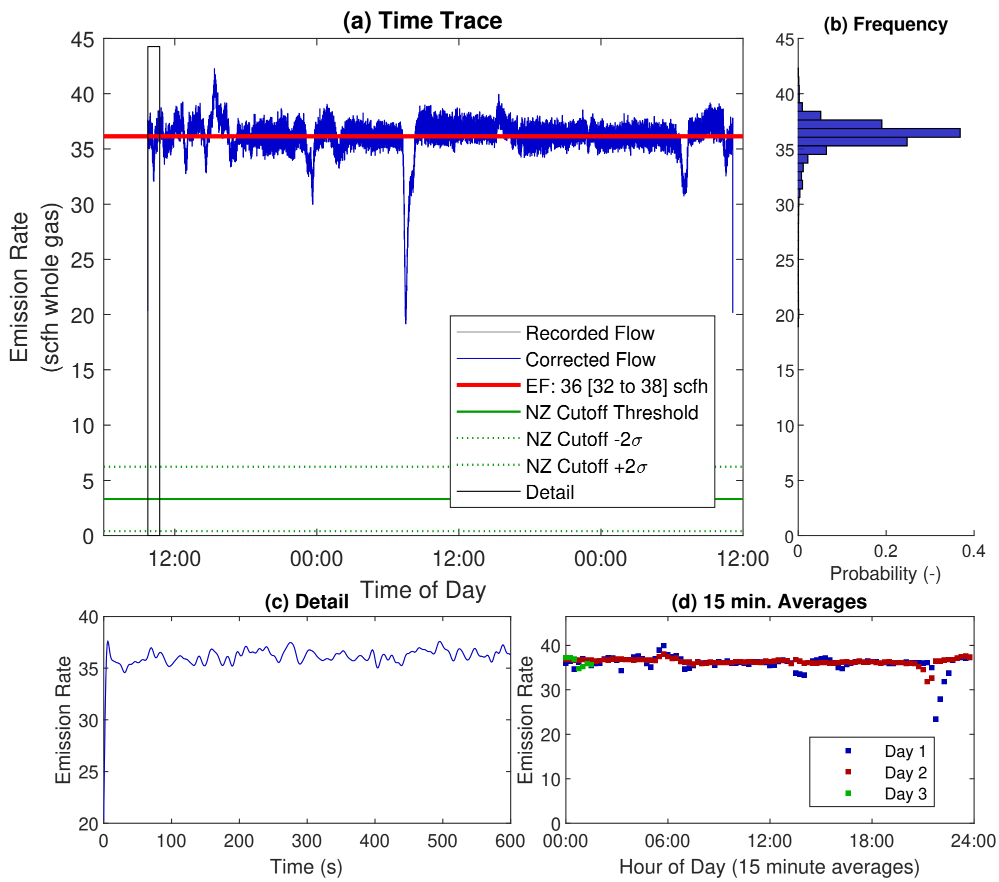

Figure A.8: Device G-6

Device H-4

Site Class: I	NEMS Region: Southwest
Install Location: Inline	Measurement Duration: 92.1 hrs
Controller Location: Separator	Avg. Gas Temperature: 73.1 $^{\circ}F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 41 psia
Controller Model: Wellmark 1800	Gas Methane Fraction: 70%
EPA Bleed Type: Intermittent	Emission Factor: 0.13 [0.054 to 0.6]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Normally Operating	

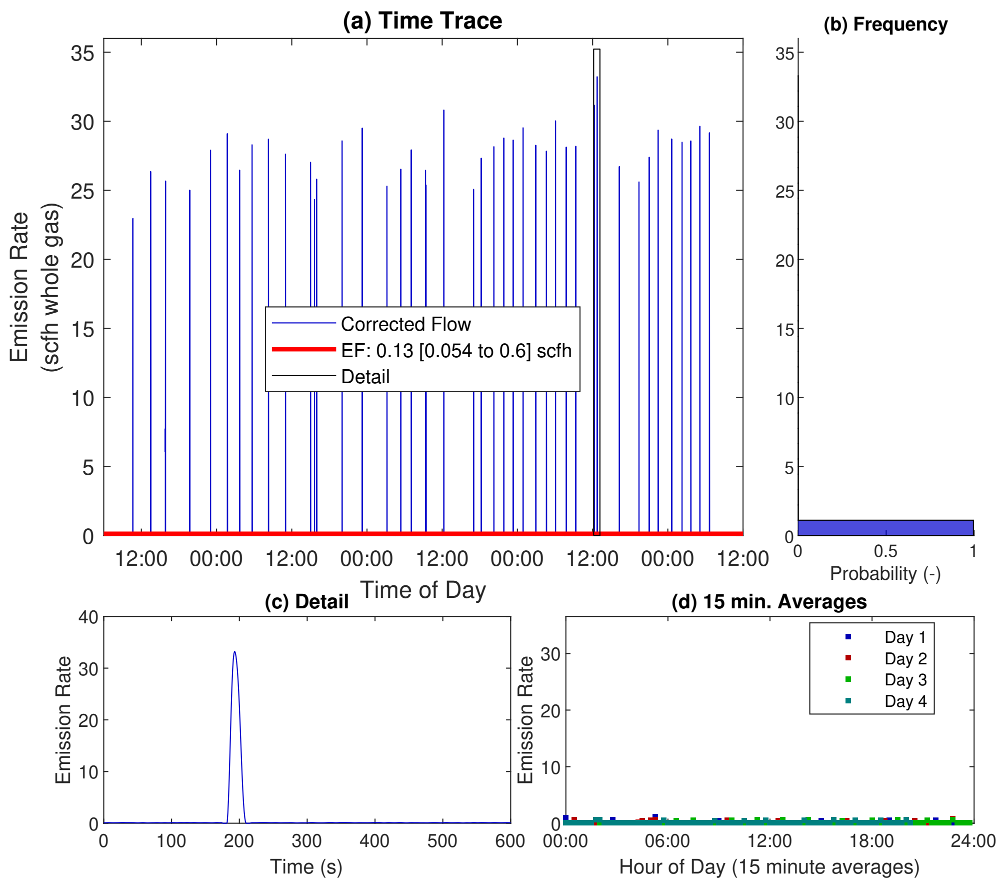

Figure A.9: Device H-4

Device H-6

Site Class: I	NEMS Region: Southwest
Install Location: Inline	Measurement Duration: 83.9 hrs
Controller Location: Compressor	Avg. Gas Temperature: 85.7 $^\circ F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 39.4 psia
Controller Model: Norriseal 1001A	Gas Methane Fraction: 70%
EPA Bleed Type: Intermittent	Emission Factor: 40 [21 to 75]
Non-zero Correction:	NZ Cutoff: 9.88 scfh
Samples Remaining: 99%	Emissions Remaining: 100%
Evaluation: Abnormally Operating	

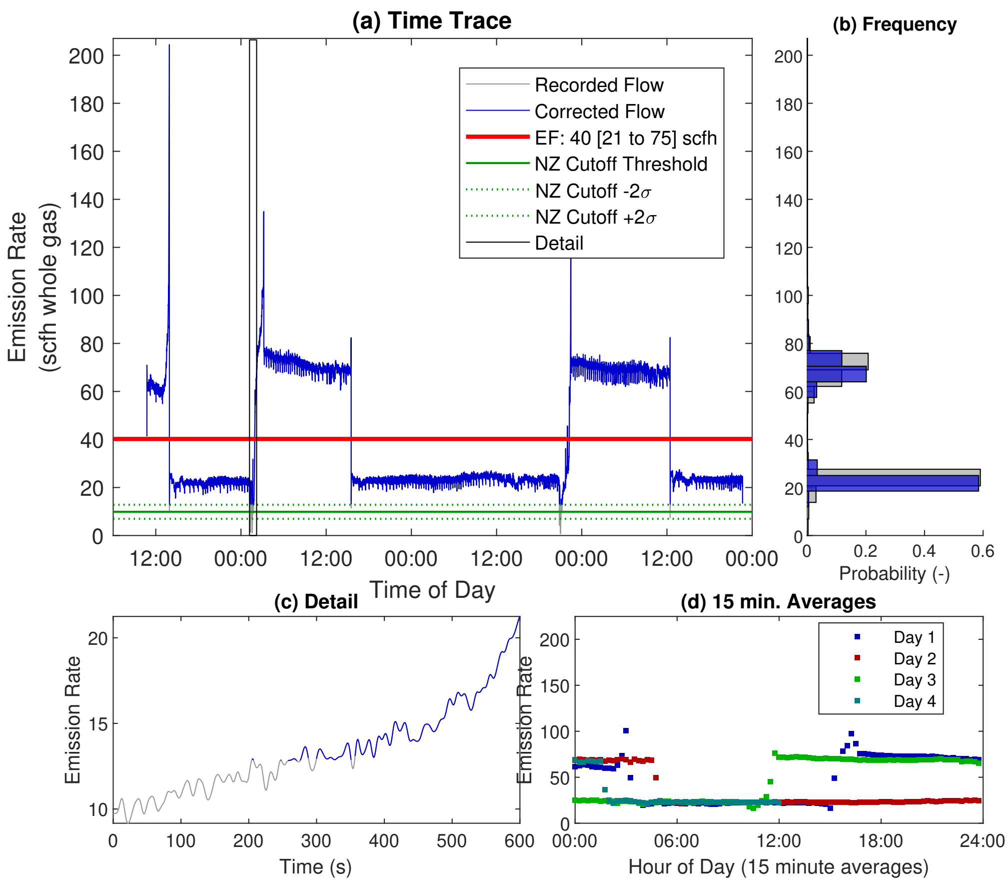

Figure A.10: Device H-6

Device I-2

Site Class: I	NEMS Region: Gulf Coast
Install Location: Exhaust	Measurement Duration: 51.1 hrs
Controller Location: Yard Piping	Avg. Gas Temperature: 67.2 $^\circ F$
Process Controlled: Pressure	Avg. Supply Pressure: 14.4 psia
Controller Model: Norriseal Series 4900	Gas Methane Fraction: 90.8%
EPA Bleed Type: Low Bleed	Emission Factor: 25 [19 to 32]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Abnormally Operating	

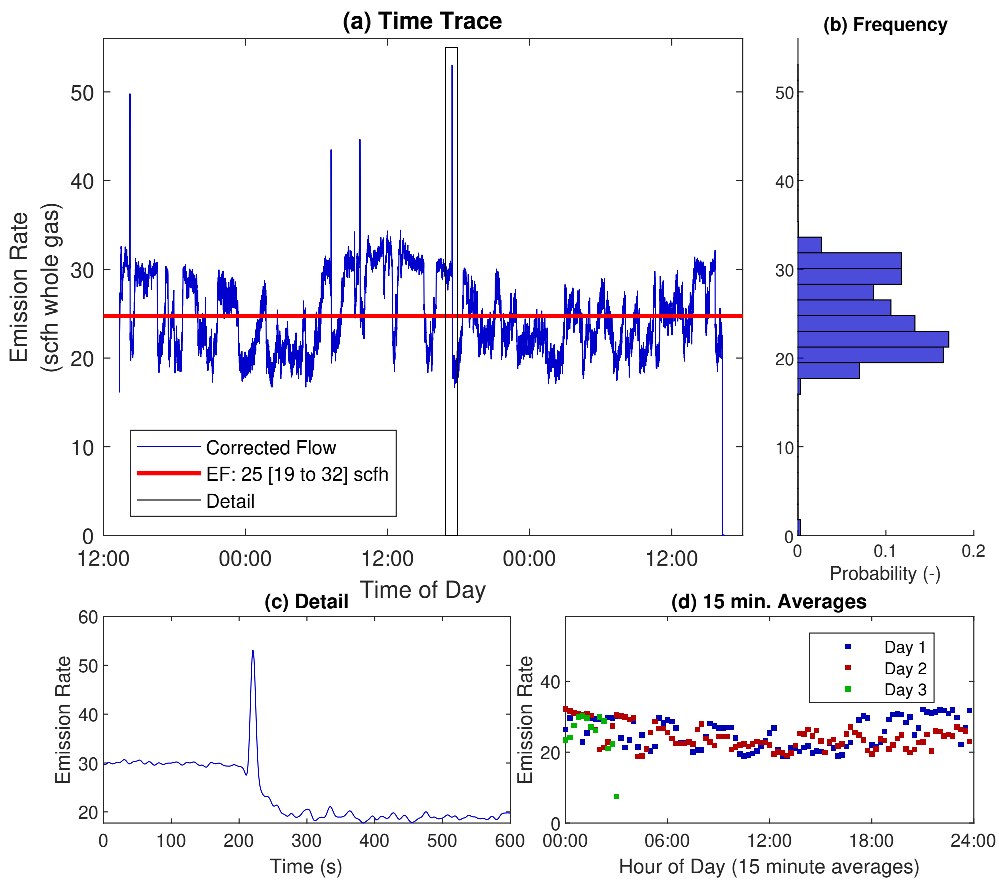

Figure A.11: Device I-2

Device I-3

Site Class: I	NEMS Region: Gulf Coast
Install Location: Exhaust	Measurement Duration: 49.7 hrs
Controller Location: Compressor	Avg. Gas Temperature: 82 $^\circ F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 14.5 psia
Controller Model: Noriseal Series 1005E	Gas Methane Fraction: 90.8%
EPA Bleed Type: Intermittent	Emission Factor: 0.042 [0.023 to 0.075]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Normally Operating	

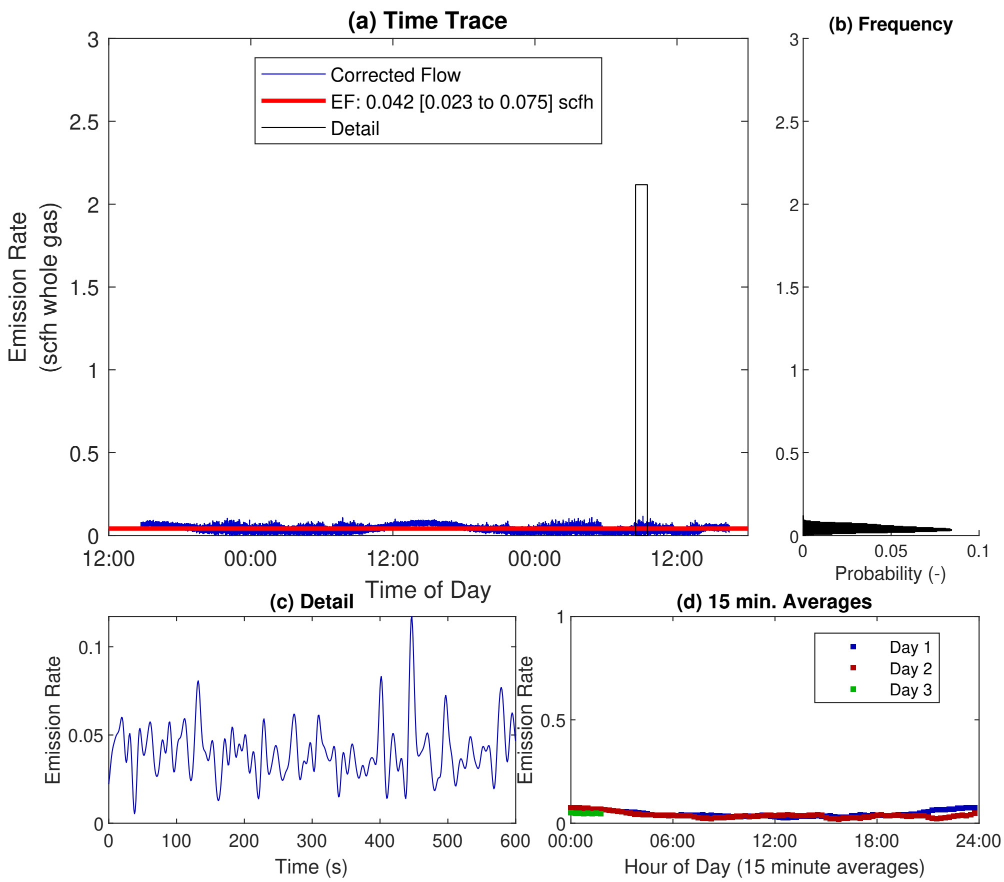

Figure A.12: Device I-3

Device I-4

Site Class: I	NEMS Region: Gulf Coast
Install Location: Exhaust	Measurement Duration: 50 hrs
Controller Location: Compressor	Avg. Gas Temperature: 76.8 $^\circ F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 14.7 psia
Controller Model: Norriseal Series 1005E	Gas Methane Fraction: 90.8%
EPA Bleed Type: Intermittent	Emission Factor: 0.08 [0.059 to 0.12]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Normally Operating	

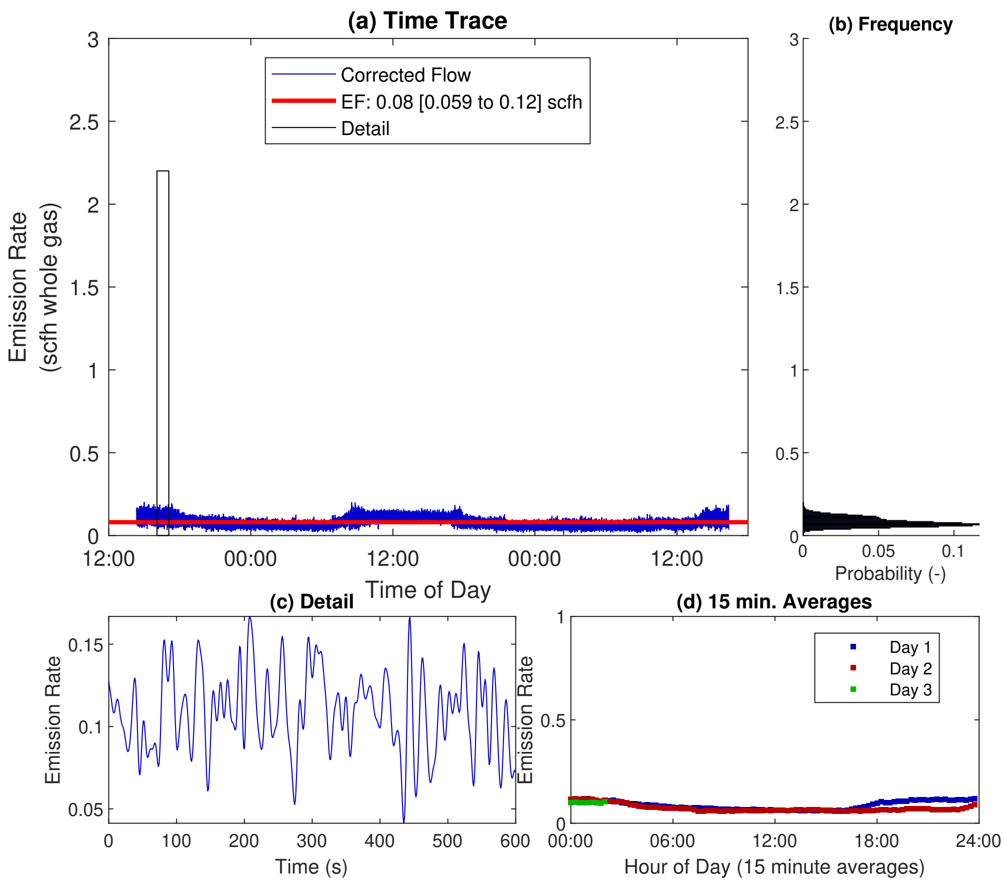

Figure A.13: Device I-4

Device I-5

Site Class: I	NEMS Region: Gulf Coast
Install Location: Exhaust	Measurement Duration: 50 hrs
Controller Location: Compressor	Avg. Gas Temperature: 67.3 $^{\circ}F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 18.2 psia
Controller Model: Norriseal Series 1005P1	Gas Methane Fraction: 90.8%
EPA Bleed Type: Intermittent	Emission Factor: 63 [0.057 to 99]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Abnormally Operating	

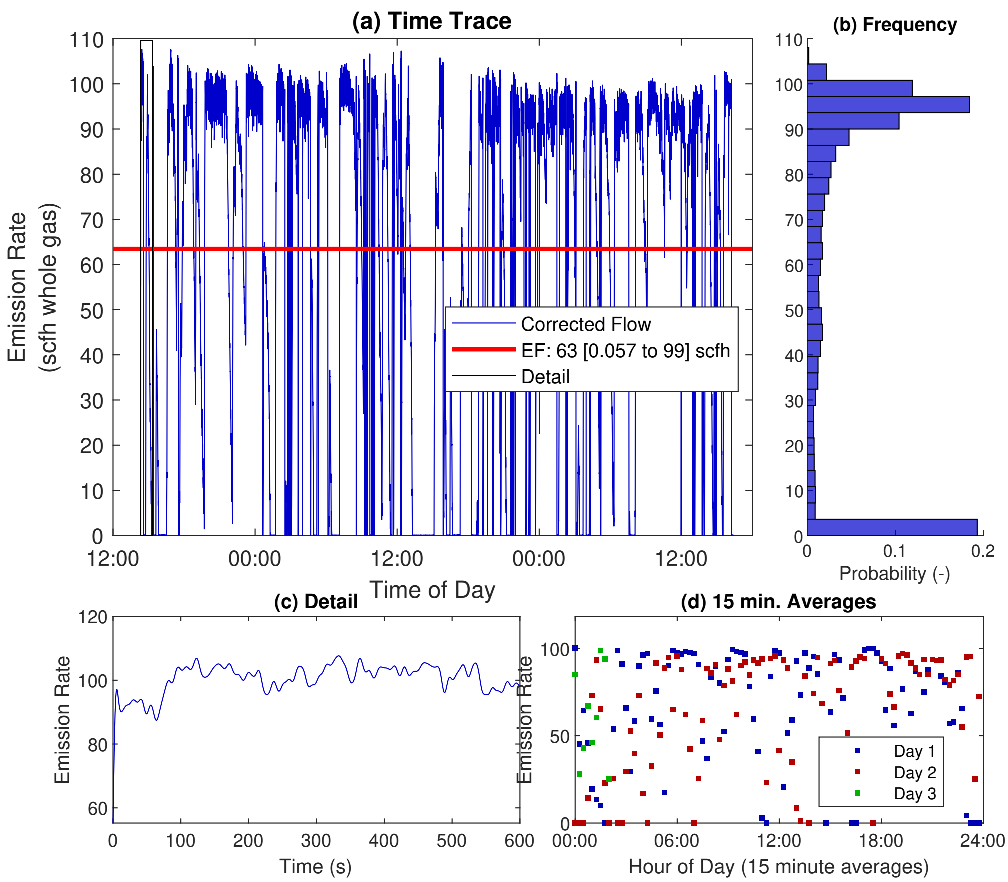

Figure A.14: Device I-5

Device J-1

Site Class: III	NEMS Region: Southwest
Install Location: Exhaust	Measurement Duration: 102 hrs
Controller Location: Yard Piping	Avg. Gas Temperature: 56.4 °F
Process Controlled: Liquid Level	Avg. Supply Pressure: 13.2 psia
Controller Model: Fisher L2	Gas Methane Fraction: 92%
EPA Bleed Type: Intermittent	Emission Factor: 0.022 [0.0099 to 0.038]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Normally Operating	

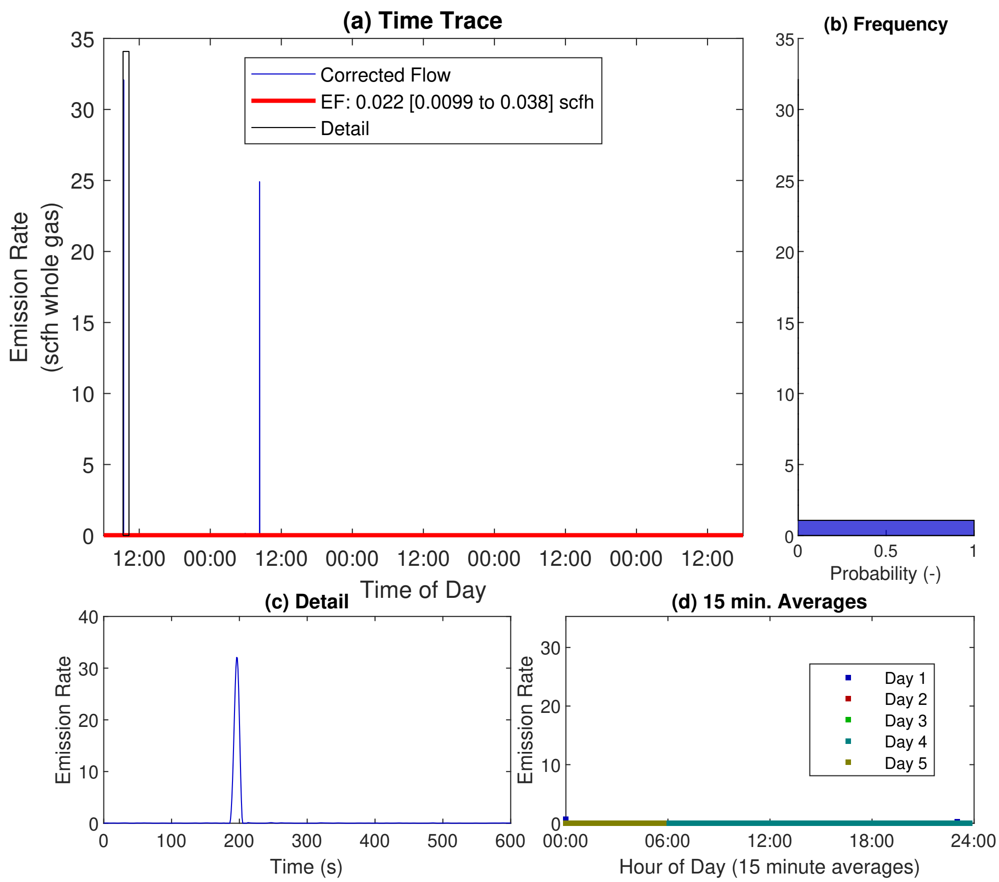

Figure A.15: Device J-1

Device J-2

Site Class: III	NEMS Region: Southwest
Install Location: Inline	Measurement Duration: 81.7 hrs
Controller Location: Yard Piping	Avg. Gas Temperature: 56.4 $^\circ F$
Process Controlled: Pressure	Avg. Supply Pressure: 45.1 psia
Controller Model: Fisher C1	Gas Methane Fraction: 92%
EPA Bleed Type: Low Bleed	Emission Factor: 55 [50 to 59]
Non-zero Correction:	NZ Cutoff: 17.2 scfh
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Abnormally Operating	

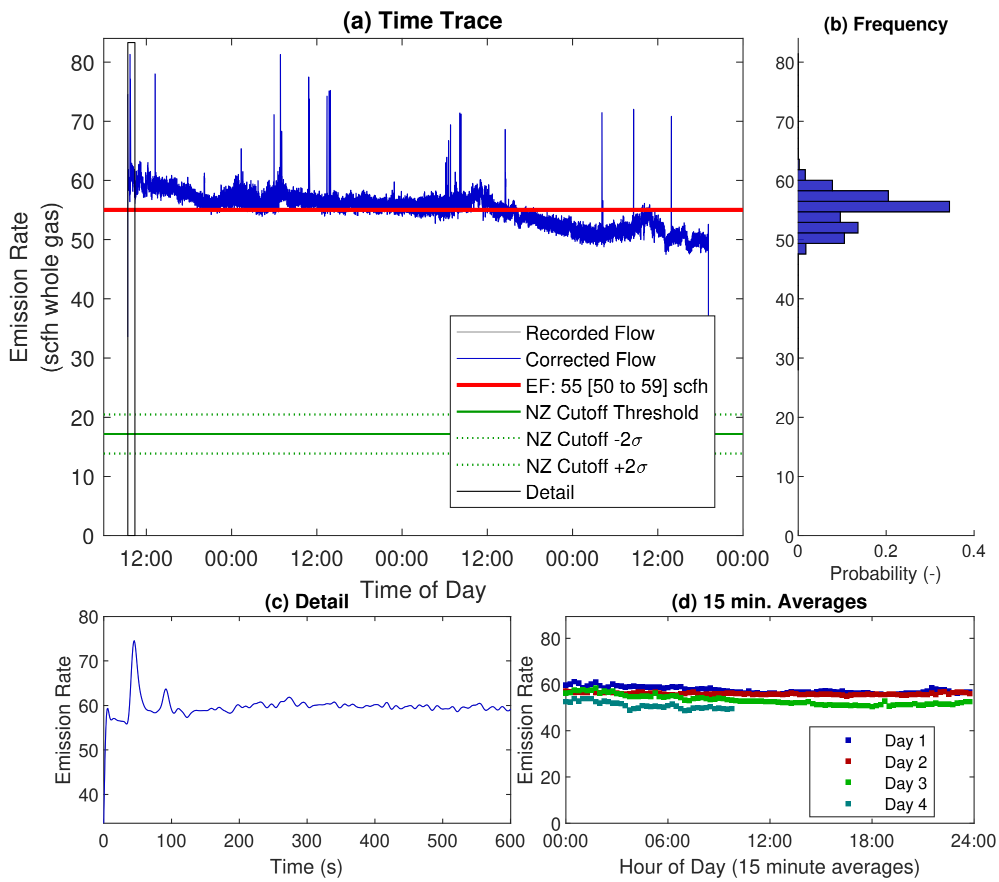

Figure A.16: Device J-2

Device J-3

Site Class: III	NEMS Region: Southwest
Install Location: Inline	Measurement Duration: 80.2 hrs
Controller Location: Yard Piping	Avg. Gas Temperature: 54.8 $^\circ F$
Process Controlled: Pressure	Avg. Supply Pressure: 47.8 psia
Controller Model: Fisher 4160k	Gas Methane Fraction: 92%
EPA Bleed Type: High Bleed	Emission Factor: 55 [53 to 57]
Non-zero Correction:	NZ Cutoff: 16.4 scfh
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Normally Operating	

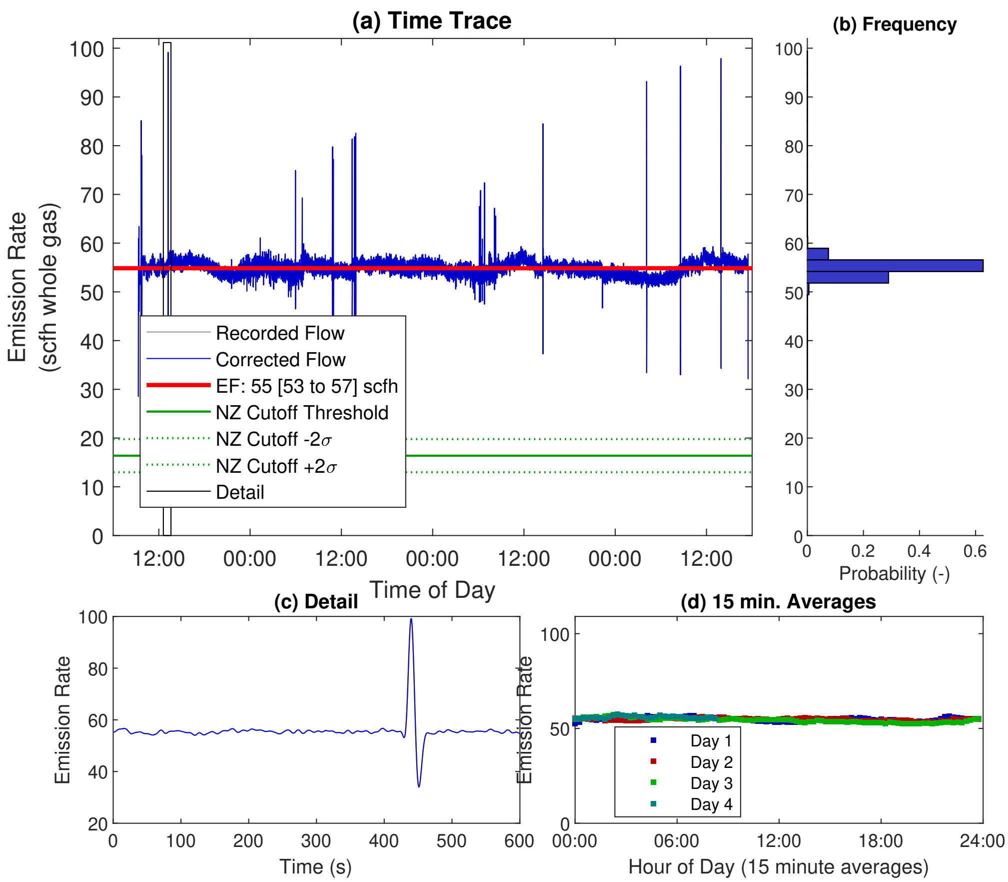

Figure A.17: Device J-3

Device J-6

Site Class: III	NEMS Region: Southwest
Install Location: Inline	Measurement Duration: 81.4 hrs
Controller Location: Compressor	Avg. Gas Temperature: 56.7 $°F$
Process Controlled: Pressure	Avg. Supply Pressure: 46.3 psia
Controller Model: Dynaflo 4000 LBR	Gas Methane Fraction: 92%
EPA Bleed Type: Low Bleed	Emission Factor: 68 [26 to 75]
Non-zero Correction:	NZ Cutoff: 18.8 scfh
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Abnormally Operating	

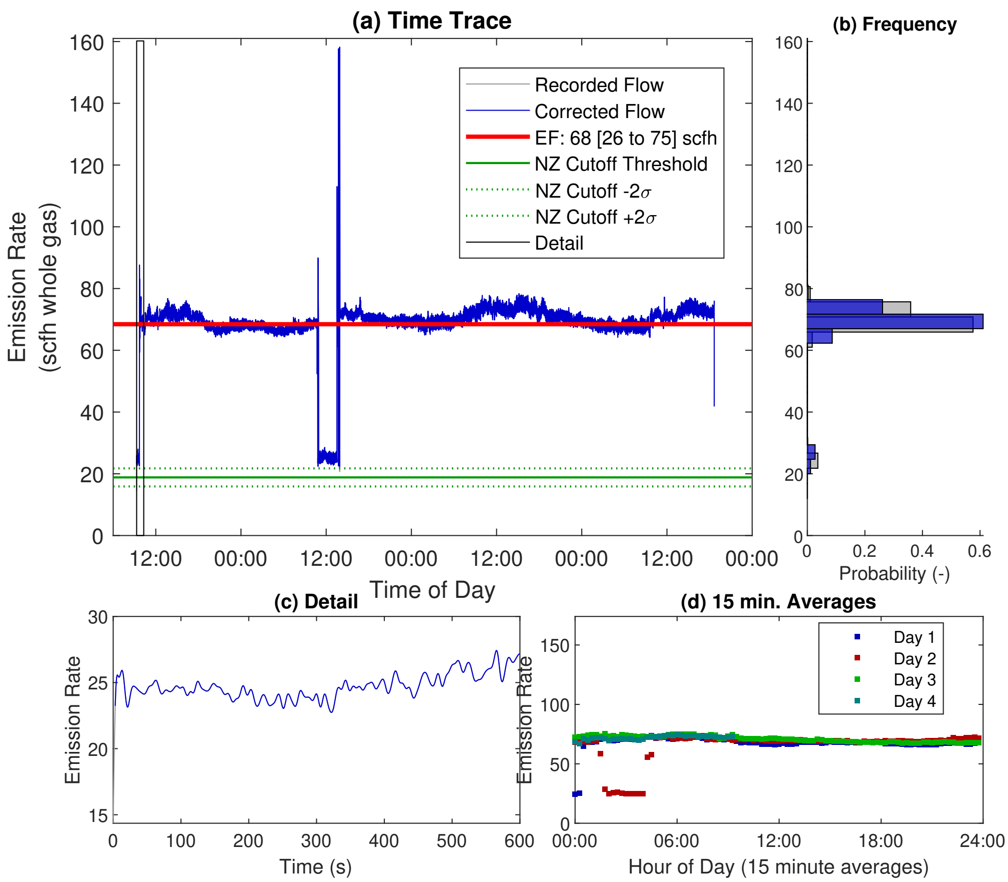

Figure A.18: Device J-6

Device L-2

Site Class: III	NEMS Region: Gulf Coast
Install Location: Exhaust	Measurement Duration: 94.7 hrs
Controller Location: Compressor	Avg. Gas Temperature: 28.2 $^\circ F$
Process Controlled: Pressure	Avg. Supply Pressure: 14.3 psia
Controller Model: Control Air 950XP	Gas Methane Fraction: 94.5%
EPA Bleed Type: Low Bleed	Emission Factor: 0.035 [0.0032 to 0.022]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Normally Operating	

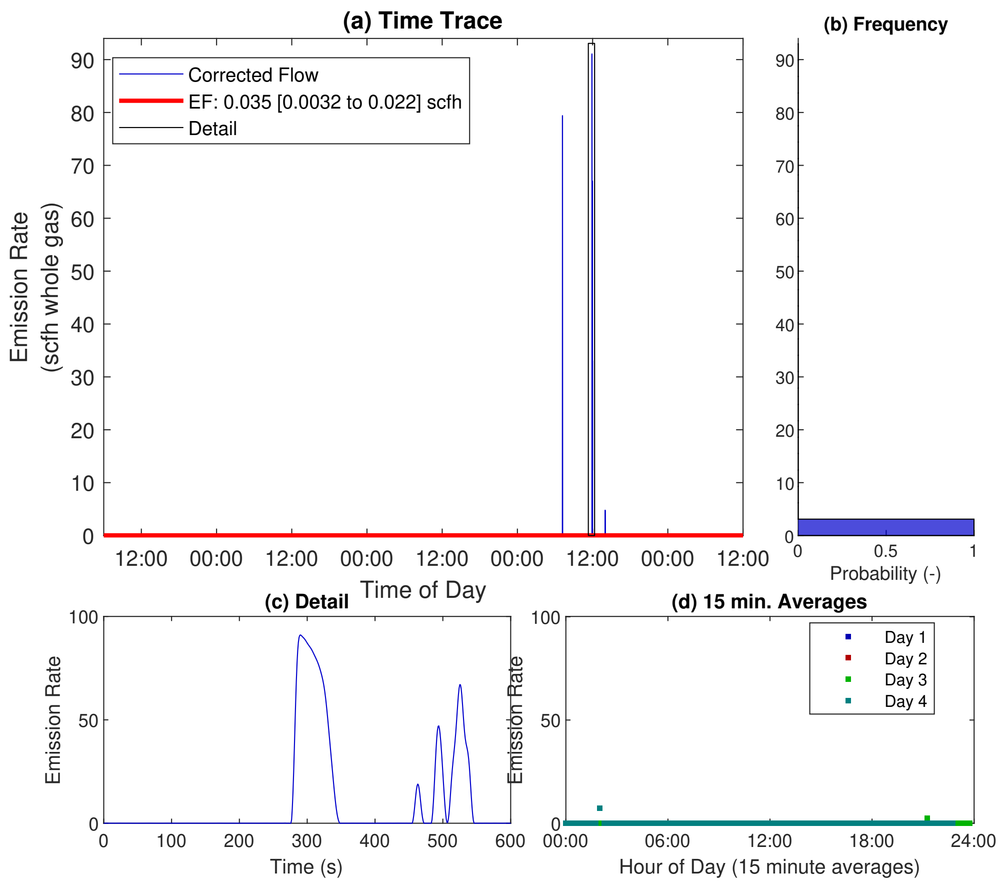

Figure A.19: Device L-2

Device L-3

Site Class: III	NEMS Region: Gulf Coast
Install Location: Exhaust	Measurement Duration: 94.7 hrs
Controller Location: Compressor	Avg. Gas Temperature: 30.7 $^\circ F$
Process Controlled: Pressure	Avg. Supply Pressure: 14.5 psia
Controller Model: Control Air 950XP	Gas Methane Fraction: 94.5%
EPA Bleed Type: Low Bleed	Emission Factor: 0.015 [0.0047 to 0.04]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Normally Operating	

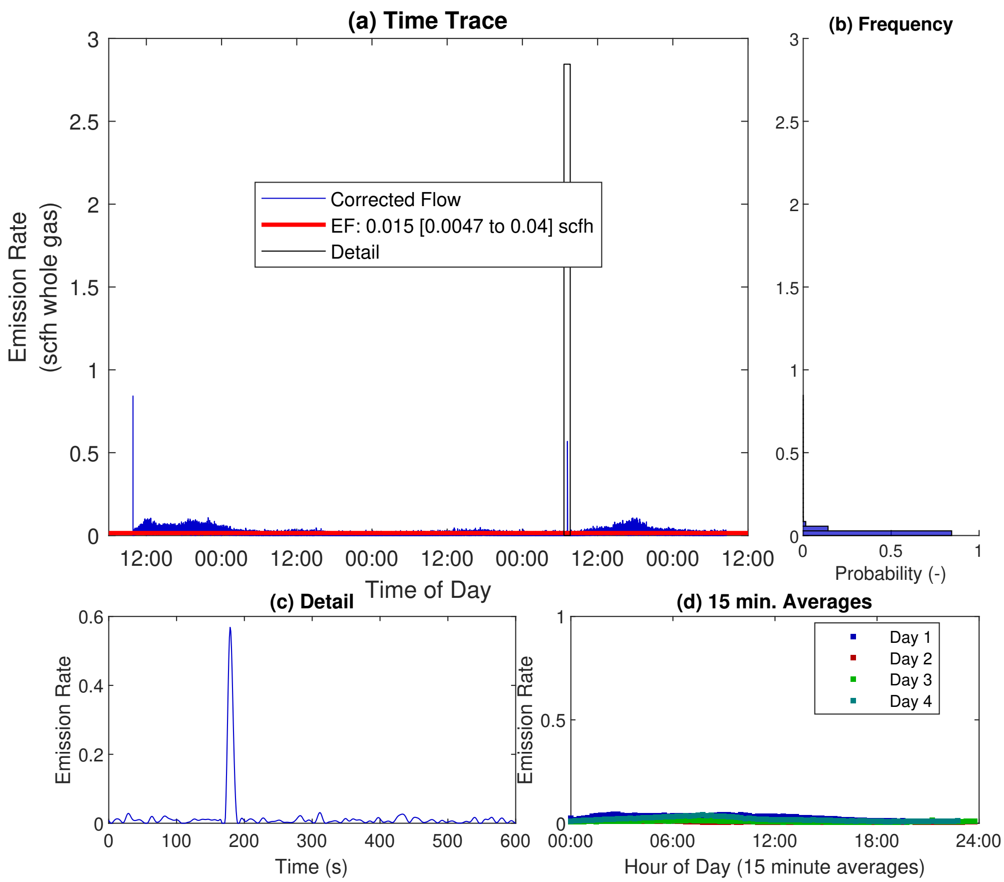

Figure A.20: Device L-3

Device L-4

Site Class: III	NEMS Region: Gulf Coast
Install Location: Exhaust	Measurement Duration: 94.9 hrs
Controller Location: Yard Piping	Avg. Gas Temperature: 19.2 °F
Process Controlled: Pressure	Avg. Supply Pressure: 14.6 psia
Controller Model: Fisher 582i	Gas Methane Fraction: 94.5%
EPA Bleed Type: High Bleed	Emission Factor: 0.56 [0.019 to 2.5]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Normally Operating	

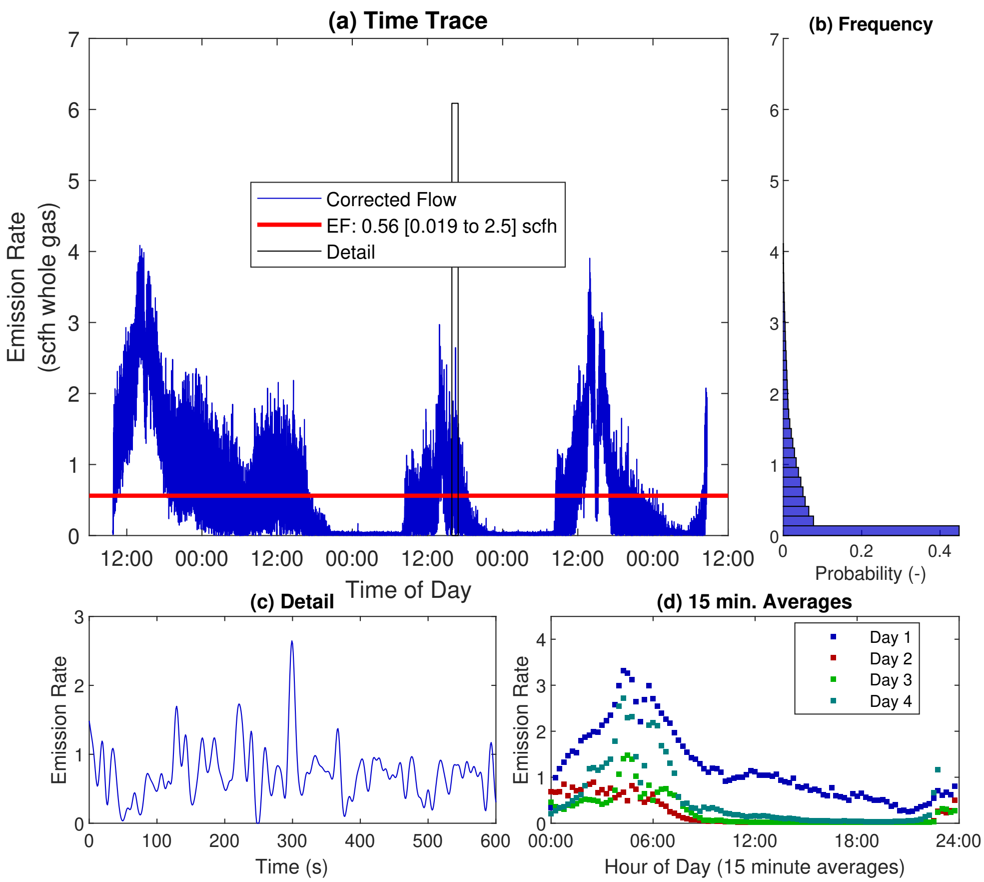

Figure A.21: Device L-4

Device N-1

Site Class: I	NEMS Region: Midcontinent
Install Location: Inline	Measurement Duration: 80.7 hrs
Controller Location: Separator	Avg. Gas Temperature: 76.8 $^\circ F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 33.9 psia
Controller Model: Solenoid Operated	Gas Methane Fraction: 77.1%
EPA Bleed Type: Intermittent	Emission Factor: 9 [3.9 to 15]
Non-zero Correction:	NZ Cutoff: 0.395 scfh
Samples Remaining: 99%	Emissions Remaining: 100%
Evaluation: Abnormally Operating	

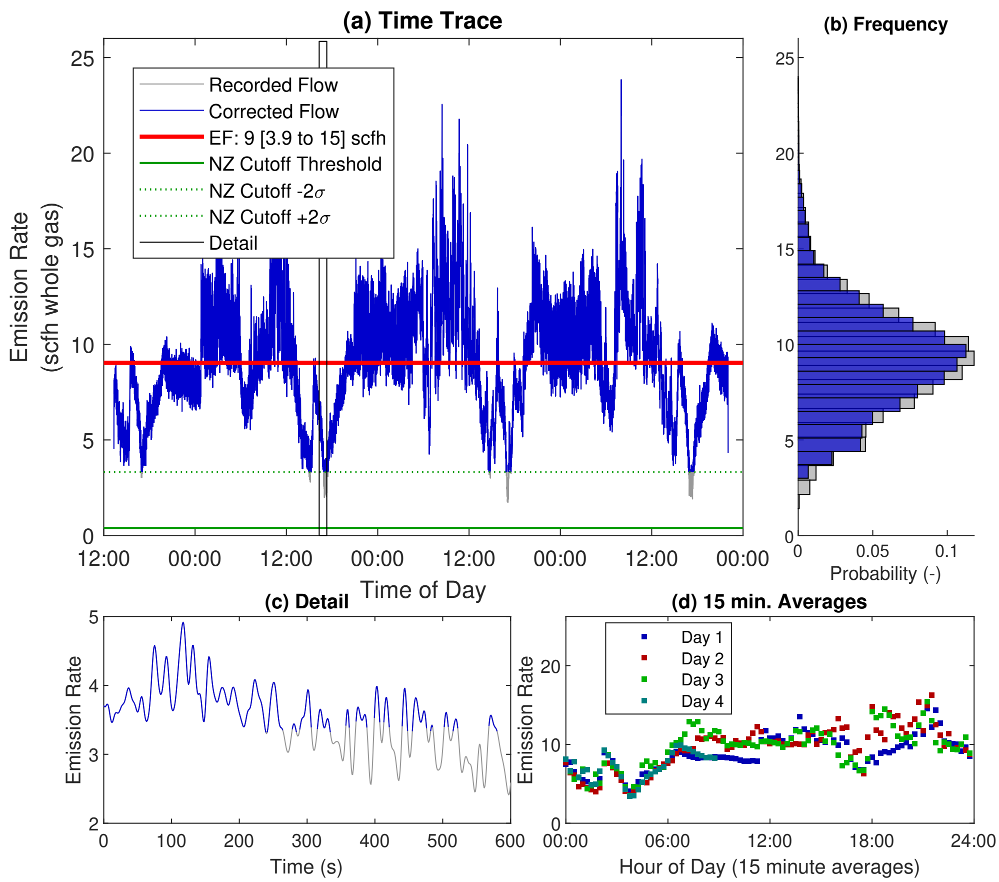

Figure A.22: Device N-1

Device N-3

Site Class: I	NEMS Region: Midcontinent
Install Location: Inline	Measurement Duration: 74.9 hrs
Controller Location: Compressor	Avg. Gas Temperature: 75.8 $^\circ F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 39.1 psia
Controller Model: Norriseal 1001A	Gas Methane Fraction: 77.1%
EPA Bleed Type: Intermittent	Emission Factor: 57 [0 to 1.7e+02]
Non-zero Correction:	NZ Cutoff: 5.9 scfh
Samples Remaining: 95%	Emissions Remaining: 99%
Evaluation: Abnormally Operating	

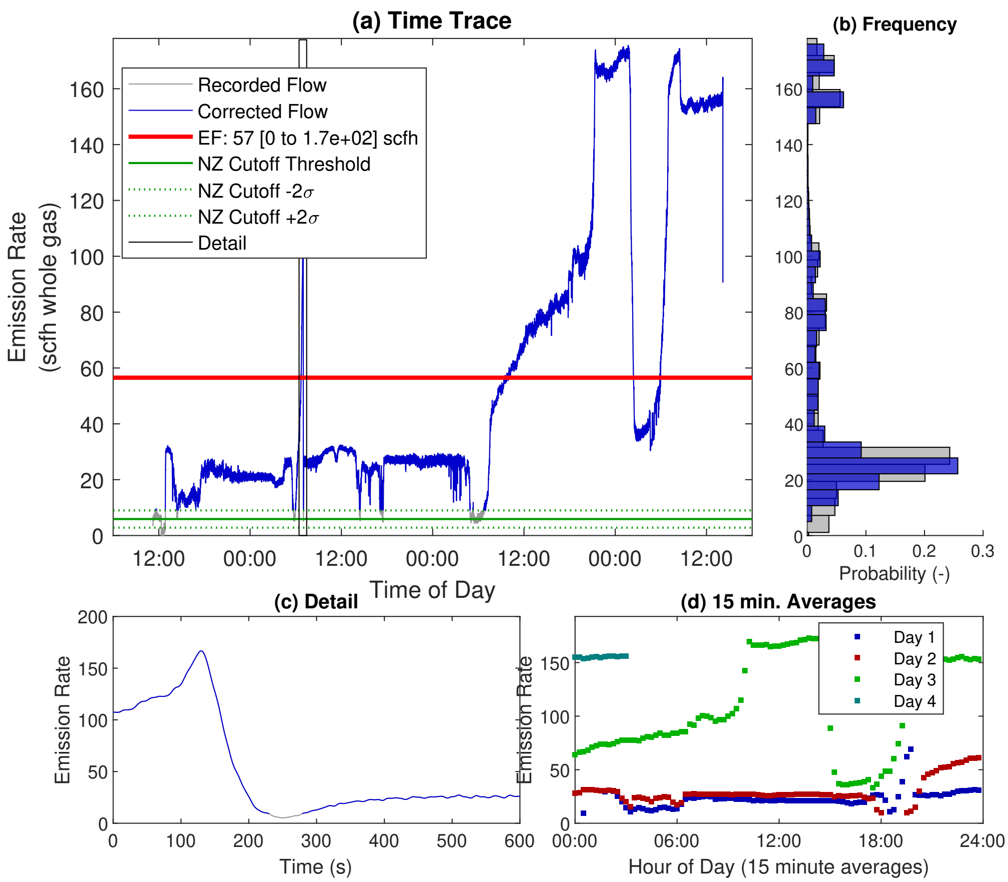

Figure A.23: Device N-3

Device N-6

Site Class: I	NEMS Region: Midcontinent
Install Location: Inline	Measurement Duration: 83.5 hrs
Controller Location: Yard Piping	Avg. Gas Temperature: 67 $^{\circ}F$
Process Controlled: Pressure	Avg. Supply Pressure: 31.9 psia
Controller Model: Moore IPX2	Gas Methane Fraction: 77.1%
EPA Bleed Type: Low Bleed	Emission Factor: 2.9 [1.3e-05 to 6.2]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Normally Operating	

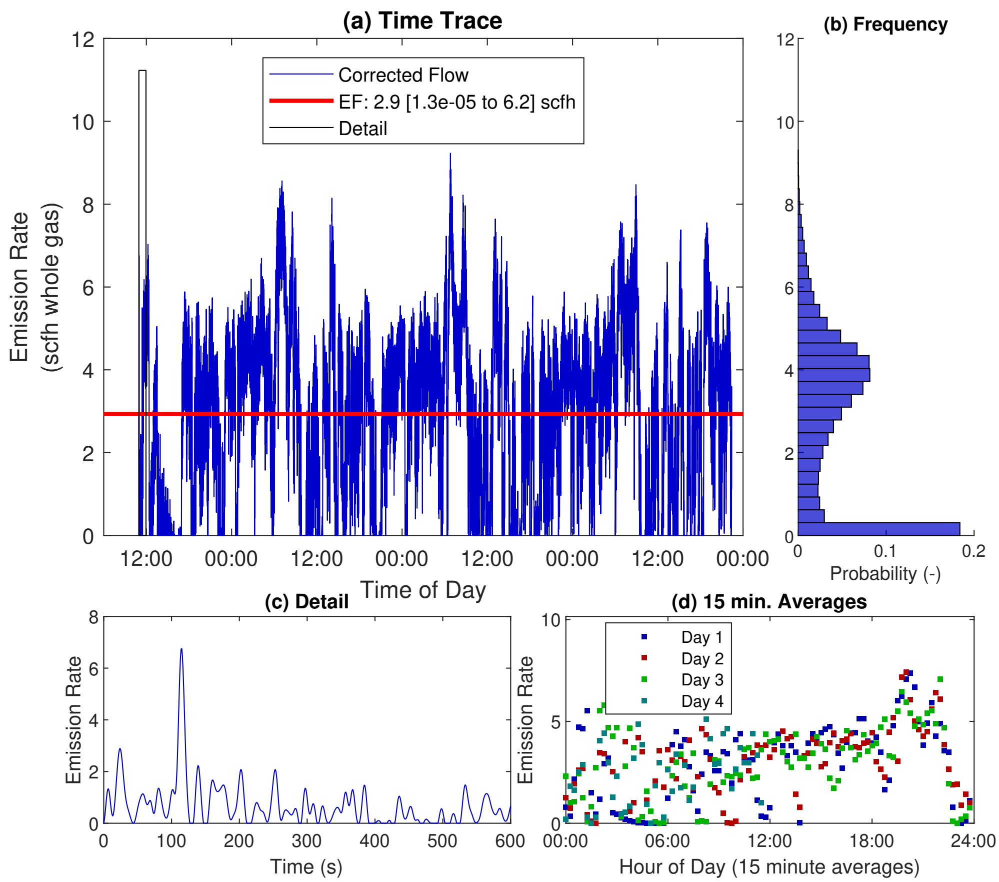

Figure A.24: Device N-6

Device O-1

Site Class: II	NEMS Region: Rocky Mountain
Install Location: Inline	Measurement Duration: 74.3 hrs
Controller Location: Separator	Avg. Gas Temperature: 19.9 $^{\circ}F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 29.4 psia
Controller Model: Solenoid Operated	Gas Methane Fraction: 89.5%
EPA Bleed Type: Intermittent	Emission Factor: 0.046 [0.0012 to 0.042]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Normally Operating	

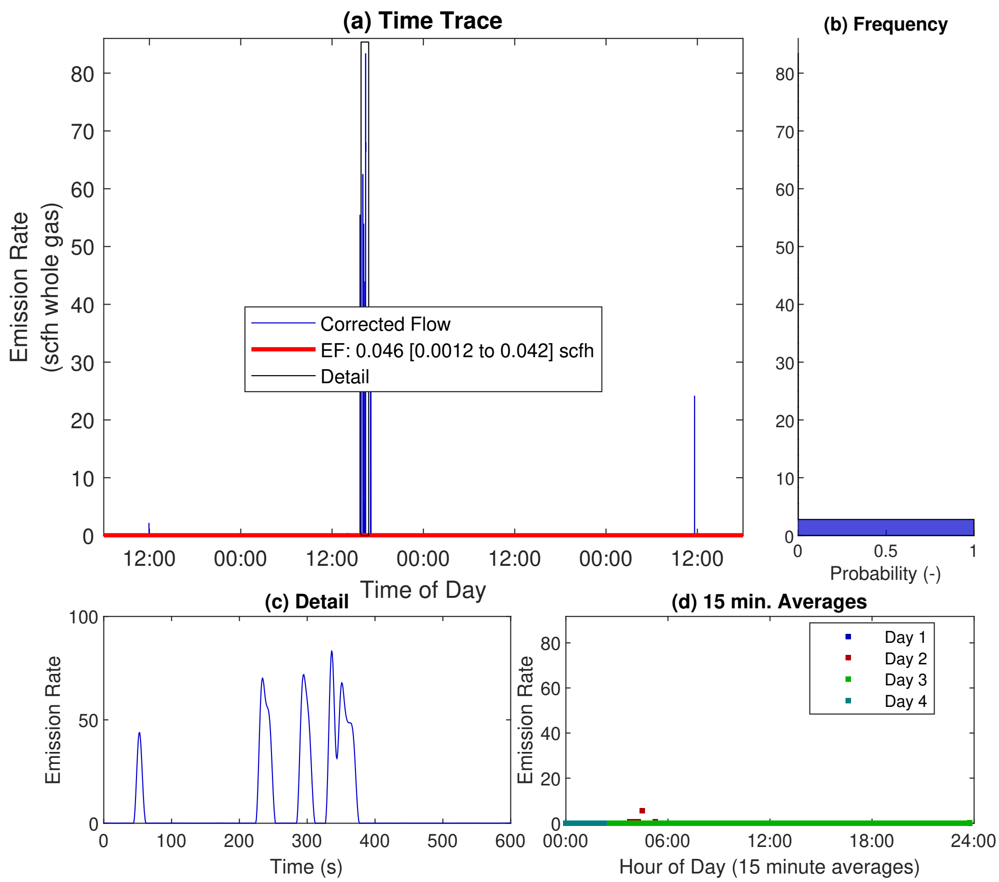

Figure A.25: Device O-1

Device O-2

Site Class: II	NEMS Region: Rocky Mountain
Install Location: Exhaust	Measurement Duration: 73.8 hrs
Controller Location: Yard Piping	Avg. Gas Temperature: 11.1 $^\circ F$
Process Controlled: Pressure	Avg. Supply Pressure: 12.1 psia
Controller Model: Fisher FieldVue DCV 6200	Gas Methane Fraction: 89.5%
EPA Bleed Type: Low Bleed	Emission Factor: 0.0051 [0.001 to 0.01]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Normally Operating	

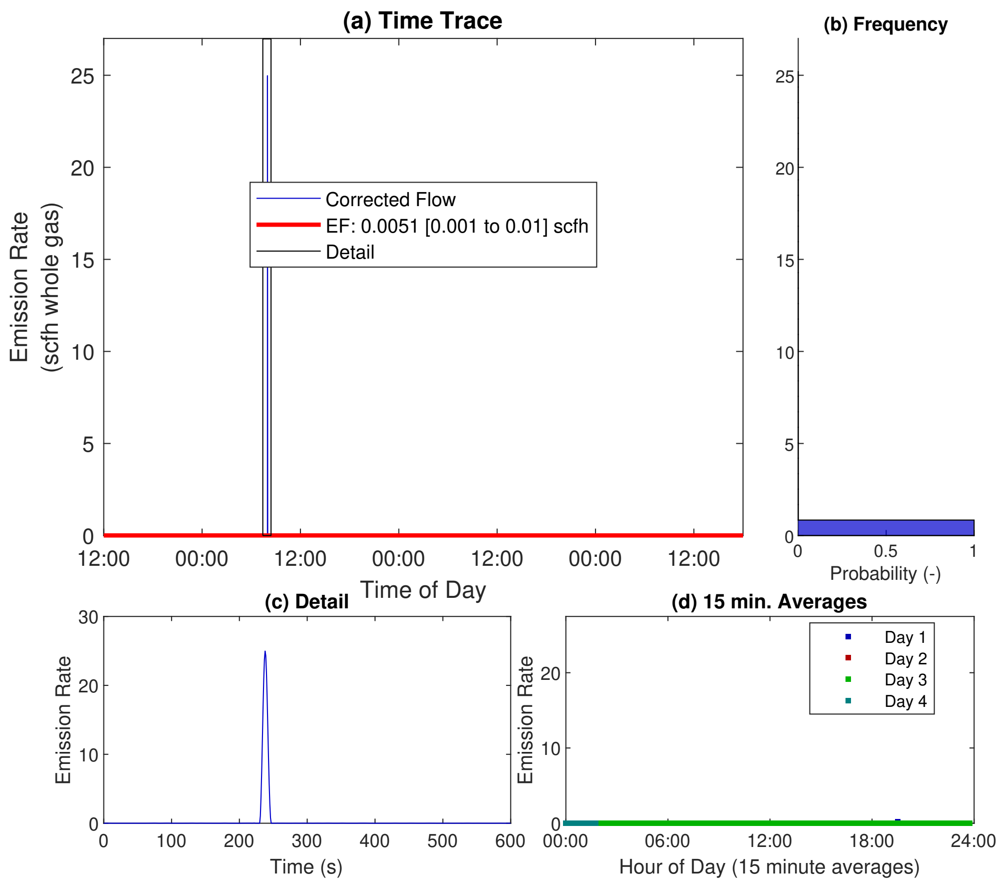

Figure A.26: Device O-2

Device O-3

Site Class: II	NEMS Region: Rocky Mountain
Install Location: Exhaust	Measurement Duration: 74 hrs
Controller Location: Yard Piping	Avg. Gas Temperature: 14 $^\circ F$
Process Controlled: Pressure	Avg. Supply Pressure: 12.2 psia
Controller Model: Fisher FieldVue DCV 6200	Gas Methane Fraction: 89.5%
EPA Bleed Type: Low Bleed	Emission Factor: 0.53 [0.0052 to 6.9]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Normally Operating	

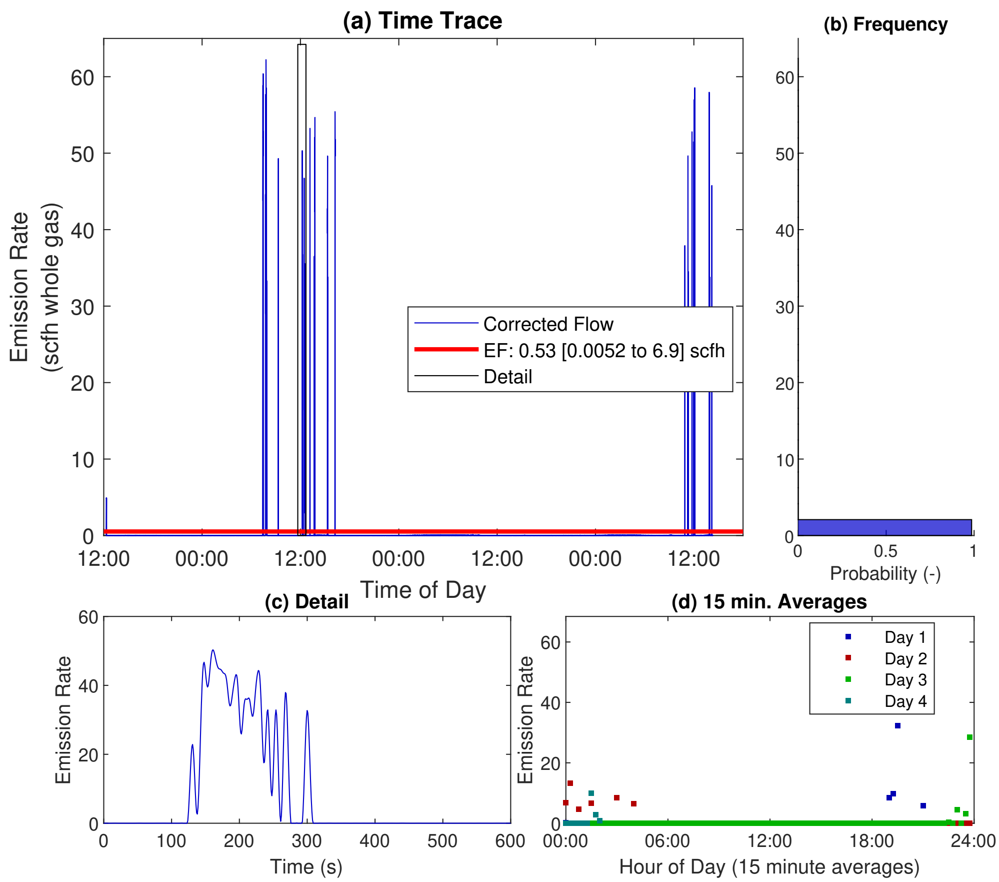

Figure A.27: Device O-3

Device Q-1

Site Class: III	NEMS Region: Southwest
Install Location: Exhaust	Measurement Duration: 101 hrs
Controller Location: Yard Piping	Avg. Gas Temperature: 74.6 $^{\circ}F$
Process Controlled: Pressure	Avg. Supply Pressure: 13.1 psia
Controller Model: Fisher FieldVue DCV 6200	Gas Methane Fraction: 80%
EPA Bleed Type: Low Bleed	Emission Factor: 0.043 [0.02 to 0.083]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Normally Operating	

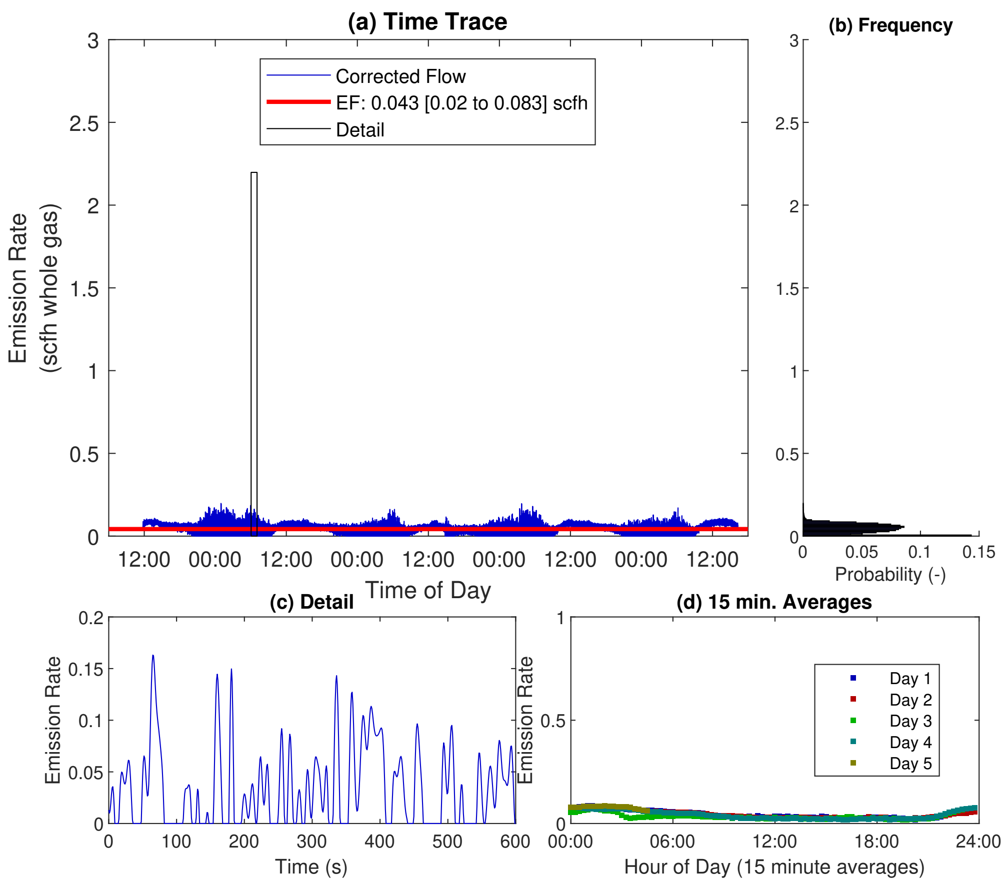

Figure A.28: Device Q-1

Device Q-4

Site Class: III	NEMS Region: Southwest
Install Location: Inline	Measurement Duration: 91.6 hrs
Controller Location: Compressor	Avg. Gas Temperature: 64.7 $^\circ F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 27.3 psia
Controller Model: Fisher 4160k	Gas Methane Fraction: 80%
EPA Bleed Type: High Bleed	Emission Factor: 25 [17 to 32]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Normally Operating	

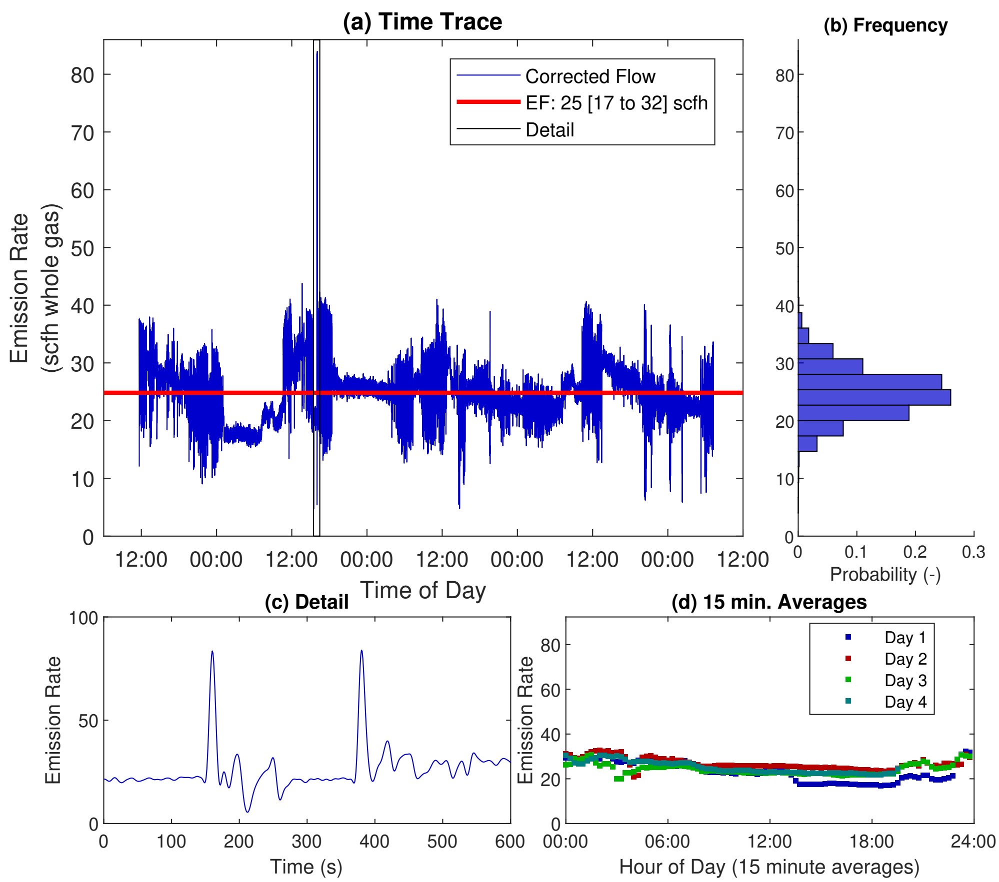

Figure A.29: Device Q-4

Device Q-6

Site Class: III	NEMS Region: Southwest
Install Location: Exhaust	Measurement Duration: 99.7 hrs
Controller Location: Yard Piping	Avg. Gas Temperature: 70.8 $^\circ F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 13.2 psia
Controller Model: Fisher FieldVue DCV 6200	Gas Methane Fraction: 80%
EPA Bleed Type: Low Bleed	Emission Factor: 0 [0 to 0]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Normally Operating	

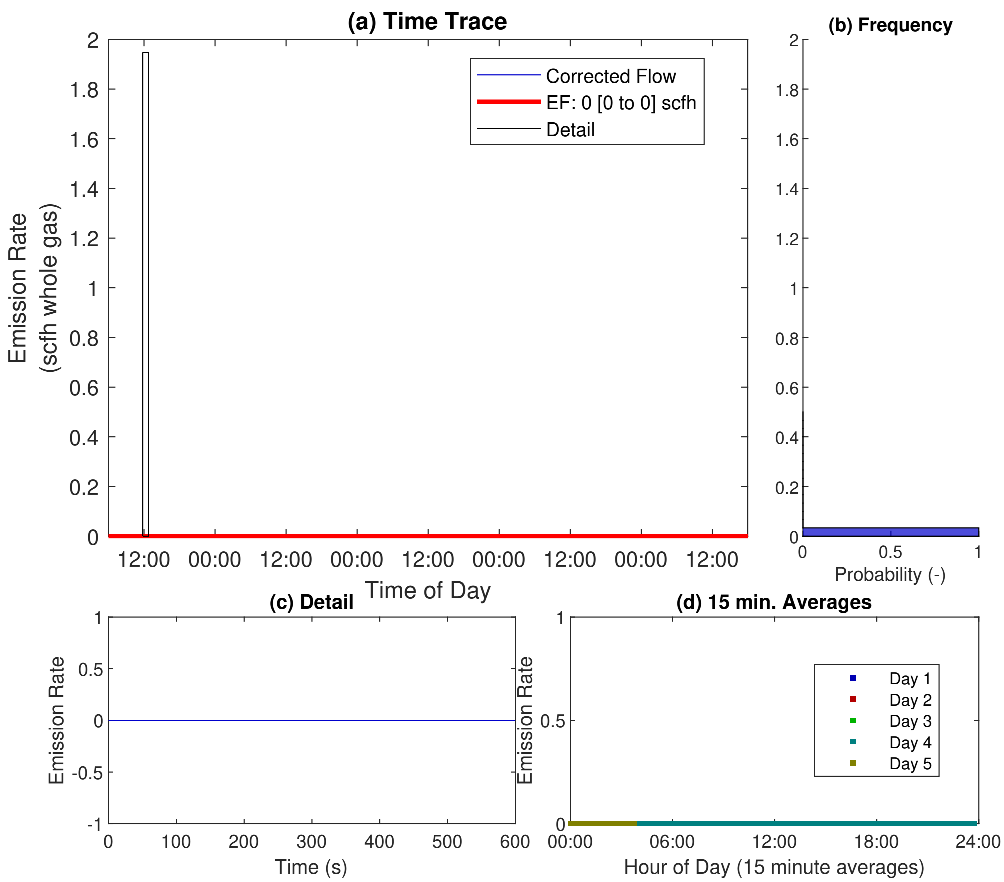

Figure A.30: Device Q-6

Device S-2

Site Class: I	NEMS Region: Midcontinent
Install Location: Exhaust	Measurement Duration: 97.8 hrs
Controller Location: Glycol Dehydrator	Avg. Gas Temperature: 62.7 $^\circ F$
Process Controlled: Temperature	Avg. Supply Pressure: 14.2 psia
Controller Model: Kimray T12	Gas Methane Fraction: 96.8%
EPA Bleed Type: Intermittent	Emission Factor: 1.3 [0.0092 to 38]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Abnormally Operating	

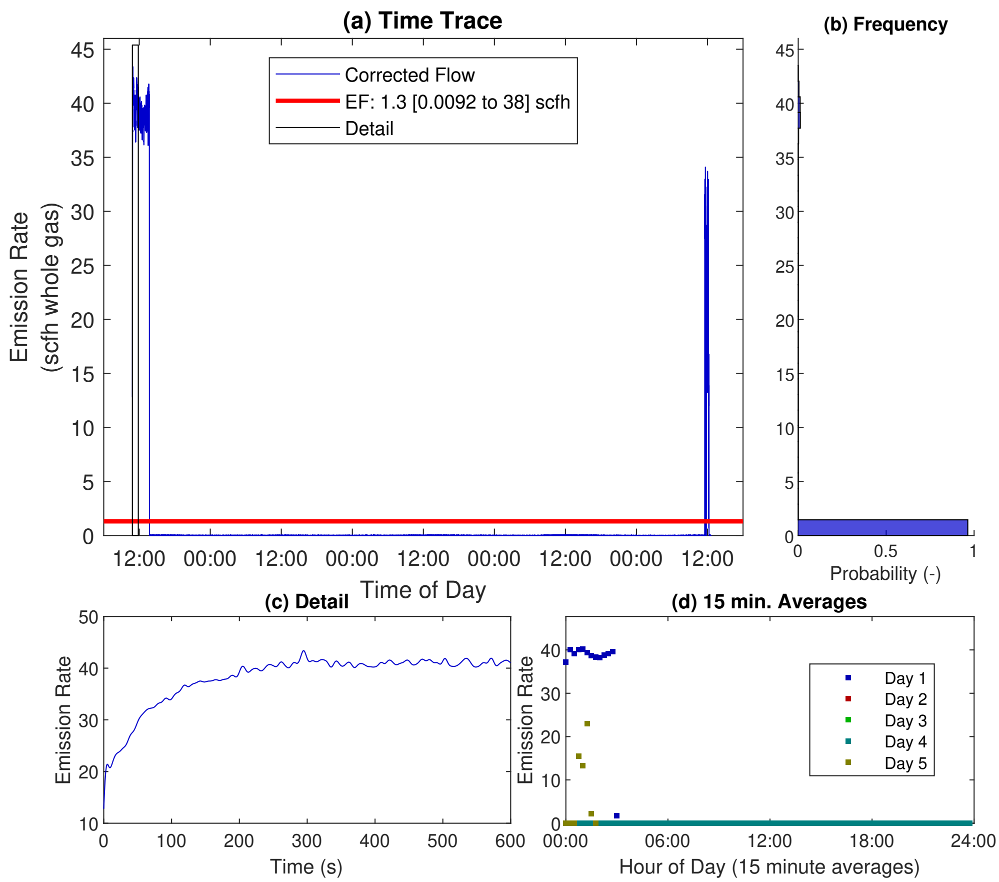

Figure A.31: Device S-2

Device S-6

Site Class: I	NEMS Region: Midcontinent
Install Location: Exhaust	Measurement Duration: 94.9 hrs
Controller Location: Glycol Dehydrator	Avg. Gas Temperature: 61.1 $^{\circ}F$
Process Controlled: Temperature	Avg. Supply Pressure: 14.3 psia
Controller Model: Kimray T12	Gas Methane Fraction: 96.8%
EPA Bleed Type: Intermittent	Emission Factor: 0.015 [0 to 0.0014]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Normally Operating	

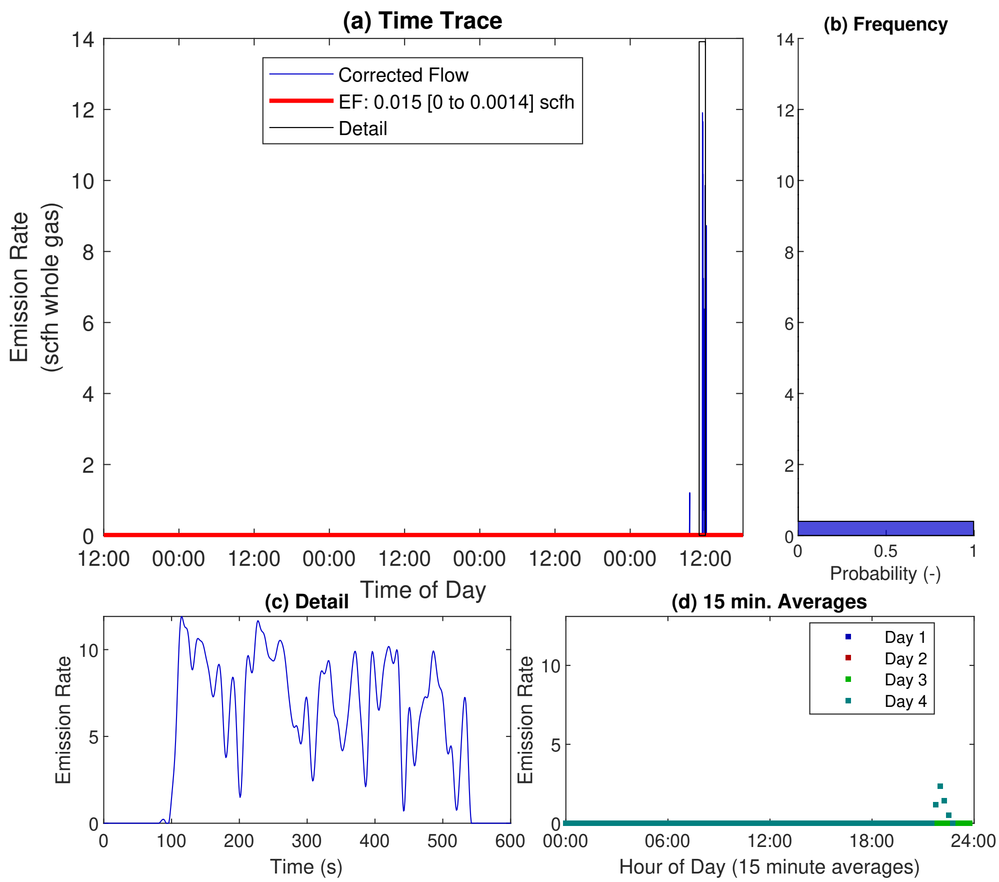

Figure A.32: Device S-6

Device T-2

Site Class: III	NEMS Region: Rocky Mountain
Install Location: Exhaust	Measurement Duration: 68.6 hrs
Controller Location: Yard Piping	Avg. Gas Temperature: 0.893 °F
Process Controlled: Pressure	Avg. Supply Pressure: 12.2 psia
Controller Model: Fisher FieldVue DCV 6200	Gas Methane Fraction: 89.5%
EPA Bleed Type: Low Bleed	Emission Factor: 4.4e-06 [0 to 4.4e-05]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Normally Operating	

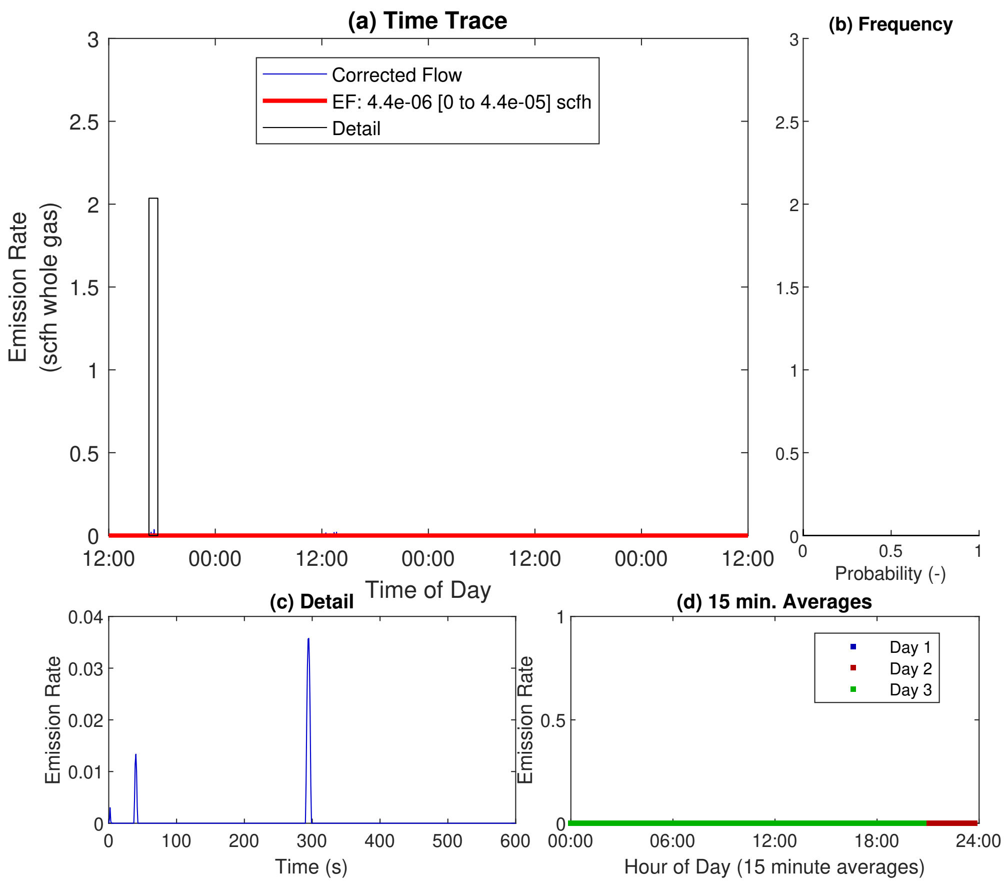

Figure A.33: Device T-2

Device U-2

Site Class: III	NEMS Region: Rocky Mountain
Install Location: Exhaust	Measurement Duration: 76.6 hrs
Controller Location: Yard Piping	Avg. Gas Temperature: 12.6 $^{\circ}F$
Process Controlled: Pressure	Avg. Supply Pressure: 12 psia
Controller Model: Fisher FieldVue DCV 6200	Gas Methane Fraction: 89.5%
EPA Bleed Type: Low Bleed	Emission Factor: 0.0048 [0.0015 to 0.011]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Normally Operating	

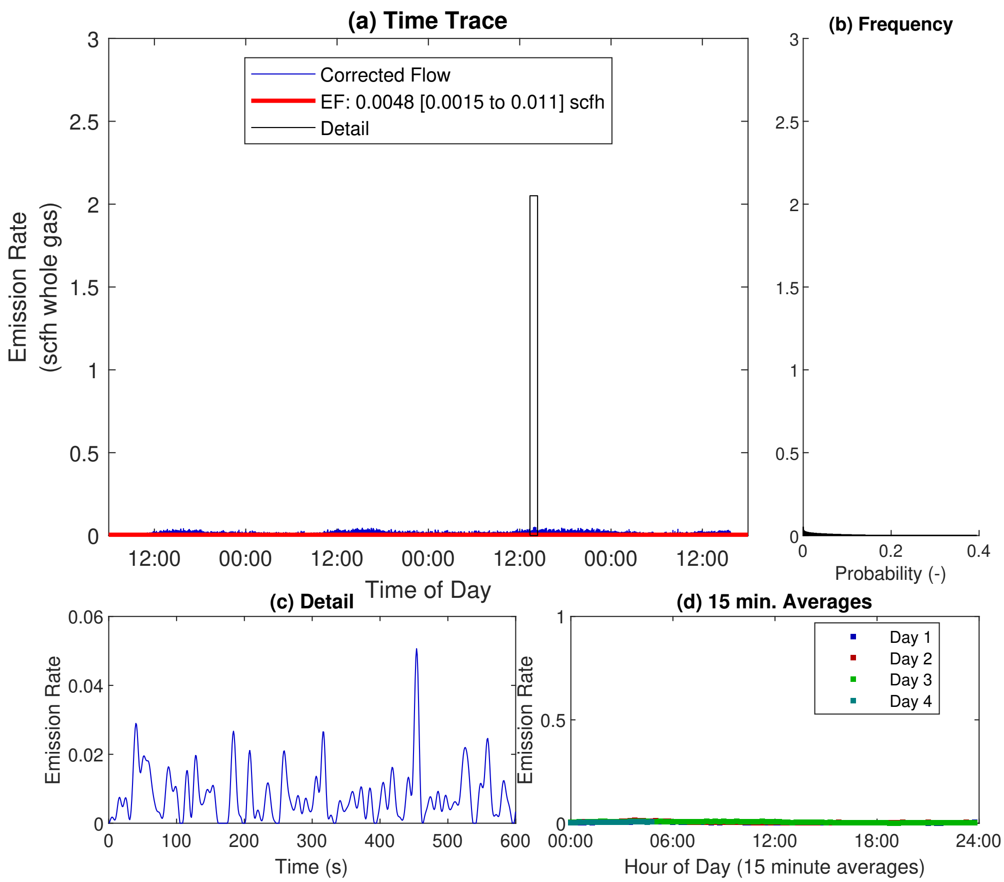

Figure A.34: Device U-2

Device U-3

Site Class: III	NEMS Region: Rocky Mountain
Install Location: Exhaust	Measurement Duration: 76.6 hrs
Controller Location: Yard Piping	Avg. Gas Temperature: 10.6 $^{\circ}F$
Process Controlled: Pressure	Avg. Supply Pressure: 12.2 psia
Controller Model: Fisher FieldVue DCV 6200	Gas Methane Fraction: 89.5%
EPA Bleed Type: Low Bleed	Emission Factor: 0.31 [0.006 to 0.034]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Normally Operating	

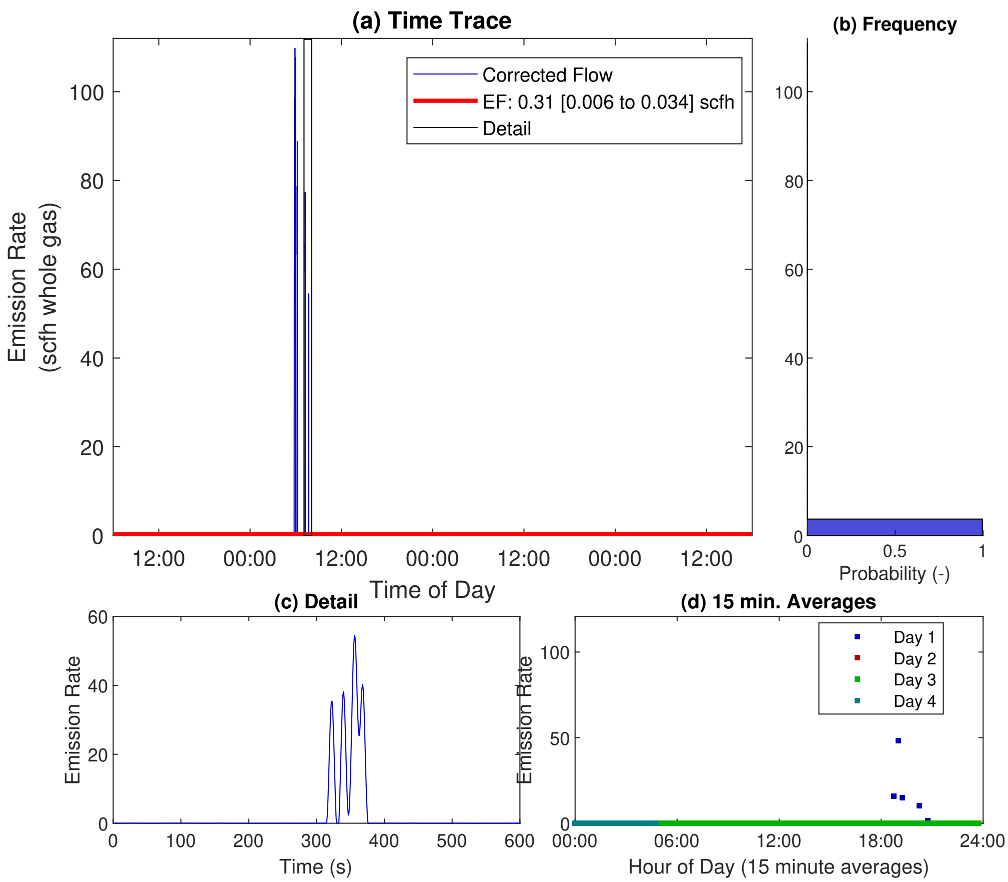

Figure A.35: Device U-3

Device V-1

Site Class: II	NEMS Region: Rocky Mountain
Install Location: Inline	Measurement Duration: 78.3 hrs
Controller Location: Yard Piping	Avg. Gas Temperature: 16.5 $^{\circ}F$
Process Controlled: Pressure	Avg. Supply Pressure: 30.1 psia
Controller Model: Fisher C1	Gas Methane Fraction: 75%
EPA Bleed Type: Low Bleed	Emission Factor: 0.027 [0 to 0.32]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Normally Operating	

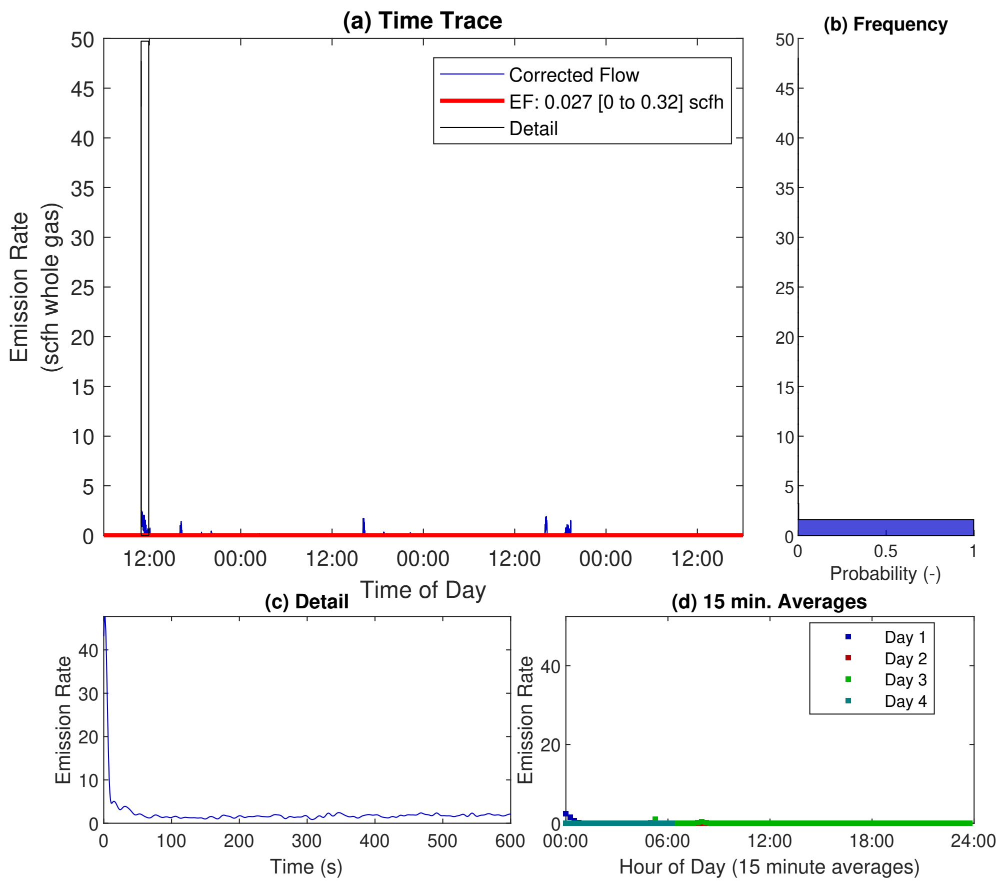

Figure A.36: Device V-1

Device V-4

Site Class: II	NEMS Region: Rocky Mountain
Install Location: Exhaust	Measurement Duration: 78.2 hrs
Controller Location: Separator	Avg. Gas Temperature: 42 $^{\circ}F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 12.4 psia
Controller Model: Murphy L1200N	Gas Methane Fraction: 75%
EPA Bleed Type: Intermittent	Emission Factor: 0.72 [0.014 to 2.7]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Normally Operating	

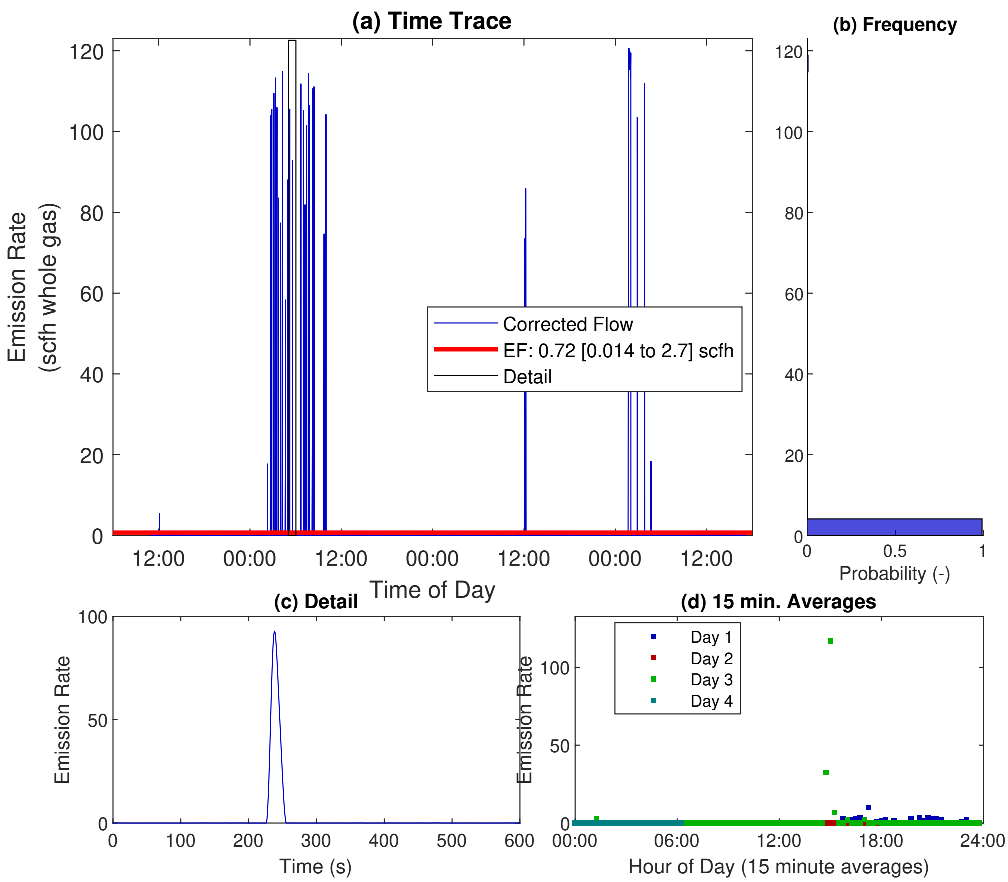

Figure A.37: Device V-4

Device Y-1

Site Class: I	NEMS Region: Appalachian
Install Location: Exhaust	Measurement Duration: 95.9 hrs
Controller Location: Yard Piping	Avg. Gas Temperature: 41.4 $^{\circ}F$
Process Controlled: Pressure	Avg. Supply Pressure: 14 psia
Controller Model: Fisher FieldVue DCV 6200	Gas Methane Fraction: 77.8%
EPA Bleed Type: Low Bleed	Emission Factor: 1.6 [0.0099 to 8.5]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Normally Operating	

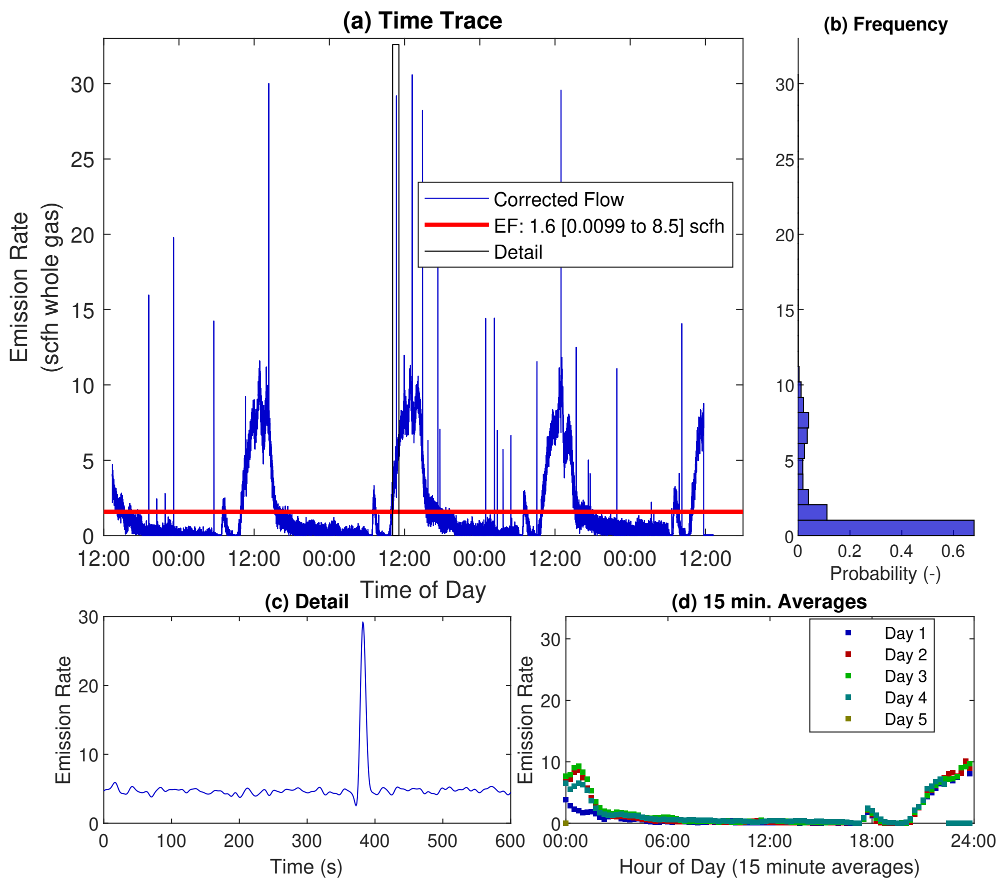

Figure A.38: Device Y-1

Device Y-2

Site Class: I	NEMS Region: Appalachian
Install Location: Exhaust	Measurement Duration: 92 hrs
Controller Location: Yard Piping	Avg. Gas Temperature: 27.2 $^\circ F$
Process Controlled: Pressure	Avg. Supply Pressure: 14 psia
Controller Model: Fisher FieldVue DCV 6200	Gas Methane Fraction: 77.8%
EPA Bleed Type: High Bleed	Emission Factor: 15 [12 to 18]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Normally Operating	

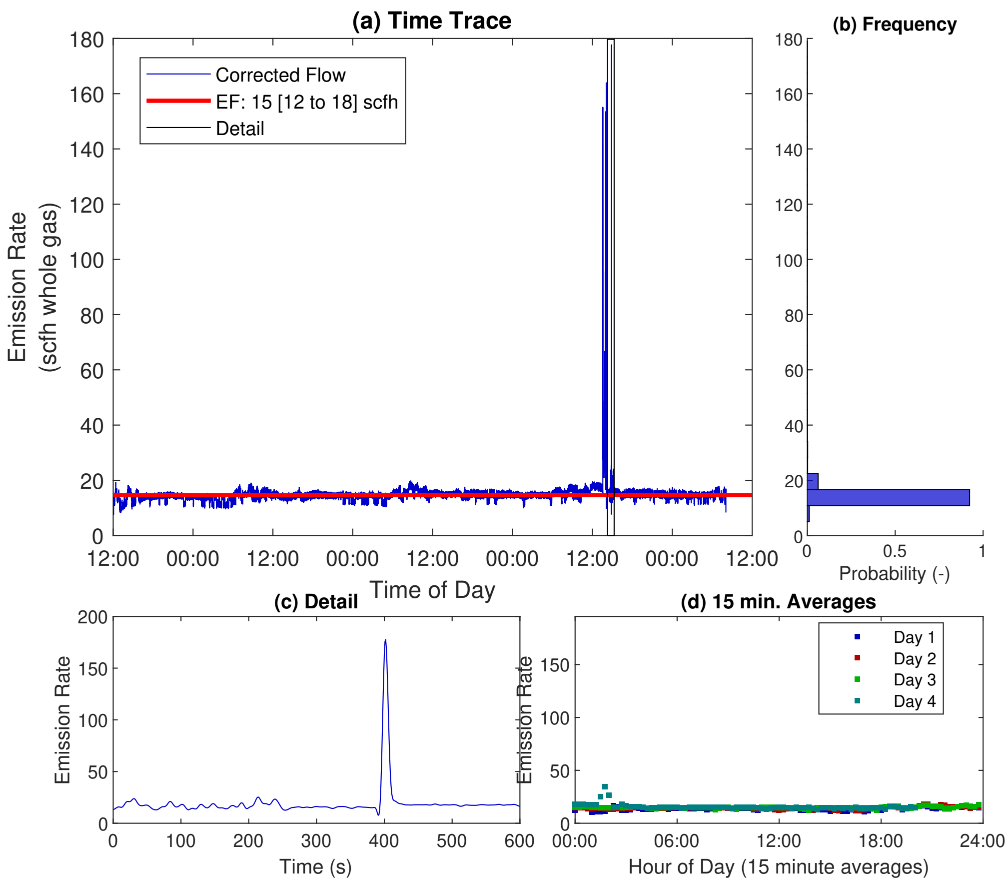

Figure A.39: Device Y-2

Device Y-4

Site Class: I	NEMS Region: Appalachian
Install Location: Exhaust	Measurement Duration: 101 hrs
Controller Location: Yard Piping	Avg. Gas Temperature: 30.5 $^\circ F$
Process Controlled: Pressure	Avg. Supply Pressure: 14.3 psia
Controller Model: Fisher C1	Gas Methane Fraction: 77.8%
EPA Bleed Type: Low Bleed	Emission Factor: 0.047 [0.015 to 0.085]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Normally Operating	

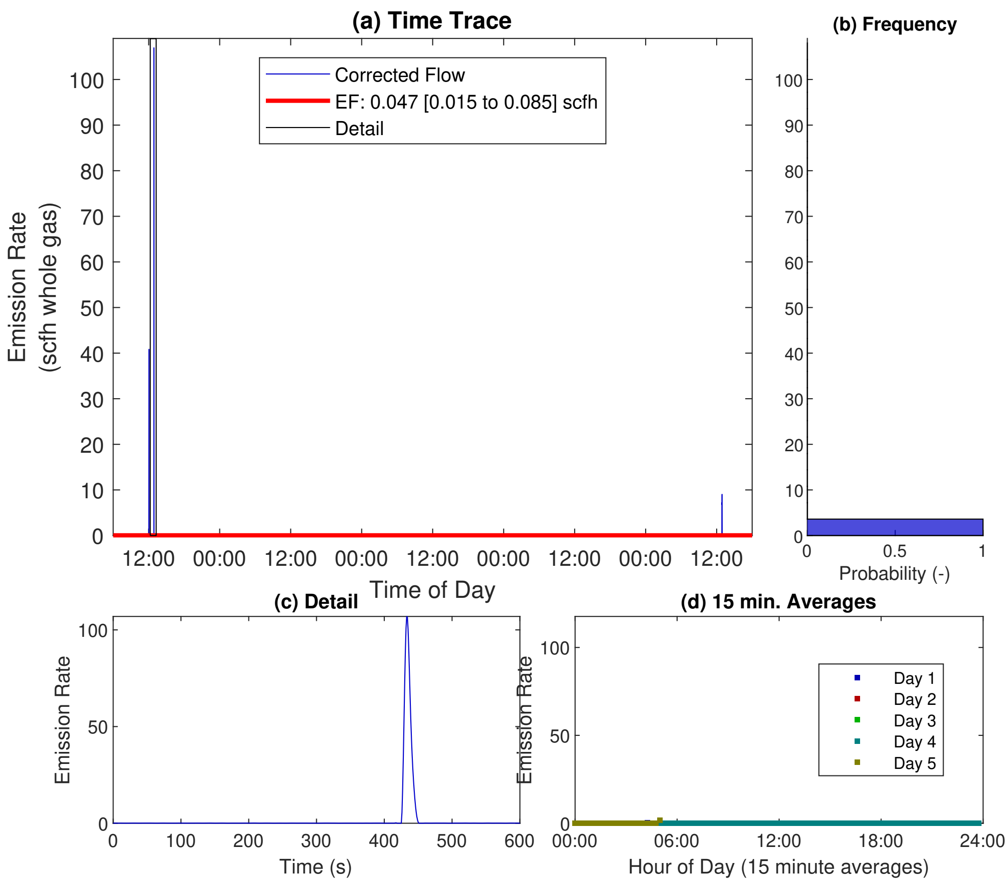

Figure A.40: Device Y-4

Device Y-5

Site Class: I	NEMS Region: Appalachian
Install Location: Exhaust	Measurement Duration: 94.8 hrs
Controller Location: Yard Piping	Avg. Gas Temperature: 23.4 $^{\circ}F$
Process Controlled: Pressure	Avg. Supply Pressure: 14.2 psia
Controller Model: Fisher FieldVue DCV 6200	Gas Methane Fraction: 77.8%
EPA Bleed Type: High Bleed	Emission Factor: 11 [9.7 to 13]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Normally Operating	

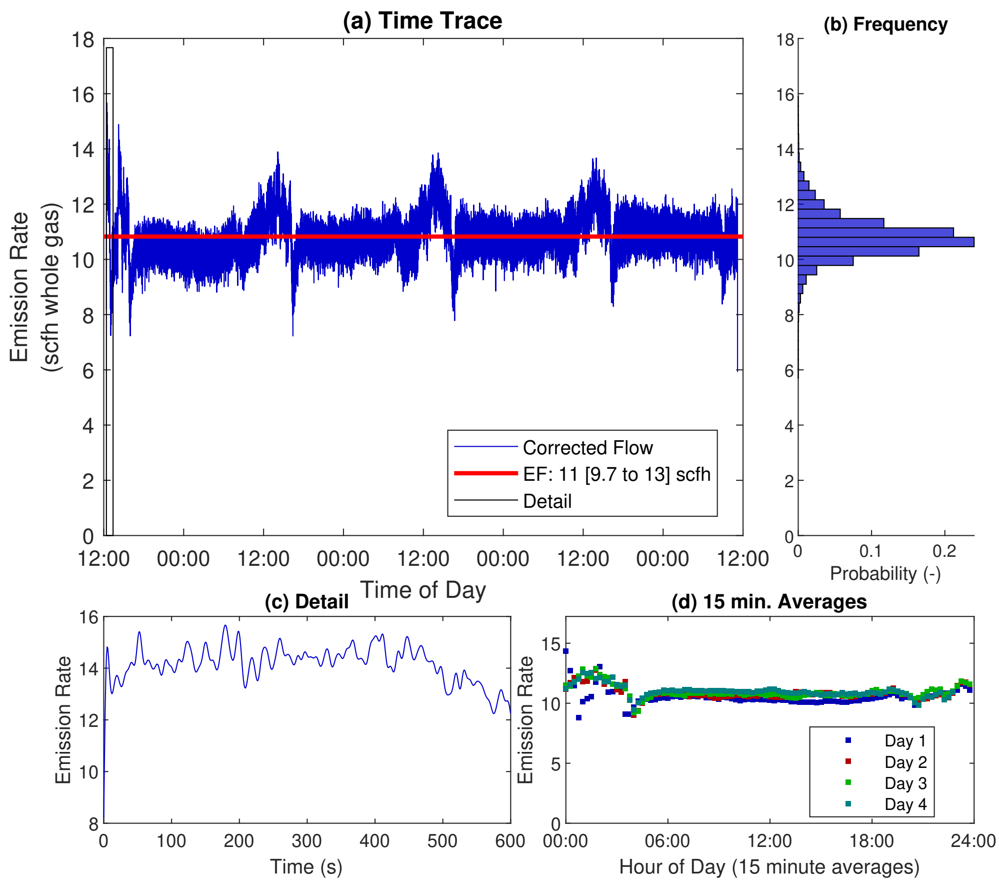

Figure A.41: Device Y-5

Device Y-6

Site Class: I	NEMS Region: Appalachian
Install Location: Exhaust	Measurement Duration: 90.9 hrs
Controller Location: Yard Piping	Avg. Gas Temperature: 24.9 °F
Process Controlled: Liquid Level	Avg. Supply Pressure: 14.1 psia
Controller Model: Fisher FieldVue DCV 6200	Gas Methane Fraction: 77.8%
EPA Bleed Type: High Bleed	Emission Factor: 12 [10 to 15]
Non-zero Correction:	NZ Cutoff: None
Samples Remaining: 100%	Emissions Remaining: 100%
Evaluation: Normally Operating	

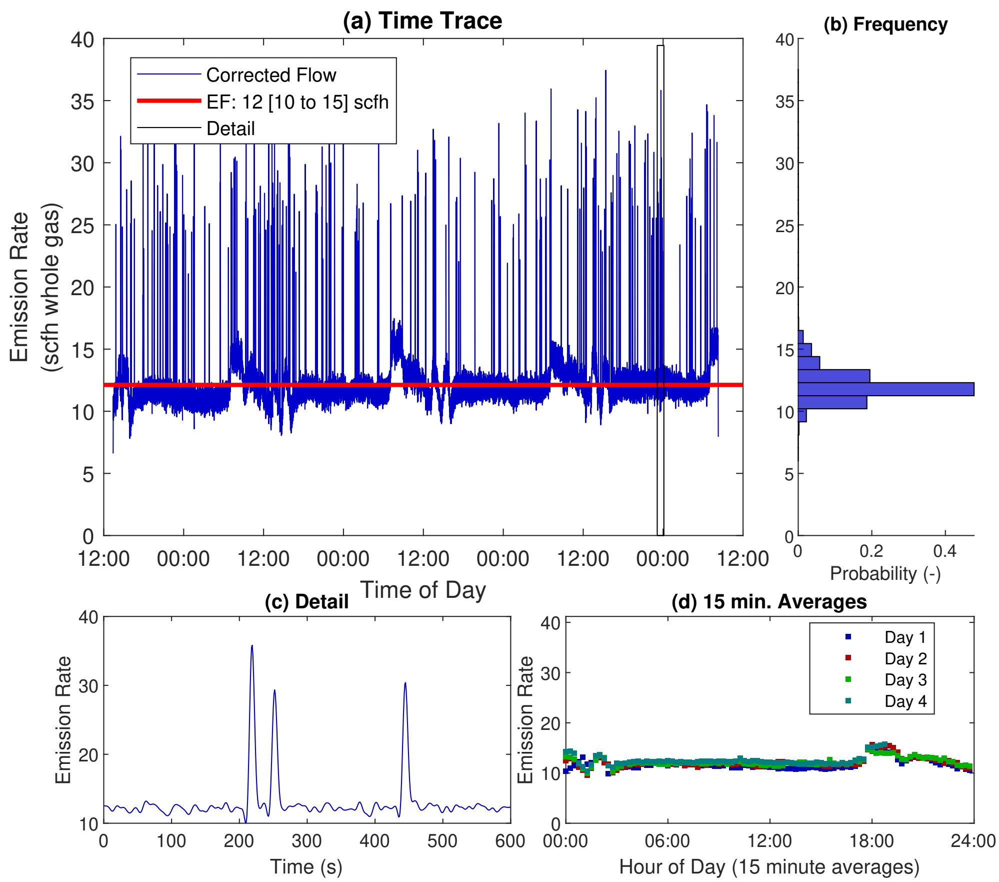

Figure A.42: Device Y-6

A.2 Low Impact

This section contains recordings that showed a clear NZ baseline, but average emission rates were decreased by <20% after applying the NZ correction.

Device D-2

Site Class: I	NEMS Region: Rocky Mountain
Install Location: Inline	Measurement Duration: 89.5 hrs
Controller Location: Compressor	Avg. Gas Temperature: 52 $^{\circ}F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 32.4 psia
Controller Model: Mallard, 3100-P1	Gas Methane Fraction: 99.2%
EPA Bleed Type: Intermittent	Emission Factor: 20 [9.2 to 32]
Non-zero Correction:	NZ Cutoff: 3.5 scfh
Samples Remaining: 73%	Emissions Remaining: 96%
Evaluation: Normally Operating	

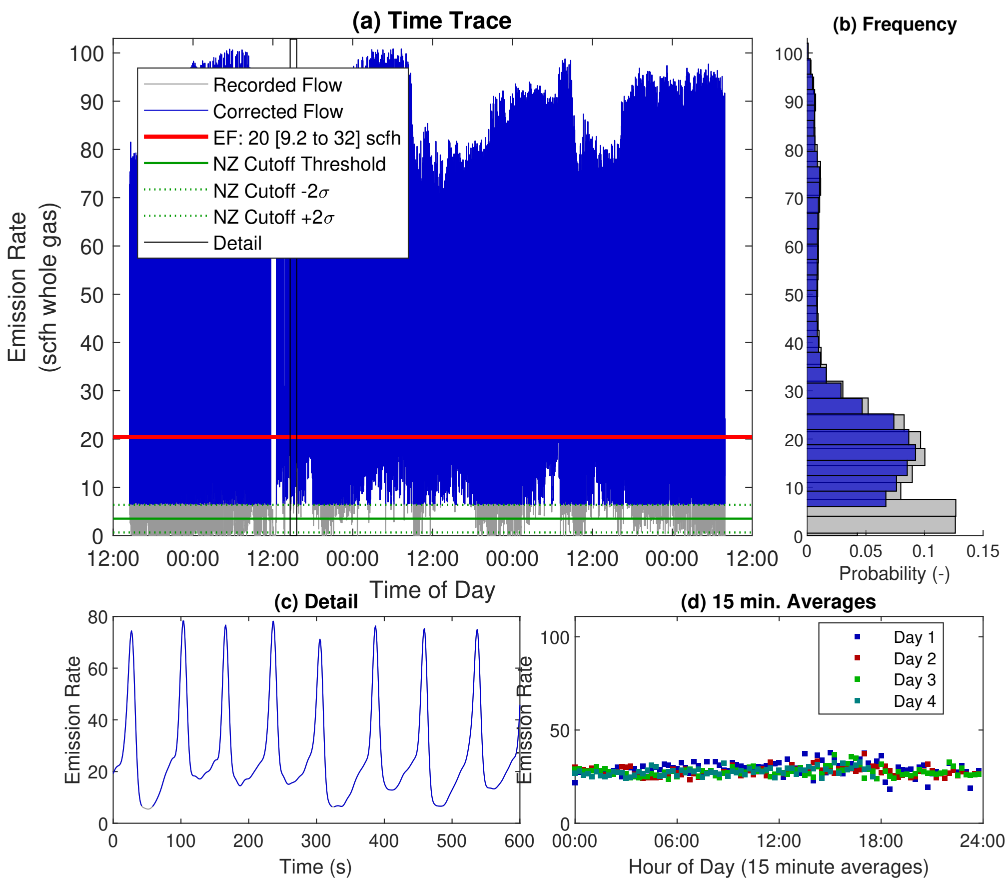

Figure A.43: Device D-2

Device D-3

Site Class: I	NEMS Region: Rocky Mountain
Install Location: Inline	Measurement Duration: 88.6 hrs
Controller Location: Compressor	Avg. Gas Temperature: 43.3 °F
Process Controlled: Pressure	Avg. Supply Pressure: 44.1 psia
Controller Model: Fisher C1	Gas Methane Fraction: 99.2%
EPA Bleed Type: Low Bleed	Emission Factor: 14 [0 to 23]
Non-zero Correction:	NZ Cutoff: 11.9 scfh
Samples Remaining: 77%	Emissions Remaining: 81%
Evaluation: Abnormally Operating	

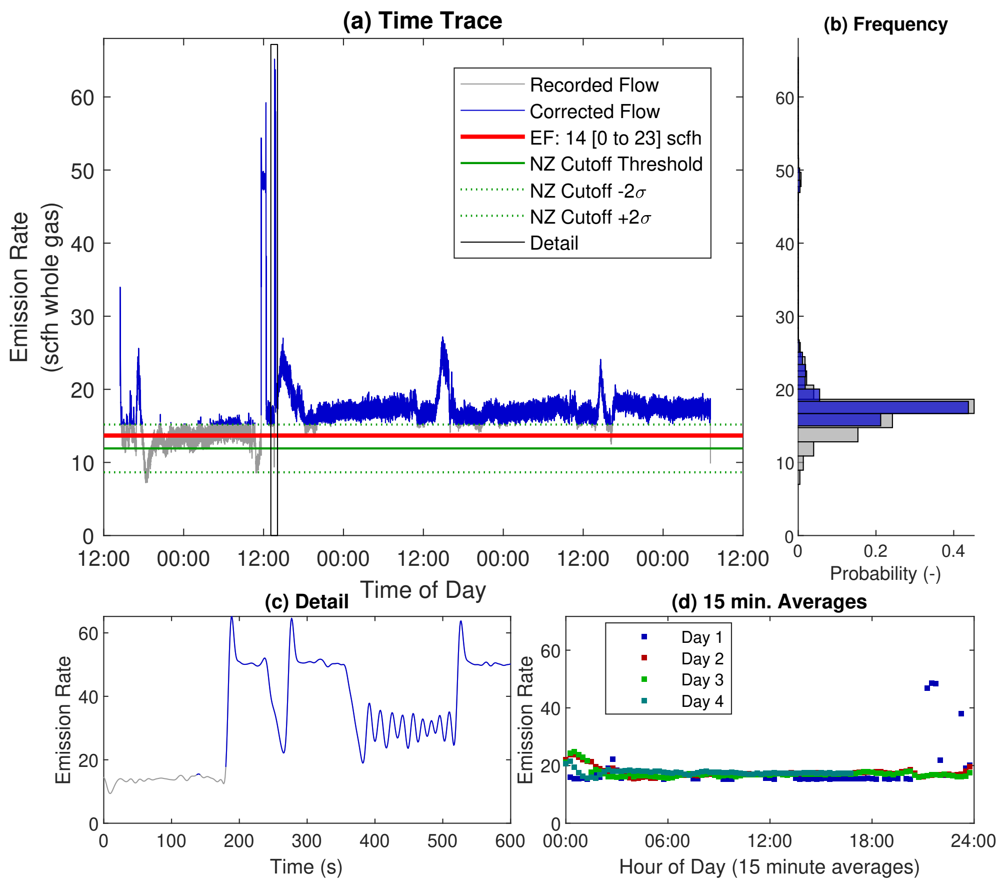

Figure A.44: Device D-3

Device H-1

Site Class: I	NEMS Region: Southwest
Install Location: Inline	Measurement Duration: 86.8 hrs
Controller Location: Compressor	Avg. Gas Temperature: 73 $^\circ F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 39.2 psia
Controller Model: Norriseal 1001A	Gas Methane Fraction: 70%
EPA Bleed Type: Intermittent	Emission Factor: 21 [0 to 42]
Non-zero Correction:	NZ Cutoff: 3.94 scfh
Samples Remaining: 42%	Emissions Remaining: 95%
Evaluation: Abnormally Operating	

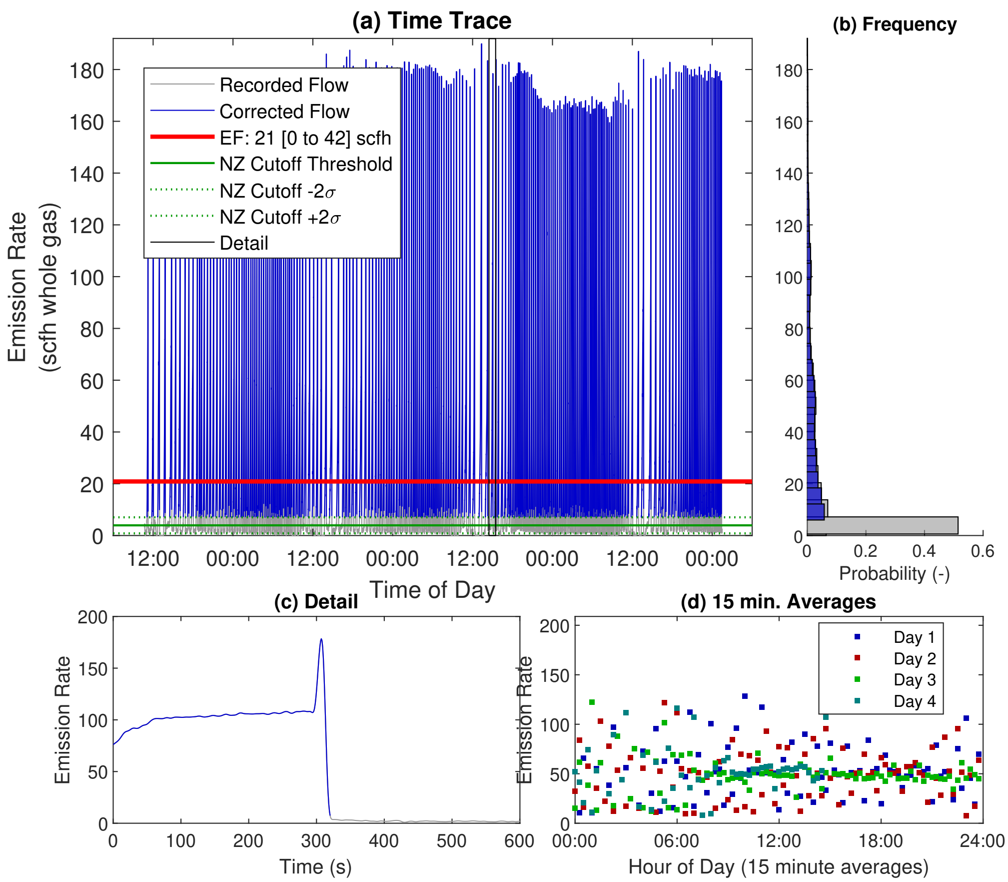

Figure A.45: Device H-1

Device S-4

Site Class: I	NEMS Region: Midcontinent
Install Location: Inline	Measurement Duration: 90.8 hrs
Controller Location: Glycol Dehydrator	Avg. Gas Temperature: 50.6 $^\circ F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 42.4 psia
Controller Model: Norriseal 1001A	Gas Methane Fraction: 96.8%
EPA Bleed Type: Intermittent	Emission Factor: 0.4 [0 to 0]
Non-zero Correction:	NZ Cutoff: 7.22 scfh
Samples Remaining: 1.8%	Emissions Remaining: 86%
Evaluation: Abnormally Operating	

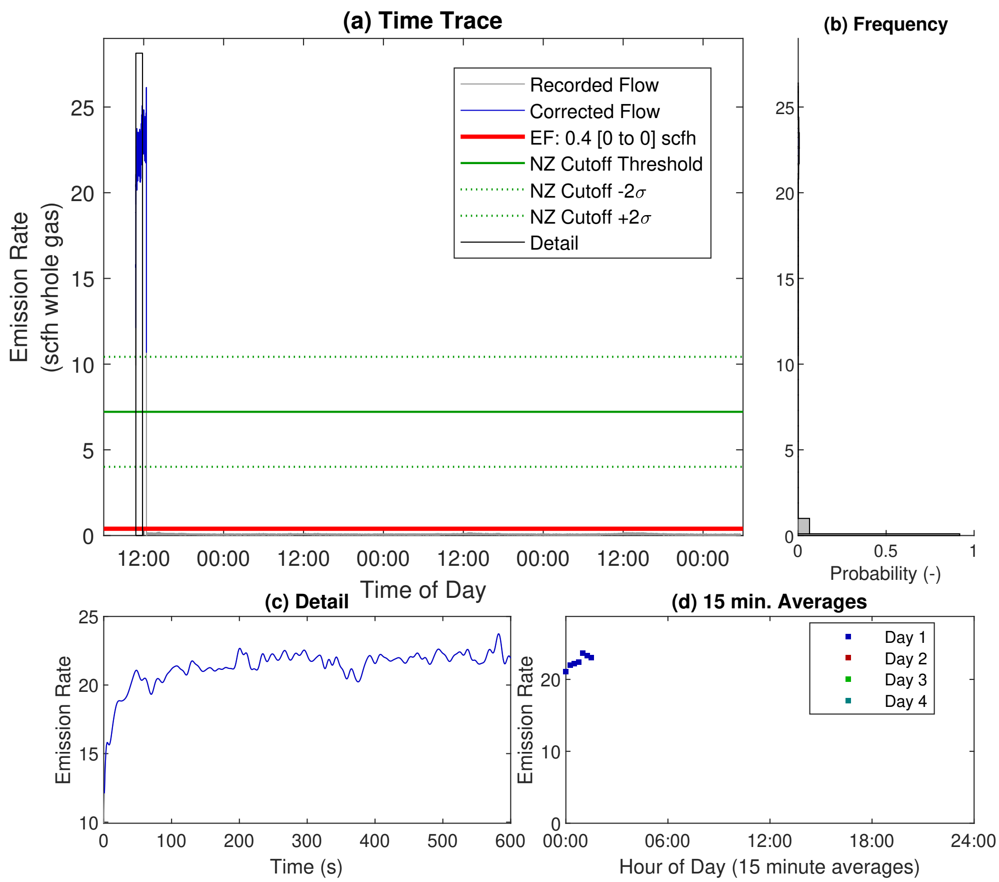

Figure A.46: Device S-4

Device T-4

Site Class: III	NEMS Region: Rocky Mountain
Install Location: Inline	Measurement Duration: 70.3 hrs
Controller Location: Compressor	Avg. Gas Temperature: 35.4 $^\circ F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 36.6 psia
Controller Model: Mallard 3200	Gas Methane Fraction: 89.5%
EPA Bleed Type: Intermittent	Emission Factor: 13 [0 to 84]
Non-zero Correction:	NZ Cutoff: 3.11 scfh
Samples Remaining: 31%	Emissions Remaining: 84%
Evaluation: Abnormally Operating	

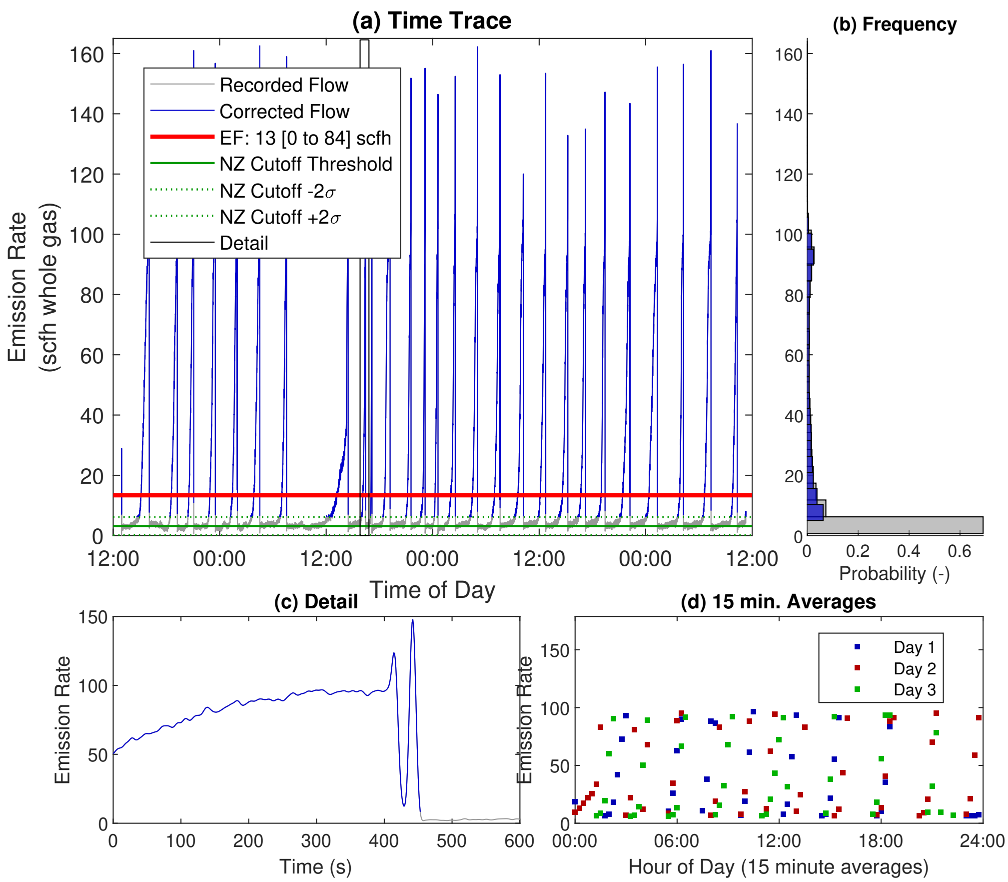

Figure A.47: Device T-4

Device U-5

Site Class: III	NEMS Region: Rocky Mountain
Install Location: Inline	Measurement Duration: 77 hrs
Controller Location: Compressor	Avg. Gas Temperature: 45.6 $^{\circ}F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 31.9 psia
Controller Model: Mallard 3200	Gas Methane Fraction: 89.5%
EPA Bleed Type: Intermittent	Emission Factor: 1.6 [0 to 25]
Non-zero Correction:	NZ Cutoff: 3.22 scfh
Samples Remaining: 4.7%	Emissions Remaining: 90%
Evaluation: Abnormally Operating	

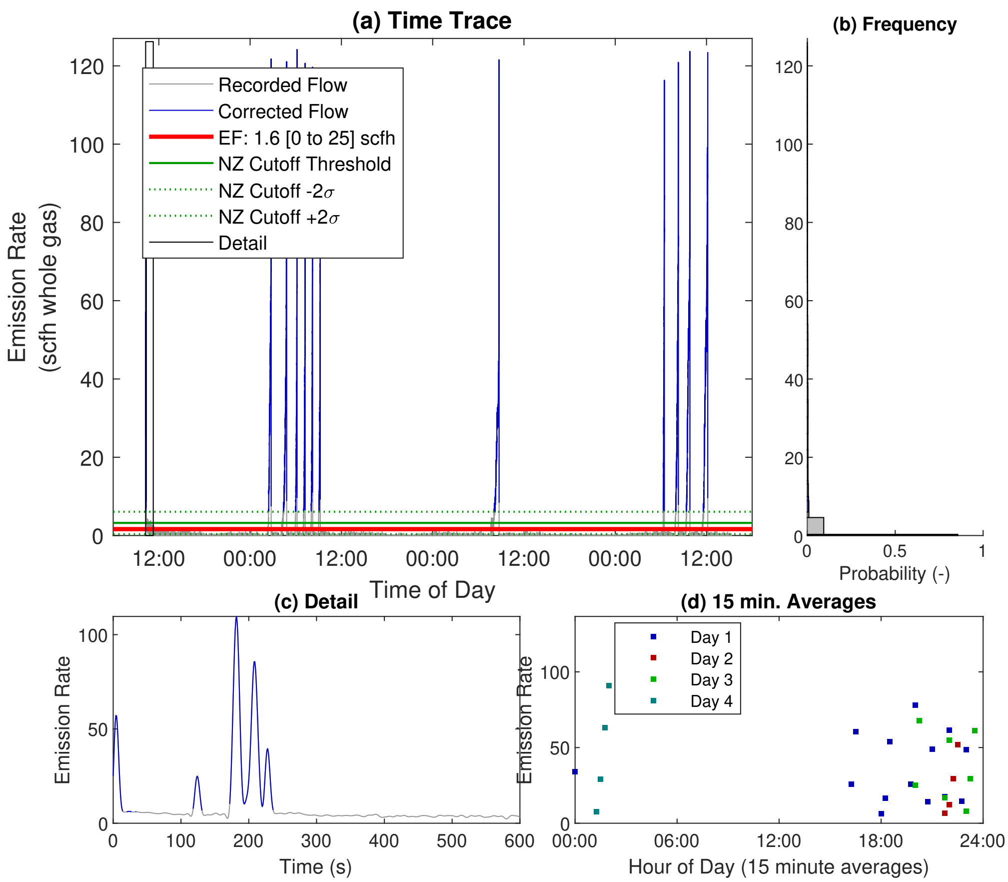

Figure A.48: Device U-5

Device V-6

Site Class: II	NEMS Region: Rocky Mountain
Install Location: Inline	Measurement Duration: 78.2 hrs
Controller Location: Separator	Avg. Gas Temperature: 21.5 $^\circ F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 48 psia
Controller Model: Murphy, L1200N	Gas Methane Fraction: 75%
EPA Bleed Type: Intermittent	Emission Factor: 25 [0 to 41]
Non-zero Correction:	NZ Cutoff: 20.8 scfh
Samples Remaining: 79%	Emissions Remaining: 85%
Evaluation: Abnormally Operating	

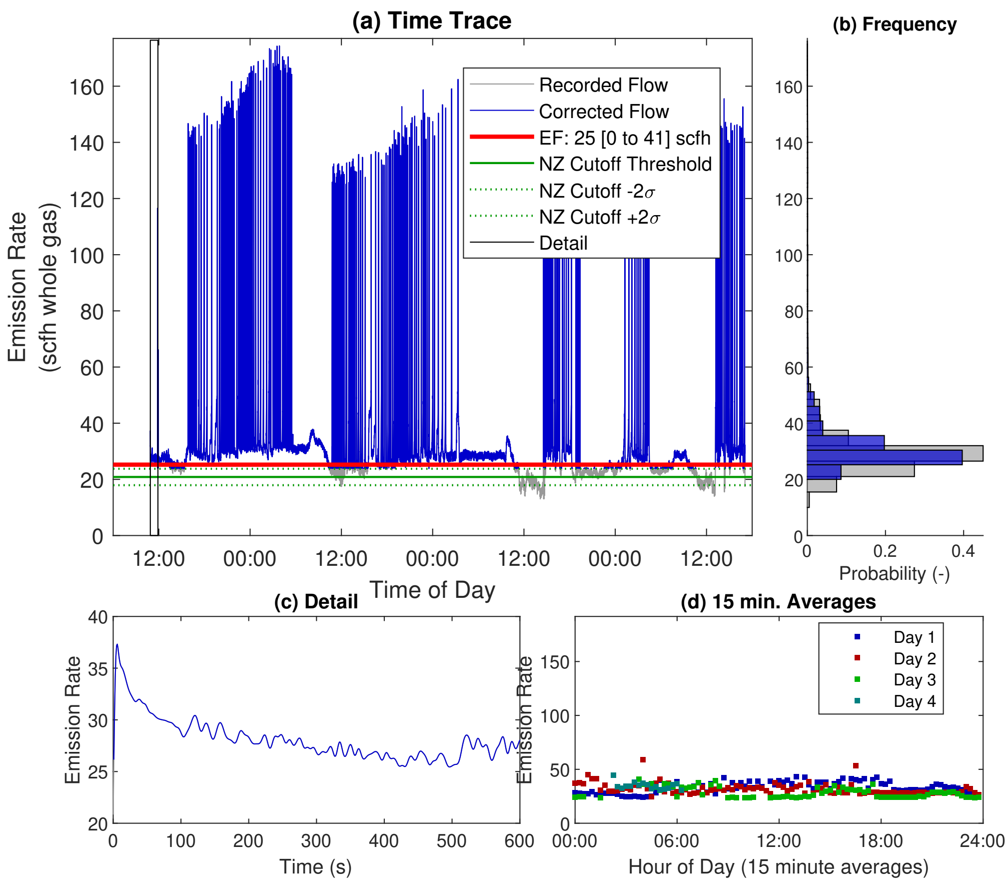

Figure A.49: Device V-6

A.3 High Impact

This section contains recordings that showed a clear NZ baseline and average emission rates were decreased by >20% after applying the NZ correction.

Device A-2

Site Class: II	NEMS Region: Southwest
Install Location: Inline	Measurement Duration: 69.8 hrs
Controller Location: Compressor	Avg. Gas Temperature: 52.8 °F
Process Controlled: Liquid Level	Avg. Supply Pressure: 34.7 psia
Controller Model: Murphy LS200N	Gas Methane Fraction: 92%
EPA Bleed Type: Intermittent	Emission Factor: 8.8 [0 to 24]
Non-zero Correction:	NZ Cutoff: 5.97 scfh
Samples Remaining: 32%	Emissions Remaining: 70%
Evaluation: Normally Operating	

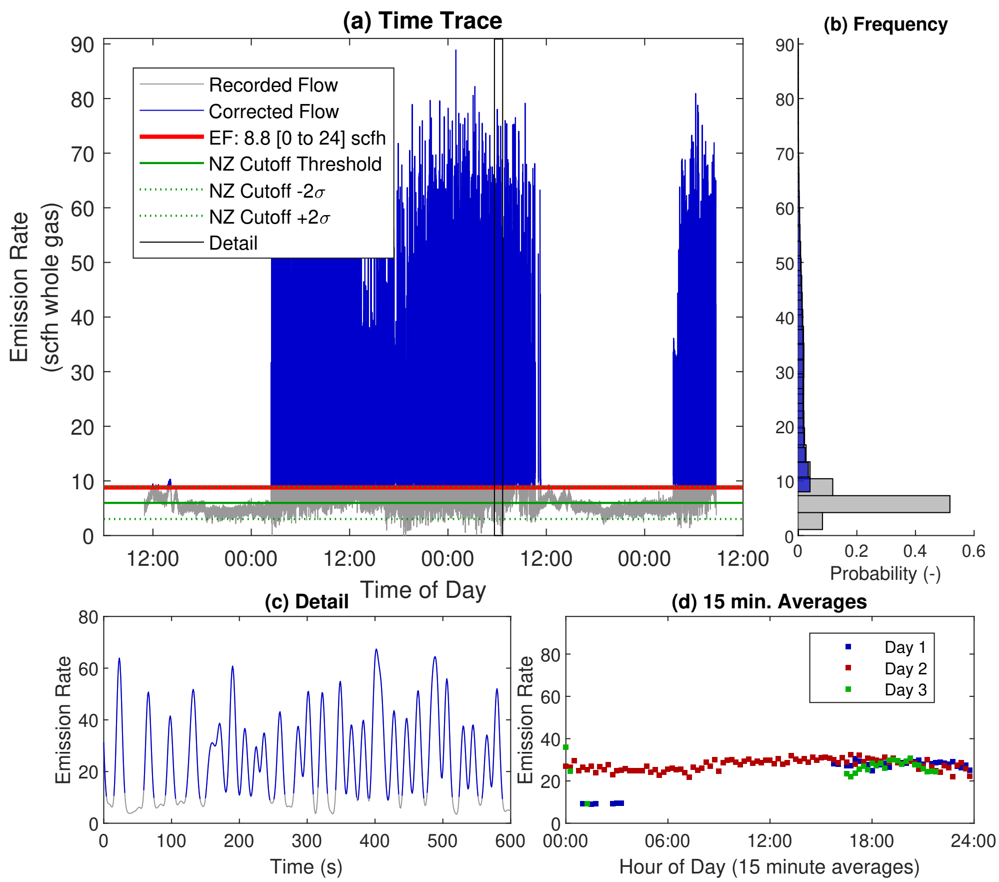

Figure A.50: Device A-2

Device A-3

Site Class: II	NEMS Region: Southwest
Install Location: Inline	Measurement Duration: 69.9 hrs
Controller Location: Glycol Dehydrator	Avg. Gas Temperature: 41 $^\circ F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 37.5 psia
Controller Model: Wellmark 2100NB	Gas Methane Fraction: 92%
EPA Bleed Type: Intermittent	Emission Factor: 3.5 [0 to 7.4]
Non-zero Correction:	NZ Cutoff: 3.96 scfh
Samples Remaining: 40%	Emissions Remaining: 58%
Evaluation: Abnormally Operating	

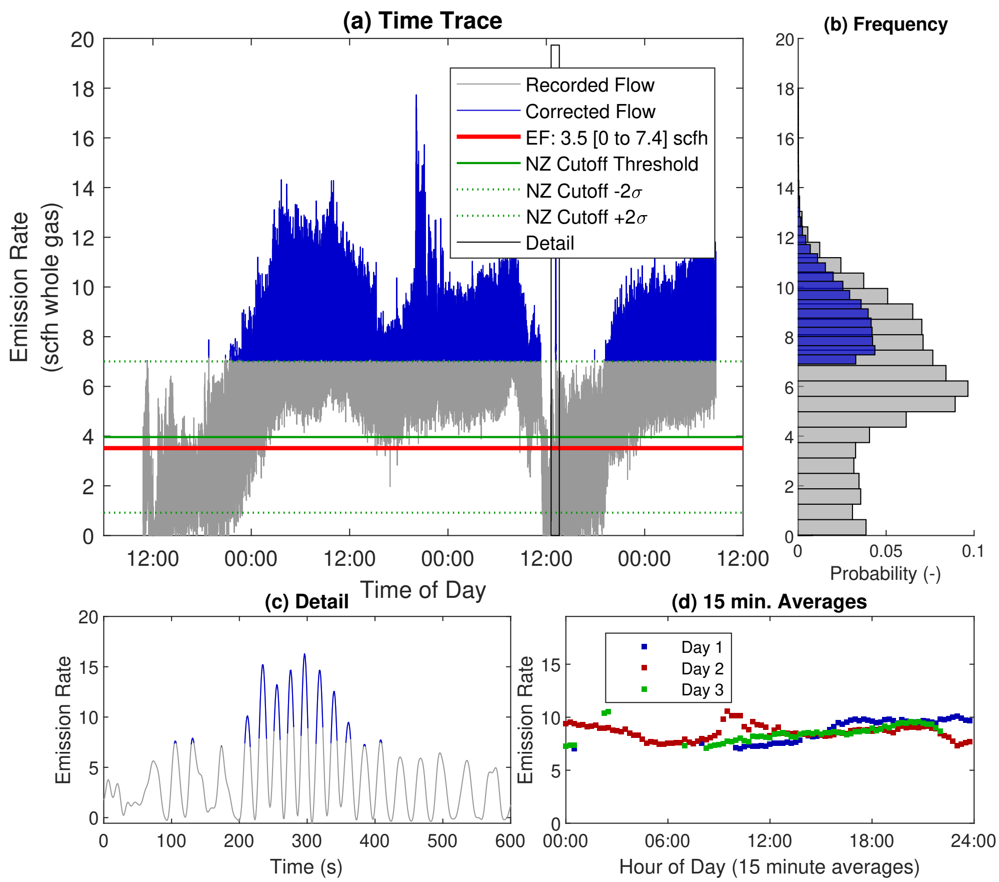

Figure A.51: Device A-3

Device A-4

Site Class: II	NEMS Region: Southwest
Install Location: Inline	Measurement Duration: 69.1 hrs
Controller Location: Compressor	Avg. Gas Temperature: 44.4 $^{\circ}F$
Process Controlled: Pressure	Avg. Supply Pressure: 52 psia
Controller Model: Kimray 30 HPG D	Gas Methane Fraction: 92%
EPA Bleed Type: Intermittent	Emission Factor: 15 [0 to 39]
Non-zero Correction:	NZ Cutoff: 14 scfh
Samples Remaining: 60%	Emissions Remaining: 73%
Evaluation: Abnormally Operating	

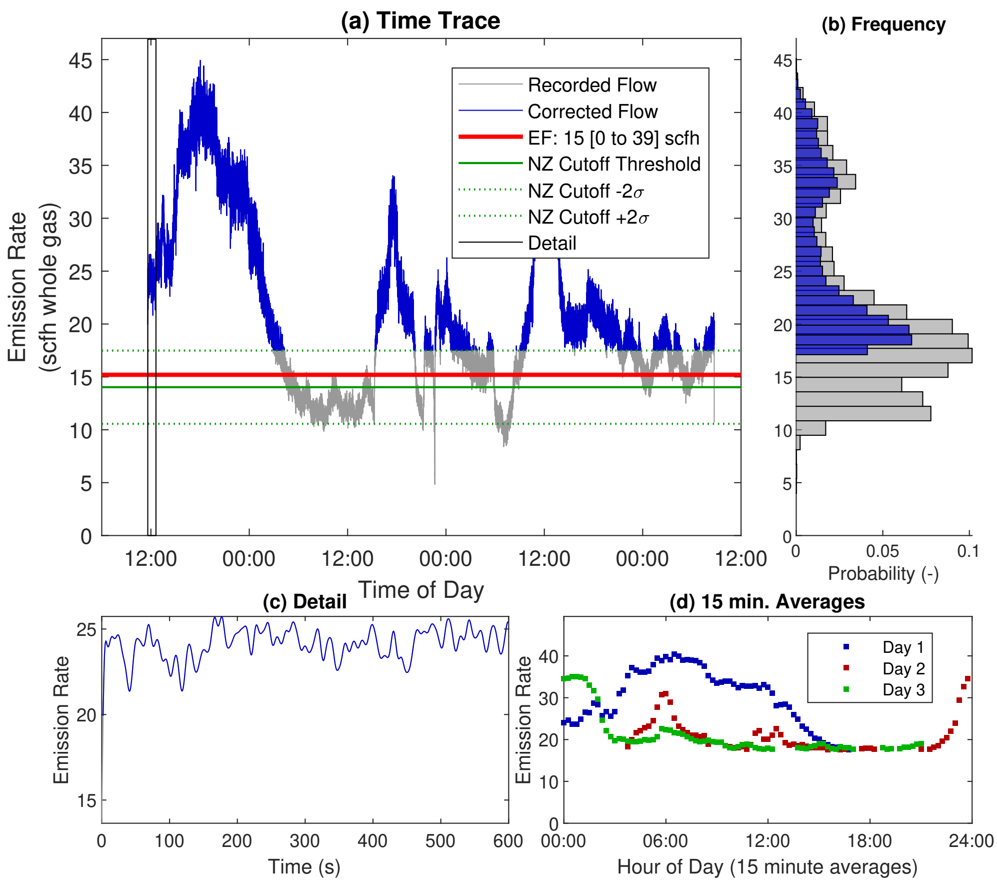

Figure A.52: Device A-4

Device A-6

Site Class: II	NEMS Region: Southwest
Install Location: Inline	Measurement Duration: 69.2 hrs
Controller Location: Compressor	Avg. Gas Temperature: 45.2 $^\circ F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 34.9 psia
Controller Model: Murphy, LS200N	Gas Methane Fraction: 92%
EPA Bleed Type: Intermittent	Emission Factor: 8.7 [0 to 34]
Non-zero Correction:	NZ Cutoff: 3.67 scfh
Samples Remaining: 29%	Emissions Remaining: 73%
Evaluation: Normally Operating	

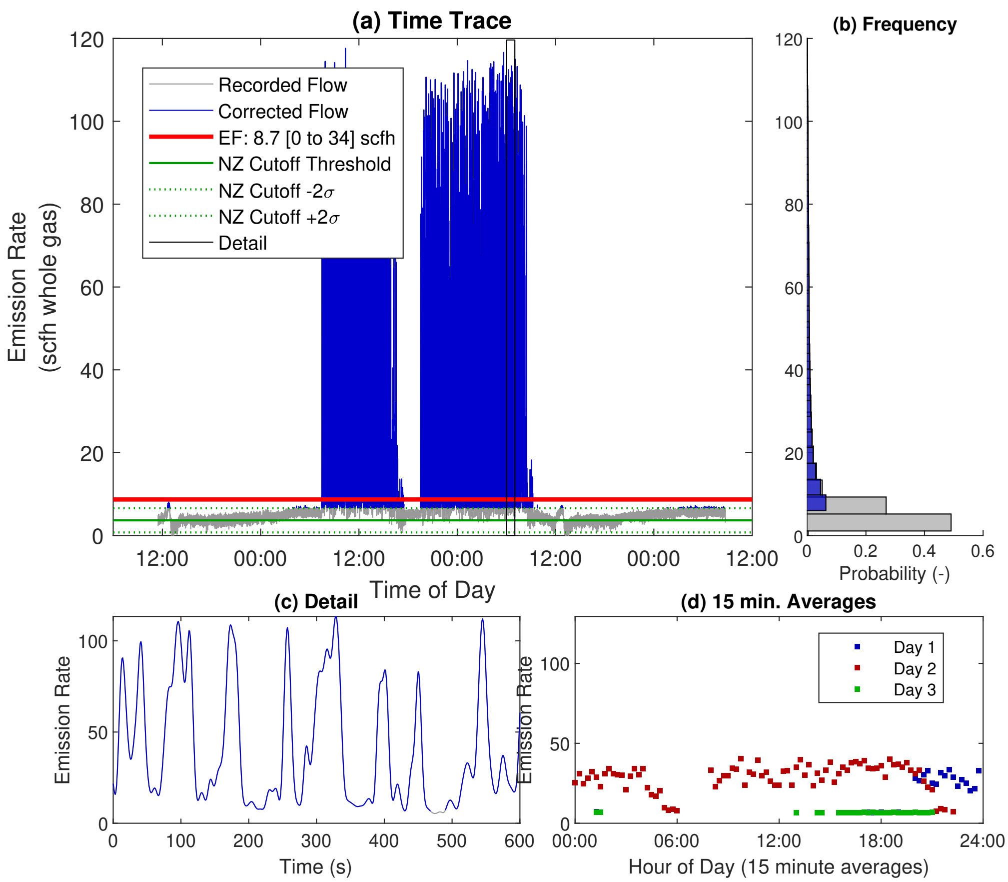

Figure A.53: Device A-6

Device G-5

Site Class: II	NEMS Region: Gulf Coast
Install Location: Inline	Measurement Duration: 49.7 hrs
Controller Location: Separator	Avg. Gas Temperature: 36.8 $^\circ F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 41.3 psia
Controller Model: Norriseal 1001, 25M60N	Gas Methane Fraction: 94.5%
EPA Bleed Type: Intermittent	Emission Factor: 2 [0 to 33]
Non-zero Correction:	NZ Cutoff: 12.1 scfh
Samples Remaining: 3.2%	Emissions Remaining: 17%
Evaluation: Abnormally Operating	

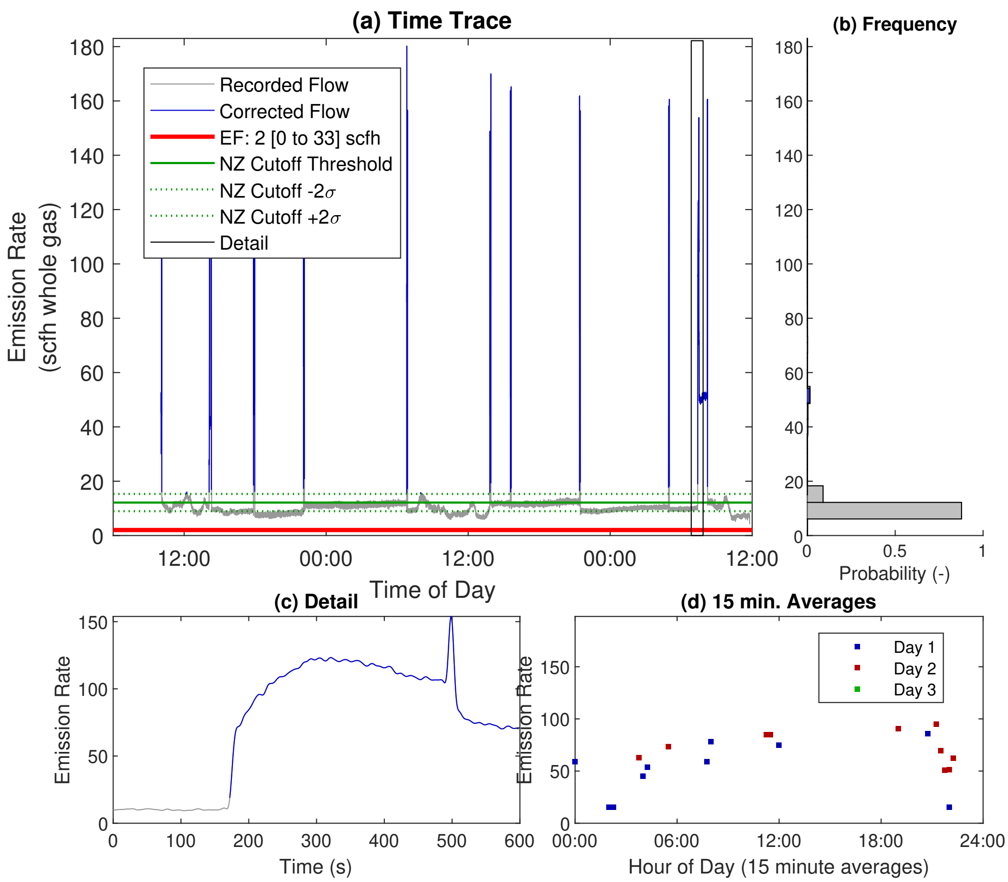

Figure A.54: Device G-5

Device J-4

Site Class: III	NEMS Region: Southwest
Install Location: Inline	Measurement Duration: 15.5 hrs
Controller Location: Compressor	Avg. Gas Temperature: 63.5 $^\circ F$
Process Controlled: Pressure	Avg. Supply Pressure: 43.1 psia
Controller Model: Dynaflo 4000 LBR	Gas Methane Fraction: 92%
EPA Bleed Type: Low Bleed	Emission Factor: 8.1 [0 to 15]
Non-zero Correction:	NZ Cutoff: 7.69 scfh
Samples Remaining: 65%	Emissions Remaining: 70%
Evaluation: Abnormally Operating	

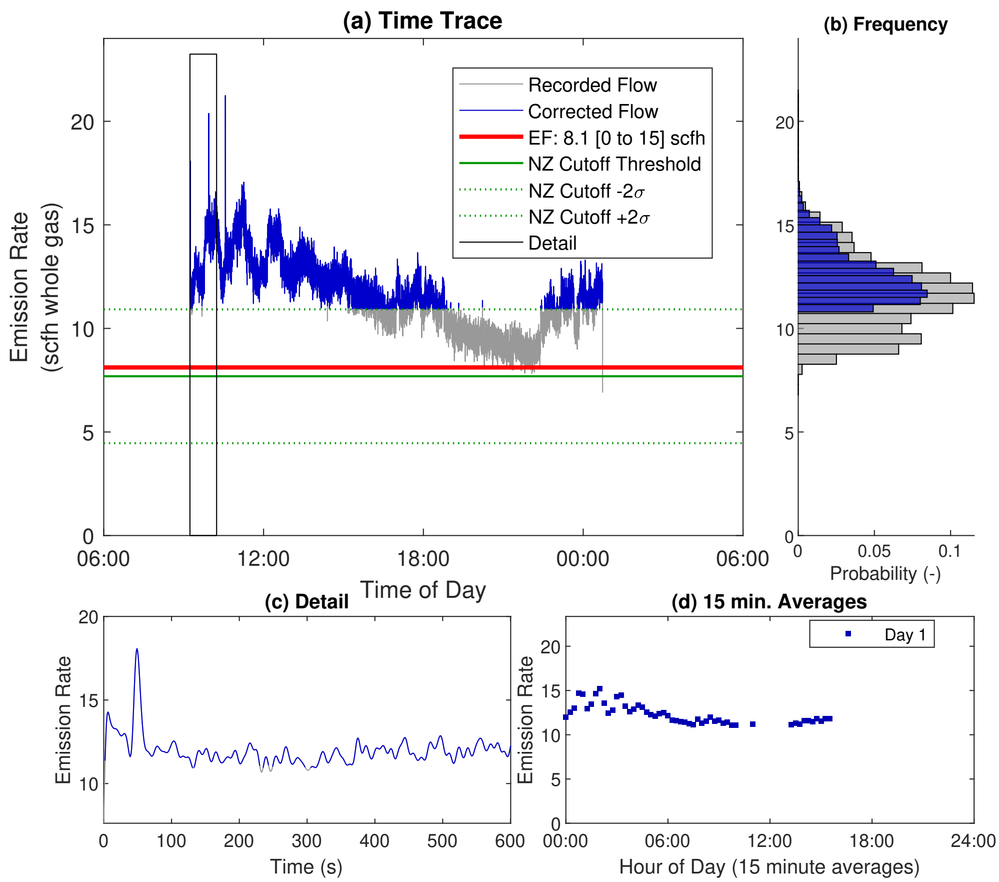

Figure A.55: Device J-4

Device N-2

Site Class: I	NEMS Region: Midcontinent
Install Location: Inline	Measurement Duration: 83.8 hrs
Controller Location: Compressor	Avg. Gas Temperature: 76.5 $^\circ F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 38.7 psia
Controller Model: Norriseal 1001A	Gas Methane Fraction: 77.1%
EPA Bleed Type: Intermittent	Emission Factor: 11 [0 to 30]
Non-zero Correction:	NZ Cutoff: 10.2 scfh
Samples Remaining: 65%	Emissions Remaining: 73%
Evaluation: Abnormally Operating	

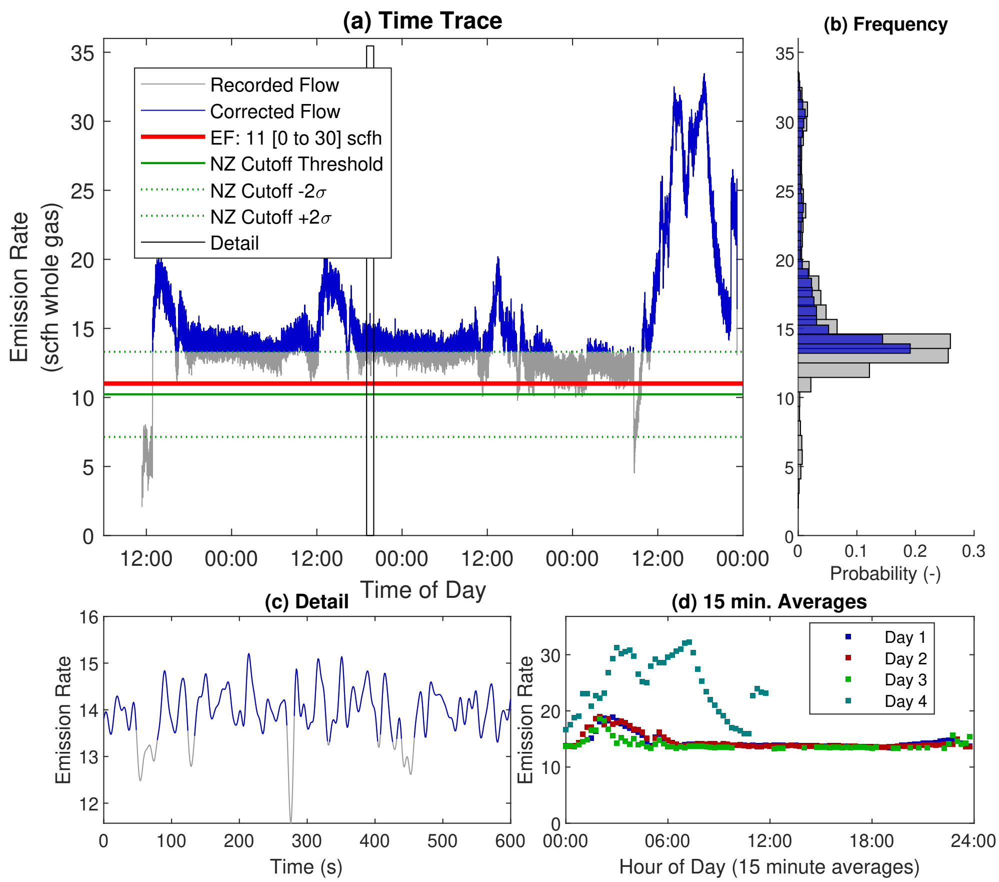

Figure A.56: Device N-2

Device N-4

Site Class: I	NEMS Region: Midcontinent
Install Location: Inline	Measurement Duration: 83.1 hrs
Controller Location: Compressor	Avg. Gas Temperature: 68.2 $^\circ F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 39 psia
Controller Model: Norriseal 1001A	Gas Methane Fraction: 77.1%
EPA Bleed Type: Intermittent	Emission Factor: 2.8 [0 to 22]
Non-zero Correction:	NZ Cutoff: 4.79 scfh
Samples Remaining: 19%	Emissions Remaining: 46%
Evaluation: Abnormally Operating	

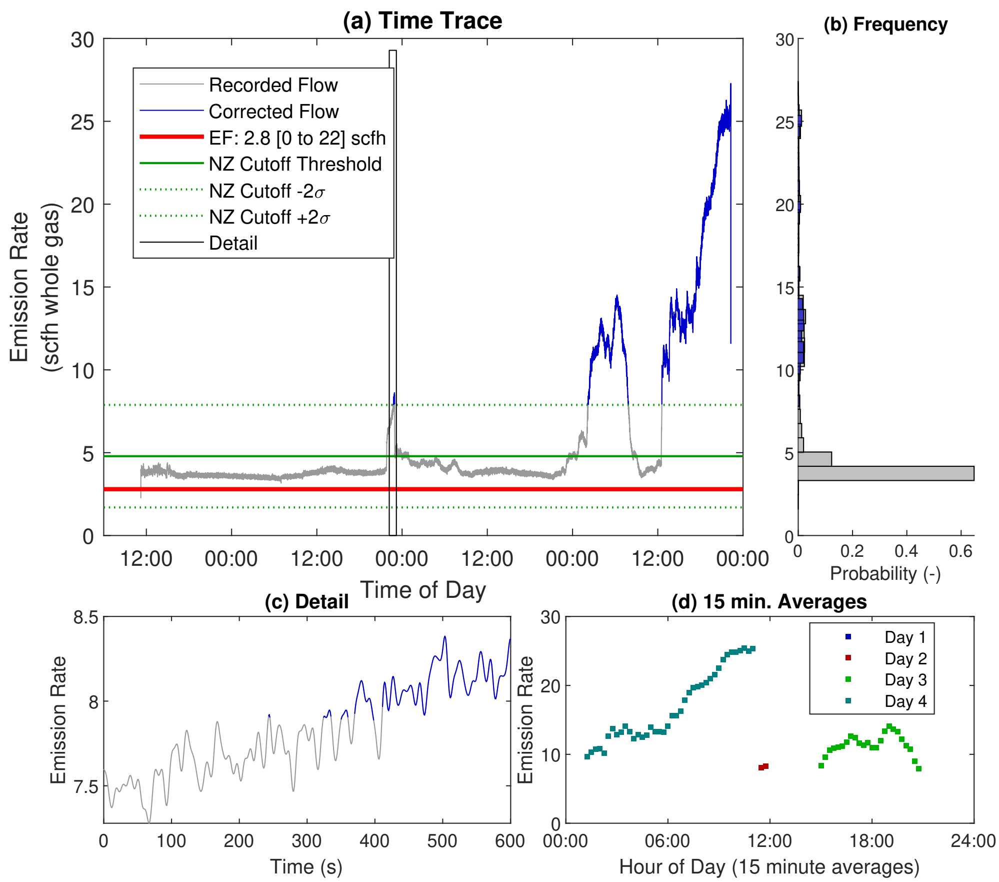

Figure A.57: Device N-4

Device N-5

Site Class: I	NEMS Region: Midcontinent
Install Location: Inline	Measurement Duration: 85.8 hrs
Controller Location: Yard Piping	Avg. Gas Temperature: 73.6 $^{\circ}F$
Process Controlled: Pressure	Avg. Supply Pressure: 34.6 psia
Controller Model: Fisher C1	Gas Methane Fraction: 77.1%
EPA Bleed Type: Low Bleed	Emission Factor: 1.9 [0 to 12]
Non-zero Correction:	NZ Cutoff: 5.78 scfh
Samples Remaining: 18%	Emissions Remaining: 29%
Evaluation: Normally Operating	

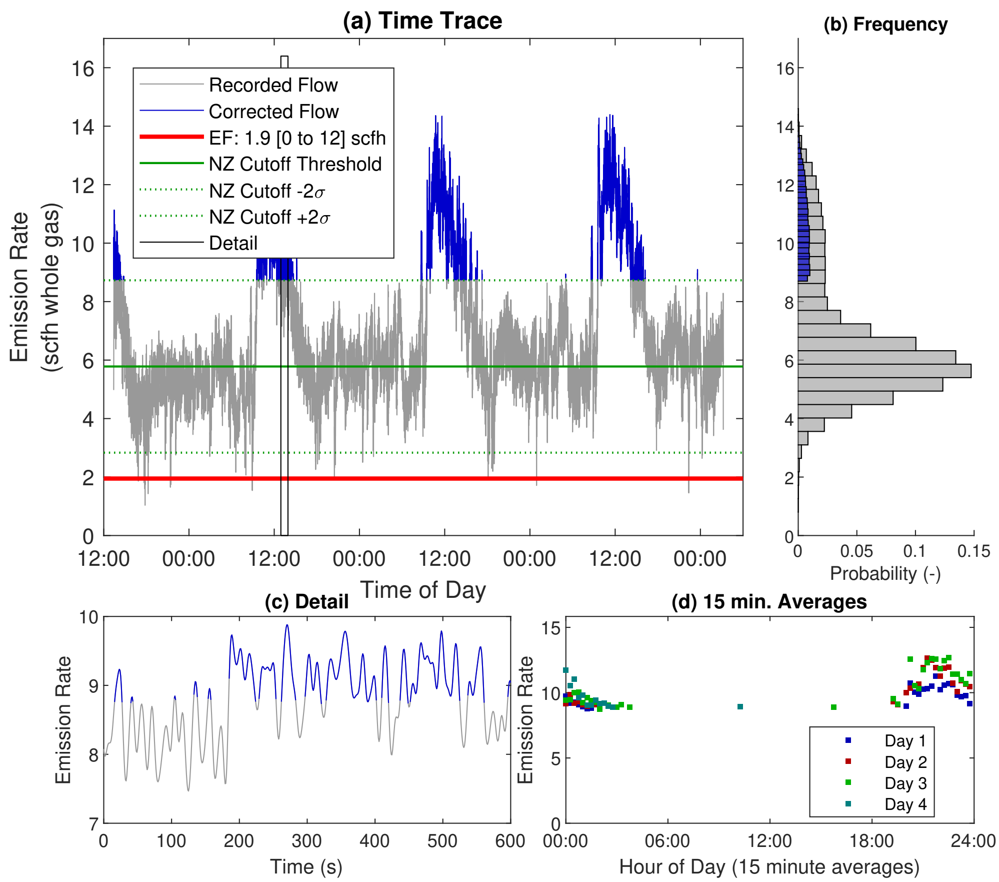

Figure A.58: Device N-5

Device O-6

Site Class: II	NEMS Region: Rocky Mountain
Install Location: Inline	Measurement Duration: 74.1 hrs
Controller Location: Compressor	Avg. Gas Temperature: 70.1 $^{\circ}F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 36.8 psia
Controller Model: Mallard 3200	Gas Methane Fraction: 89.5%
EPA Bleed Type: Intermittent	Emission Factor: 11 [0 to 47]
Non-zero Correction:	NZ Cutoff: 6.41 scfh
Samples Remaining: 56%	Emissions Remaining: 75%
Evaluation: Abnormally Operating	

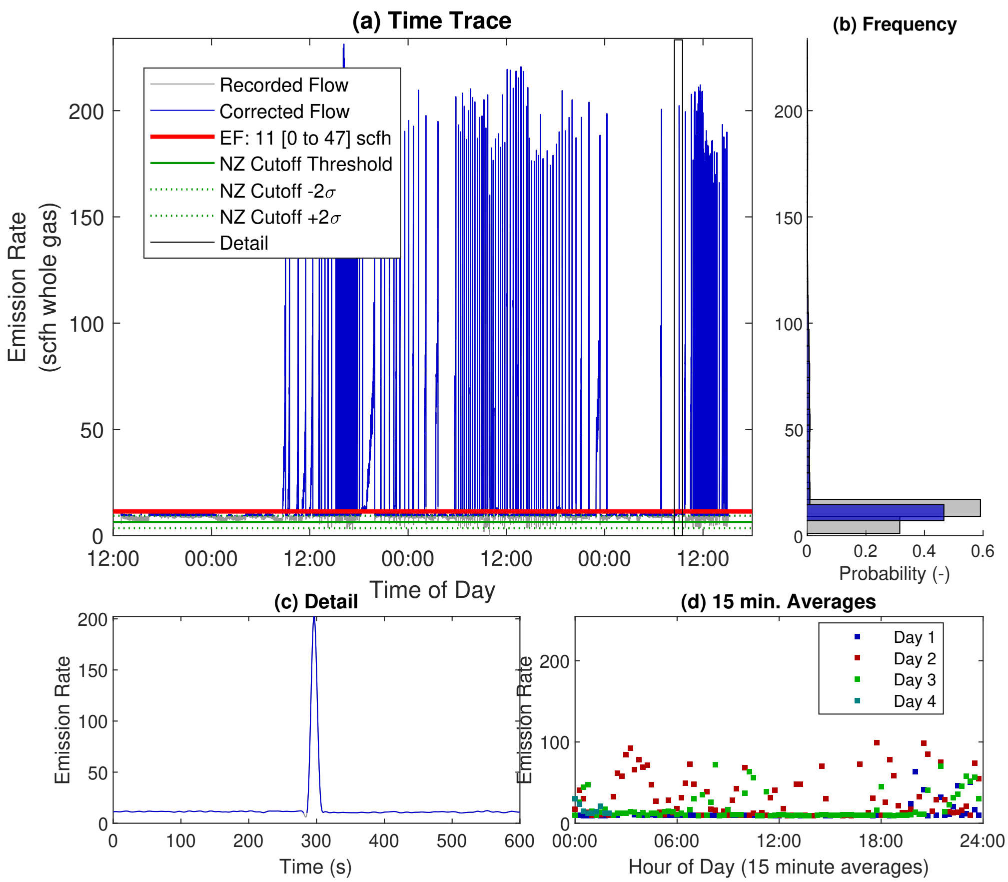

Figure A.59: Device O-6

Device P-1

Site Class: III	NEMS Region: Gulf Coast
Install Location: Inline	Measurement Duration: 69.1 hrs
Controller Location: Compressor	Avg. Gas Temperature: 50.2 $^\circ F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 67.6 psia
Controller Model: Norriseal 1001A	Gas Methane Fraction: 94.5%
EPA Bleed Type: Intermittent	Emission Factor: 1.1 [0 to 9.2]
Non-zero Correction:	NZ Cutoff: 22.8 scfh
Samples Remaining: 2.4%	Emissions Remaining: 4.6%
Evaluation: Abnormally Operating	

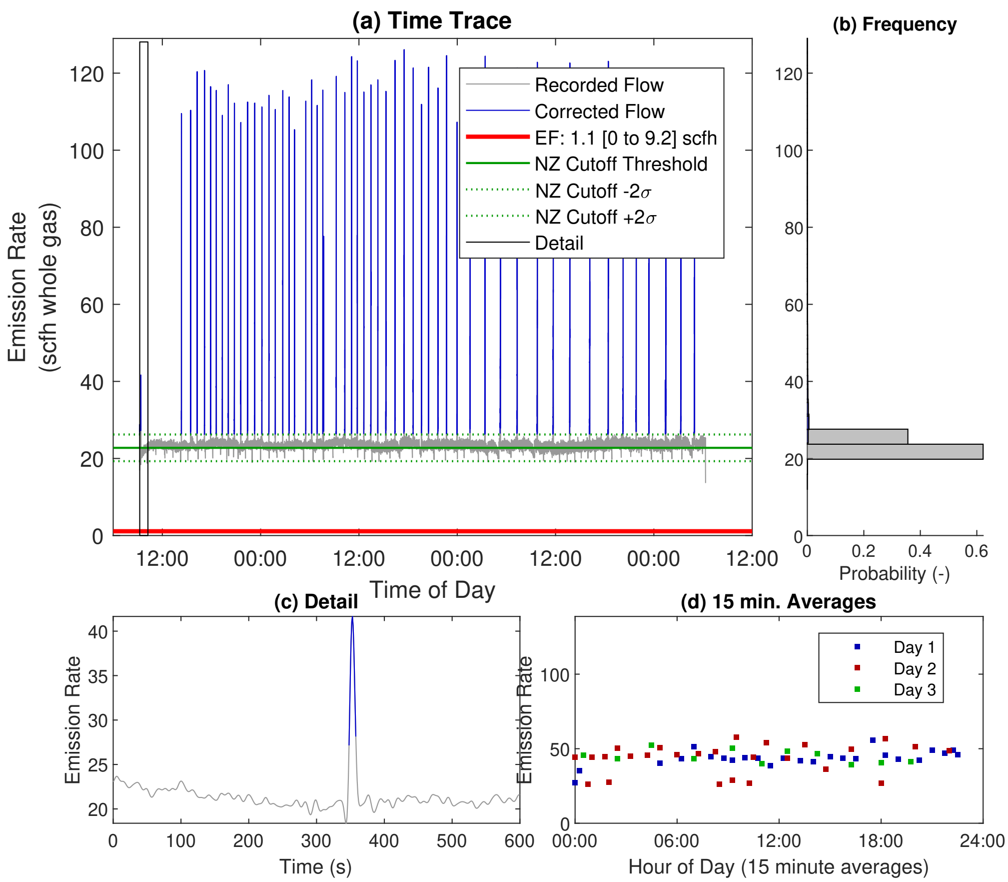

Figure A.60: Device P-1

Device P-2

Site Class: III	NEMS Region: Gulf Coast
Install Location: Inline	Measurement Duration: 2.87 hrs
Controller Location: Compressor	Avg. Gas Temperature: 46.5 $^\circ F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 68 psia
Controller Model: Norriseal 1001A	Gas Methane Fraction: 94.5%
EPA Bleed Type: Intermittent	Emission Factor: 1.4 [0 to 8.5]
Non-zero Correction:	NZ Cutoff: 41.8 scfh
Samples Remaining: 1.2%	Emissions Remaining: 4%
Evaluation: Normally Operating	

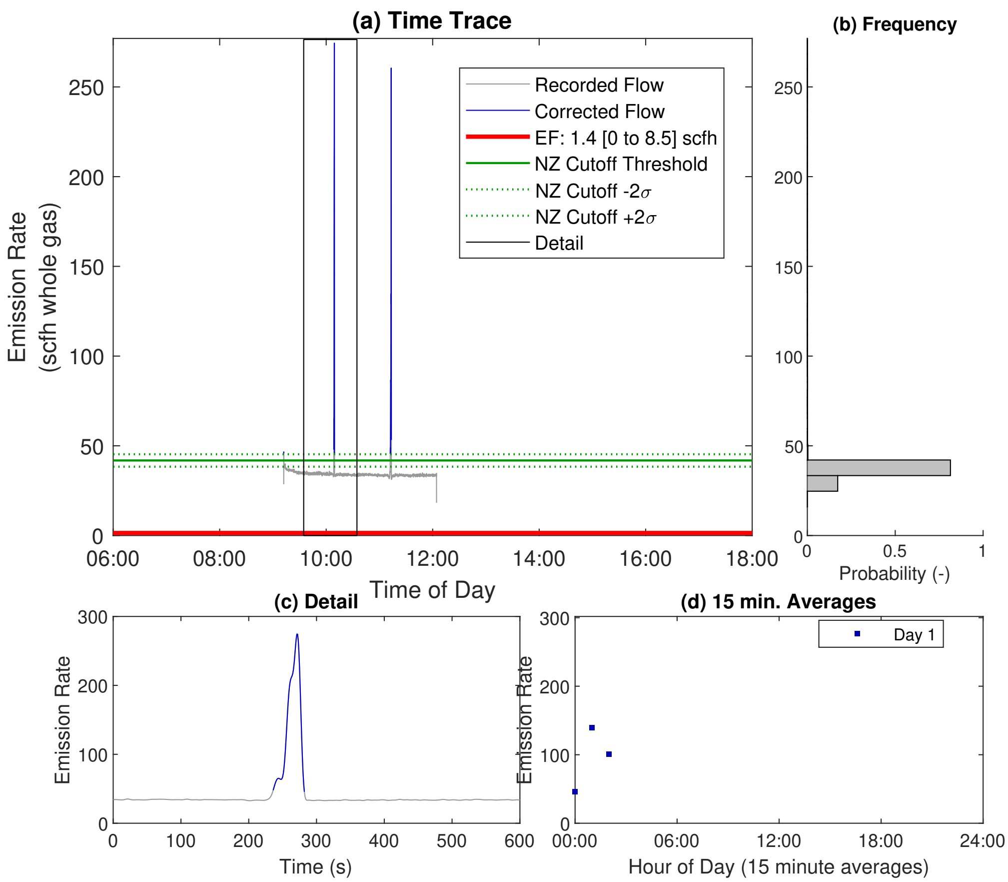

Figure A.61: Device P-2

Device P-5

Site Class: III	NEMS Region: Gulf Coast
Install Location: Inline	Measurement Duration: 68.8 hrs
Controller Location: Compressor	Avg. Gas Temperature: 48.5 $^{\circ}F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 39.4 psia
Controller Model: Norriseal 1001A	Gas Methane Fraction: 94.5%
EPA Bleed Type: Intermittent	Emission Factor: 18 [0 to 50]
Non-zero Correction:	NZ Cutoff: 10.3 scfh
Samples Remaining: 18%	Emissions Remaining: 65%
Evaluation: Abnormally Operating	

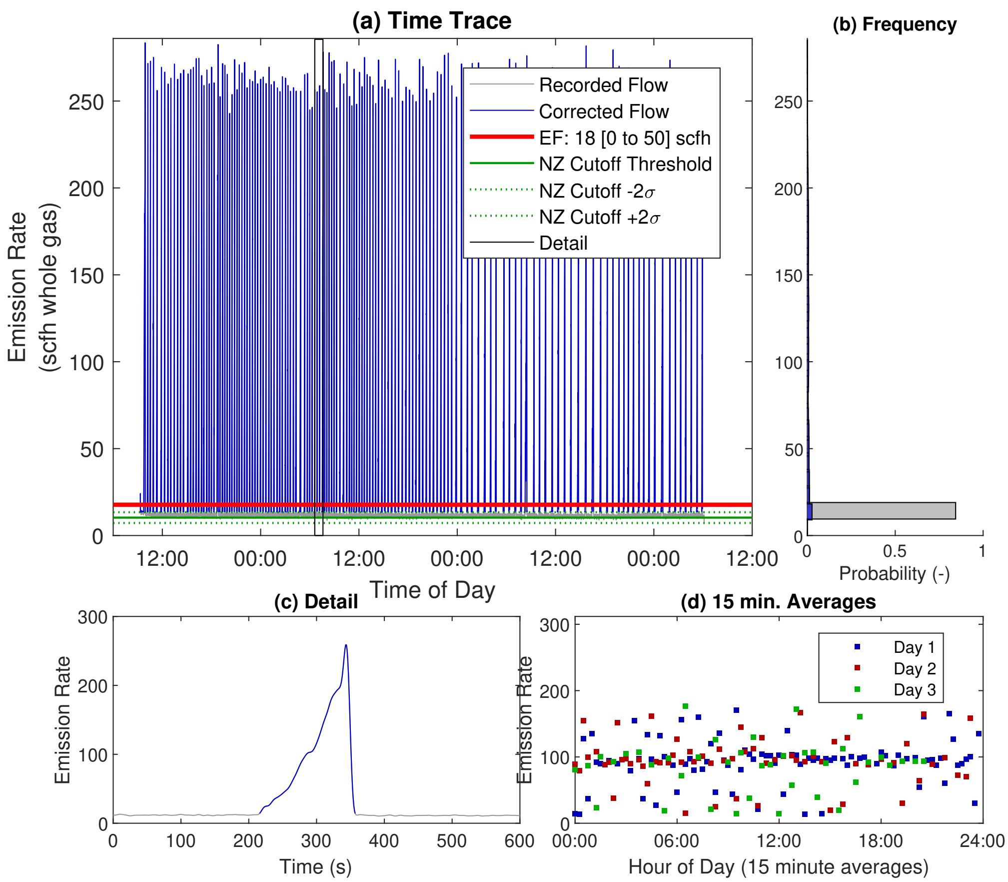

Figure A.62: Device P-5

Device Q-2

Site Class: III	NEMS Region: Southwest
Install Location: Inline	Measurement Duration: 90.4 hrs
Controller Location: Compressor	Avg. Gas Temperature: 73.4 °F
Process Controlled: Pressure	Avg. Supply Pressure: 35.2 psia
Controller Model: Dynaflo 4000 LBR	Gas Methane Fraction: 80%
EPA Bleed Type: Low Bleed	Emission Factor: 3.6 [0 to 19]
Non-zero Correction:	NZ Cutoff: 6.46 scfh
Samples Remaining: 24%	Emissions Remaining: 48%
Evaluation: Normally Operating	

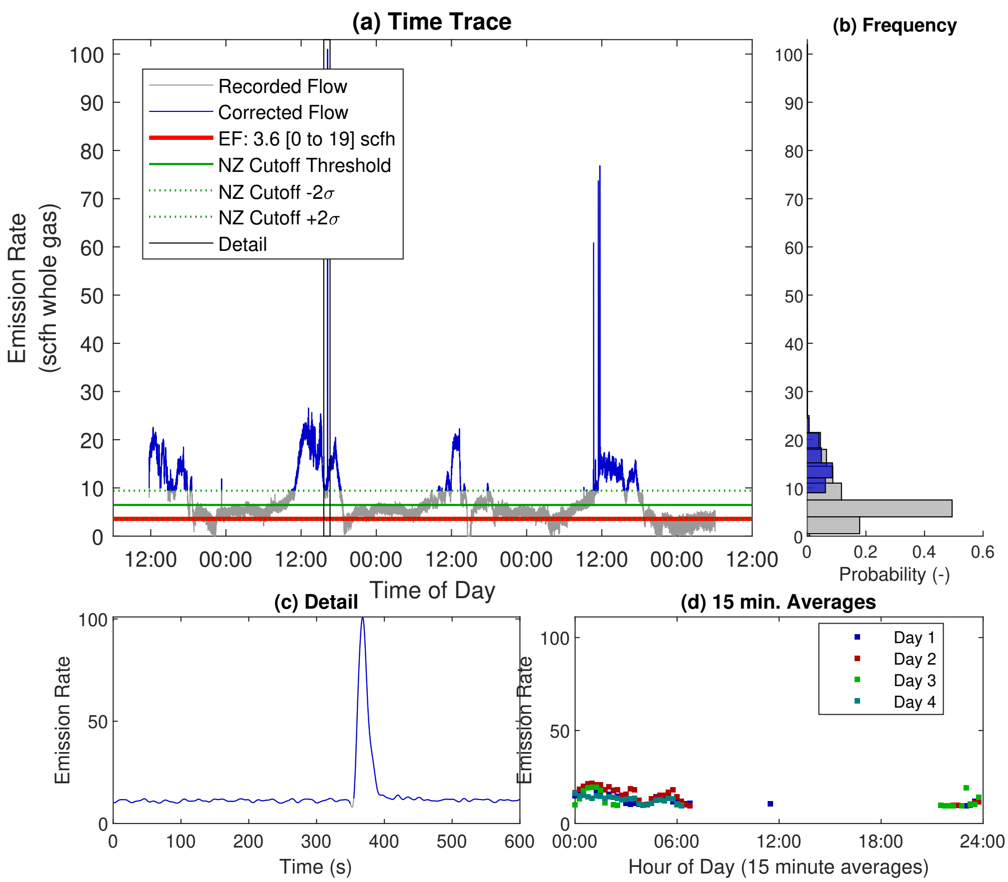

Figure A.63: Device Q-2

Device Q-5

Site Class: III	NEMS Region: Southwest
Install Location: Inline	Measurement Duration: 92.6 hrs
Controller Location: Glycol Dehydrator	Avg. Gas Temperature: 64.5 $^\circ F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 37.4 psia
Controller Model: Mallard 3201	Gas Methane Fraction: 80%
EPA Bleed Type: Intermittent	Emission Factor: 1.8 [0 to 9.7]
Non-zero Correction:	NZ Cutoff: 8.45 scfh
Samples Remaining: 5.5%	Emissions Remaining: 20%
Evaluation: Normally Operating	

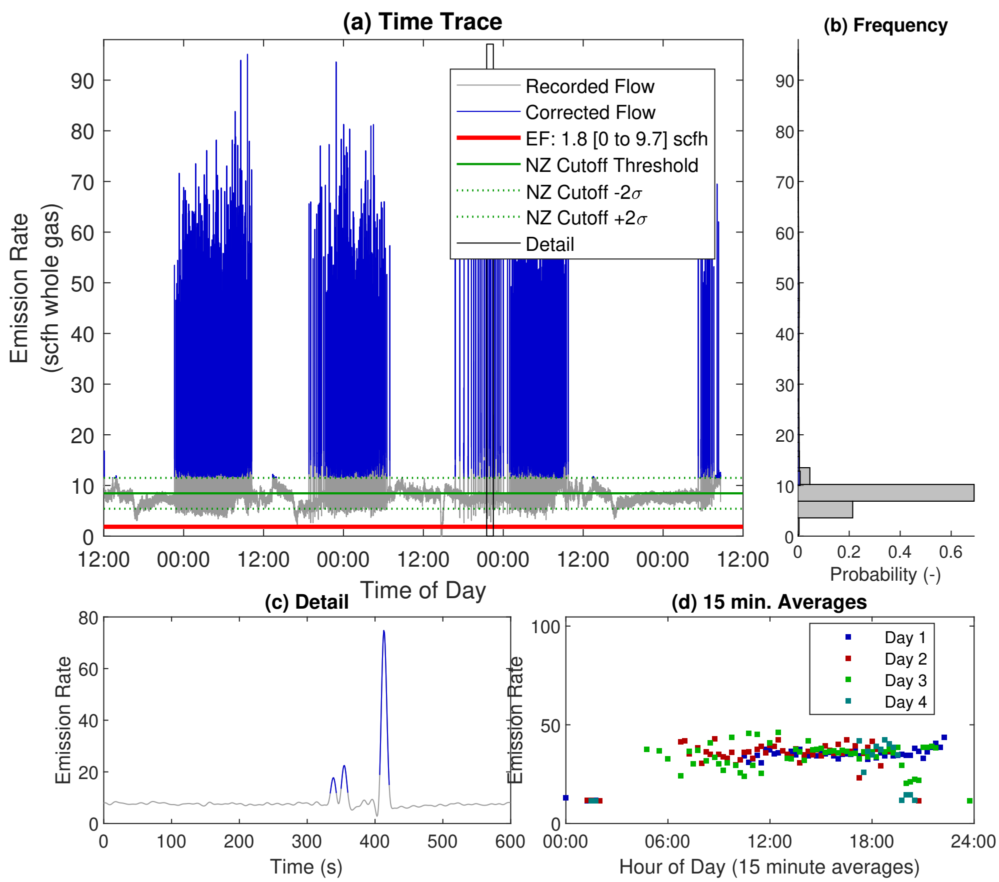

Figure A.64: Device Q-5

Device S-1

Site Class: I	NEMS Region: Midcontinent
Install Location: Inline	Measurement Duration: 87.8 hrs
Controller Location: Glycol Dehydrator	Avg. Gas Temperature: 47.6 $°F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 34.9 psia
Controller Model: Norriseal 1001A	Gas Methane Fraction: 96.8%
EPA Bleed Type: Intermittent	Emission Factor: 0.00062 [0 to 0]
Non-zero Correction:	NZ Cutoff: 1.07 scfh
Samples Remaining: 0.013%	Emissions Remaining: 0.25%
Evaluation: Normally Operating	

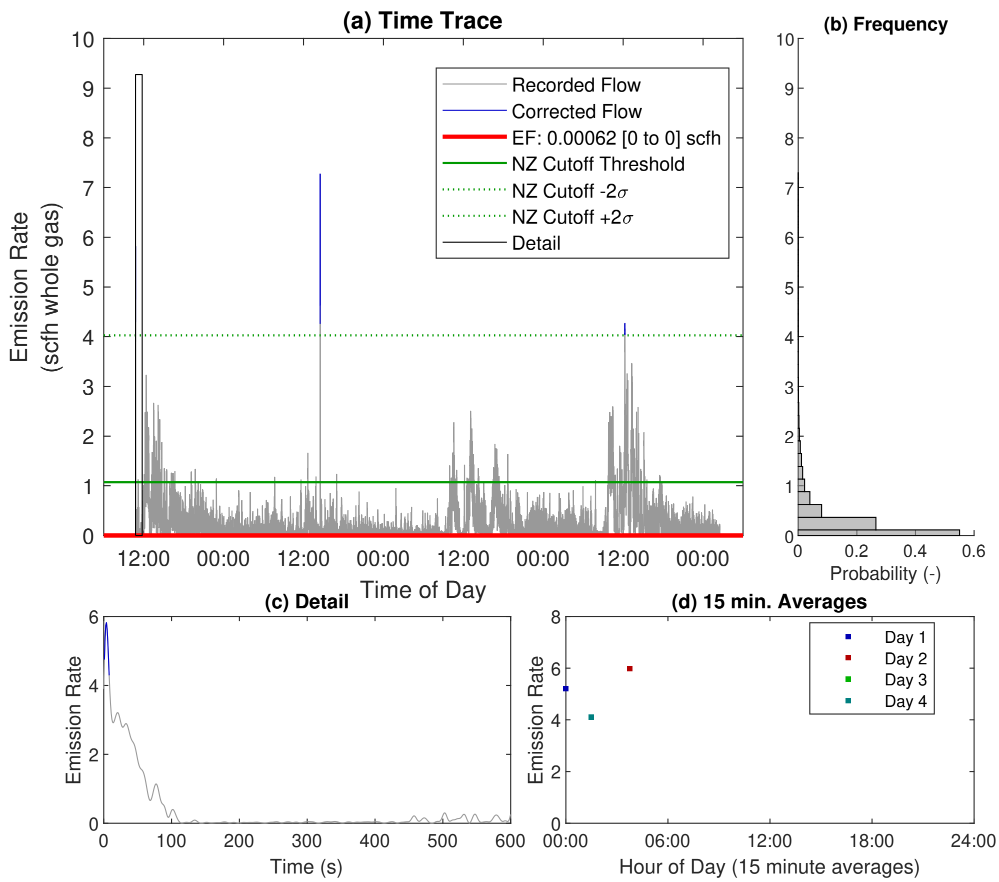

Figure A.65: Device S-1

Device S-5

Site Class: I	NEMS Region: Midcontinent
Install Location: Inline	Measurement Duration: 92.4 hrs
Controller Location: Glycol Dehydrator	Avg. Gas Temperature: 53.8 $^{\circ}F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 42.7 psia
Controller Model: Mallard, 3100-P1	Gas Methane Fraction: 96.8%
EPA Bleed Type: Intermittent	Emission Factor: 0.0048 [0 to 0]
Non-zero Correction:	NZ Cutoff: 13.5 scfh
Samples Remaining: 0.018%	Emissions Remaining: 0.053%
Evaluation: Normally Operating	

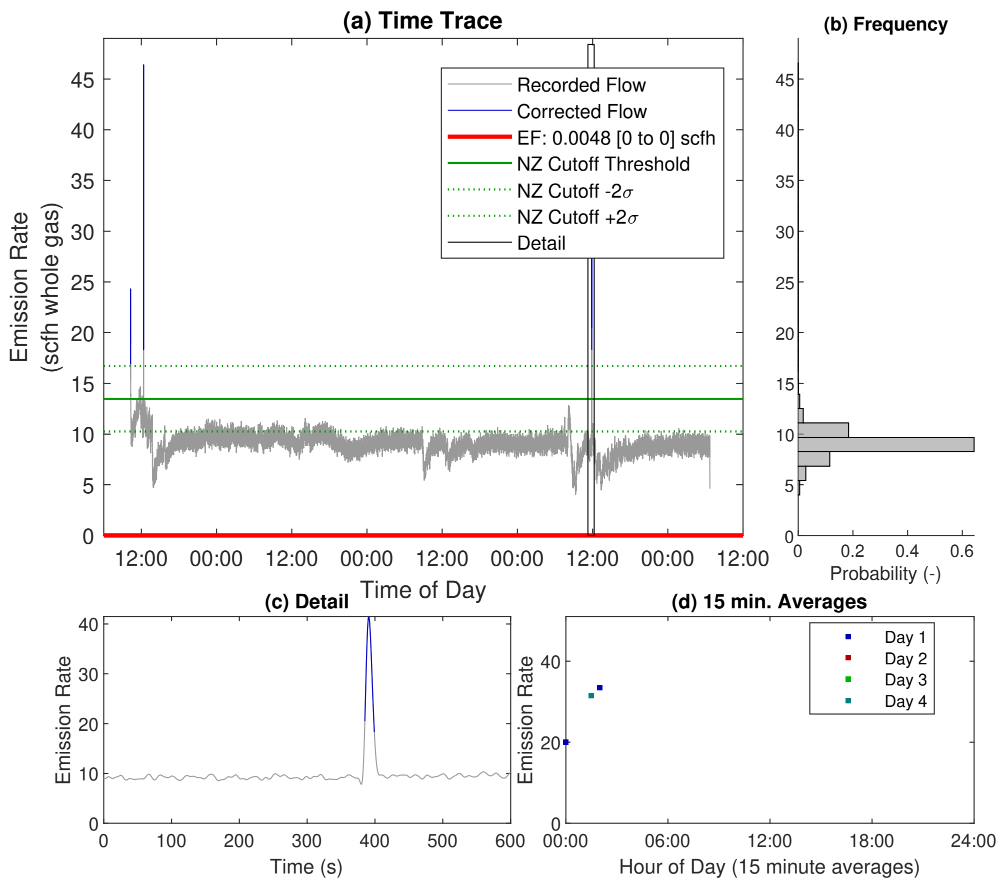

Figure A.66: Device S-5

Device T-5

Site Class: III	NEMS Region: Rocky Mountain
Install Location: Inline	Measurement Duration: 70.4 hrs
Controller Location: Compressor	Avg. Gas Temperature: 30.2 $^{\circ}F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 36.4 psia
Controller Model: Mallard 3200	Gas Methane Fraction: 89.5%
EPA Bleed Type: Intermittent	Emission Factor: 1.9 [0 to 30]
Non-zero Correction:	NZ Cutoff: 7.48 scfh
Samples Remaining: 4.1%	Emissions Remaining: 26%
Evaluation: Abnormally Operating	

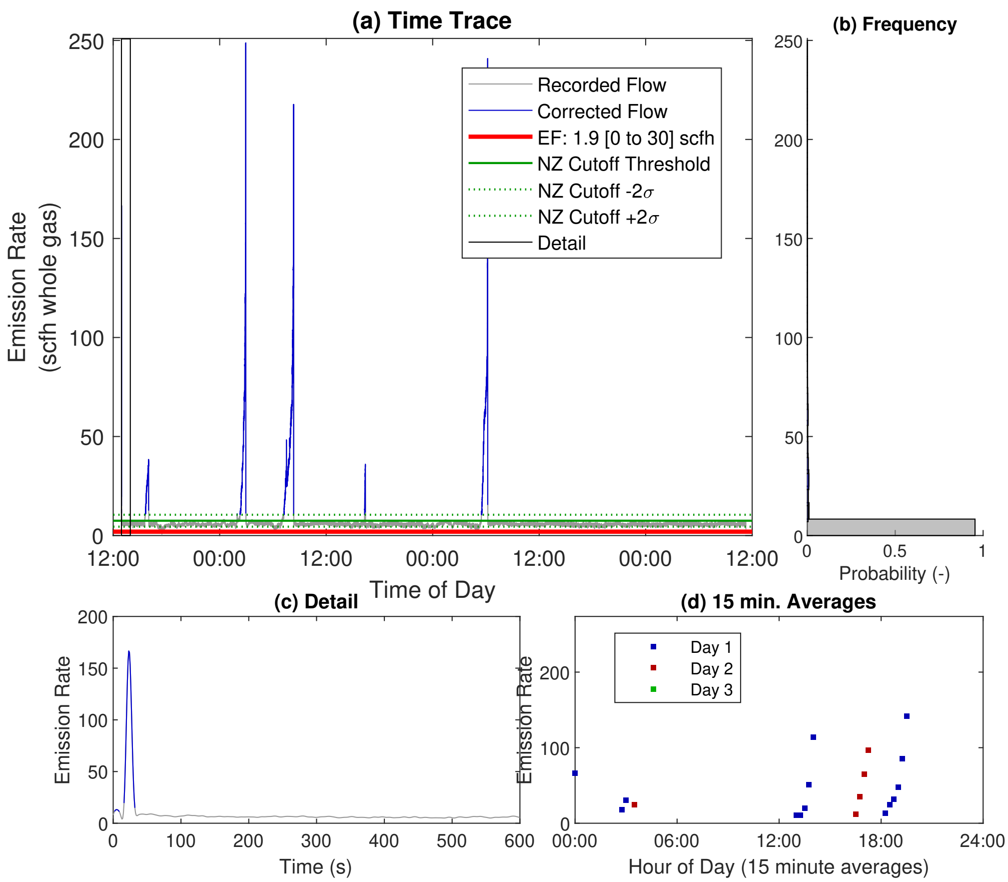

Figure A.67: Device T-5

Device T-6

Site Class: III	NEMS Region: Rocky Mountain
Install Location: Inline	Measurement Duration: 70.2 hrs
Controller Location: Compressor	Avg. Gas Temperature: 30.8 $^\circ F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 40.7 psia
Controller Model: Mallard 3200	Gas Methane Fraction: 89.5%
EPA Bleed Type: Intermittent	Emission Factor: 12 [0 to 1.5e+02]
Non-zero Correction:	NZ Cutoff: 11.7 scfh
Samples Remaining: 12%	Emissions Remaining: 58%
Evaluation: Abnormally Operating	

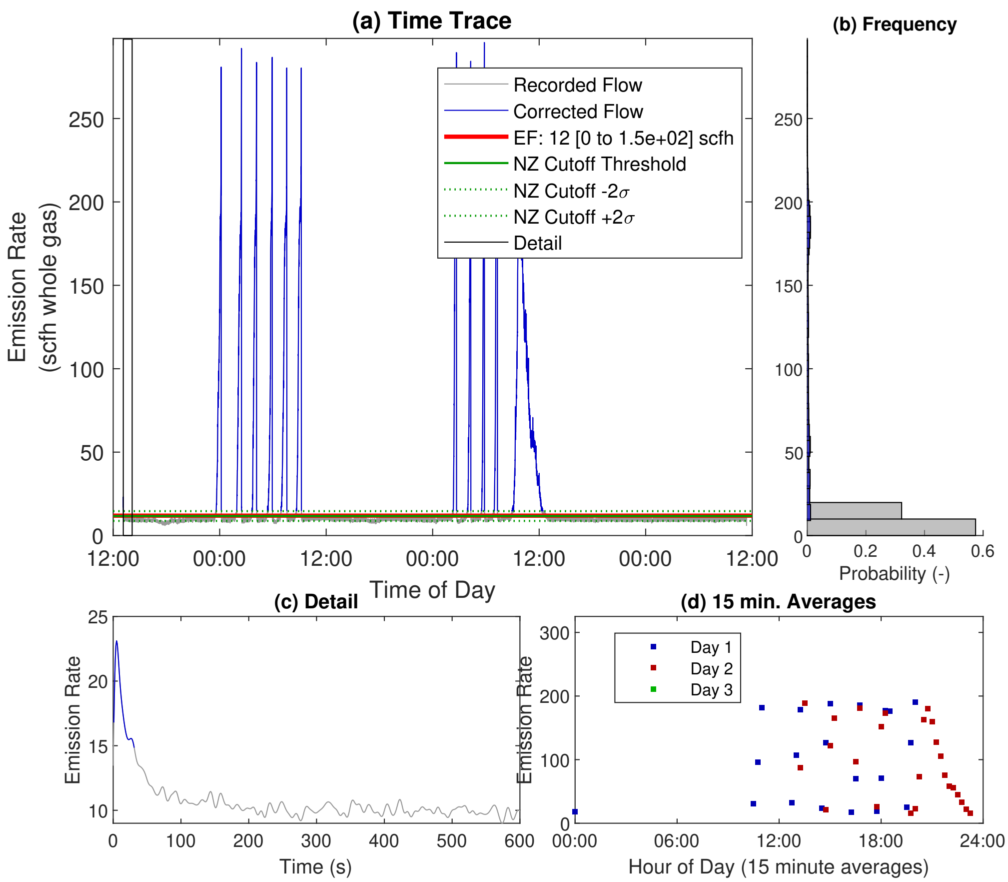

Figure A.68: Device T-6

Device U-6

Site Class: III	NEMS Region: Rocky Mountain
Install Location: Inline	Measurement Duration: 76.7 hrs
Controller Location: Compressor	Avg. Gas Temperature: 46.4 $^\circ F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 37.2 psia
Controller Model: Mallard 3200	Gas Methane Fraction: 89.5%
EPA Bleed Type: Intermittent	Emission Factor: 1.4 [0 to 16]
Non-zero Correction:	NZ Cutoff: 6.89 scfh
Samples Remaining: 8.3%	Emissions Remaining: 24%
Evaluation: Abnormally Operating	

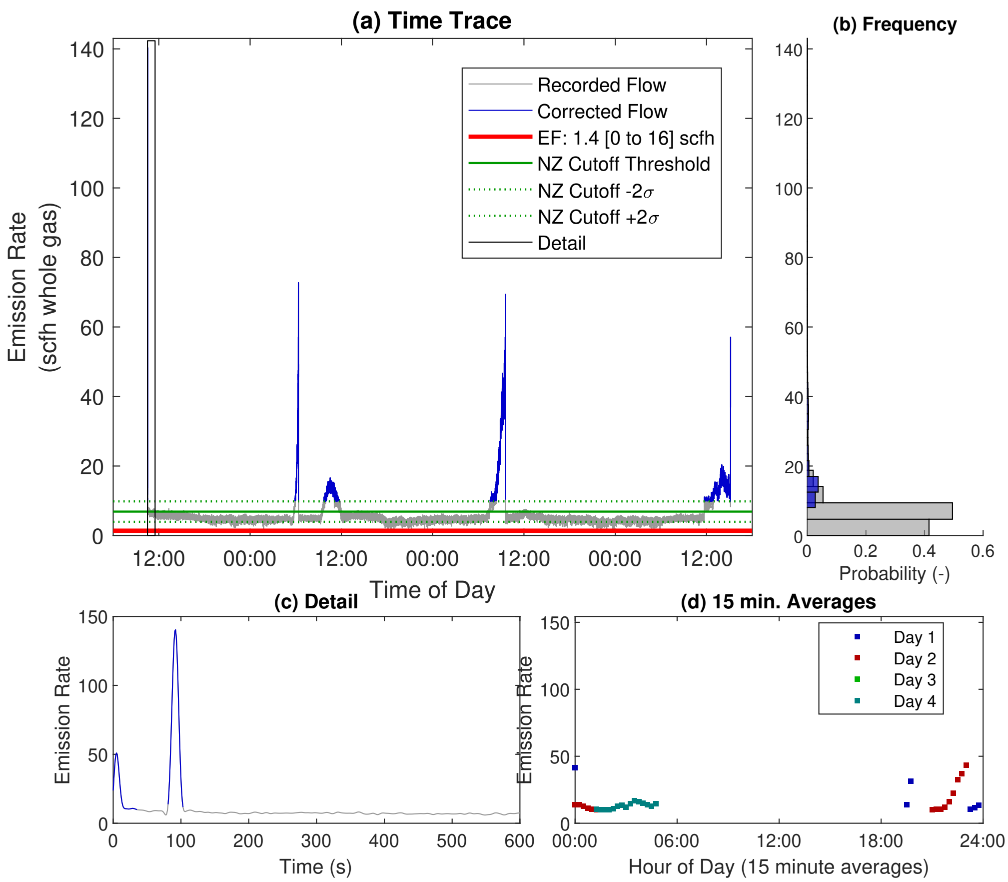

Figure A.69: Device U-6

Device V-2

Site Class: II	NEMS Region: Rocky Mountain
Install Location: Inline	Measurement Duration: 76.1 hrs
Controller Location: Yard Piping	Avg. Gas Temperature: 23.3 $^\circ F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 84.9 psia
Controller Model: Murphy, LS200N	Gas Methane Fraction: 75%
EPA Bleed Type: Intermittent	Emission Factor: 29 [0 to 1.2e+02]
Non-zero Correction:	NZ Cutoff: 60 scfh
Samples Remaining: 29%	Emissions Remaining: 46%
Evaluation: Abnormally Operating	

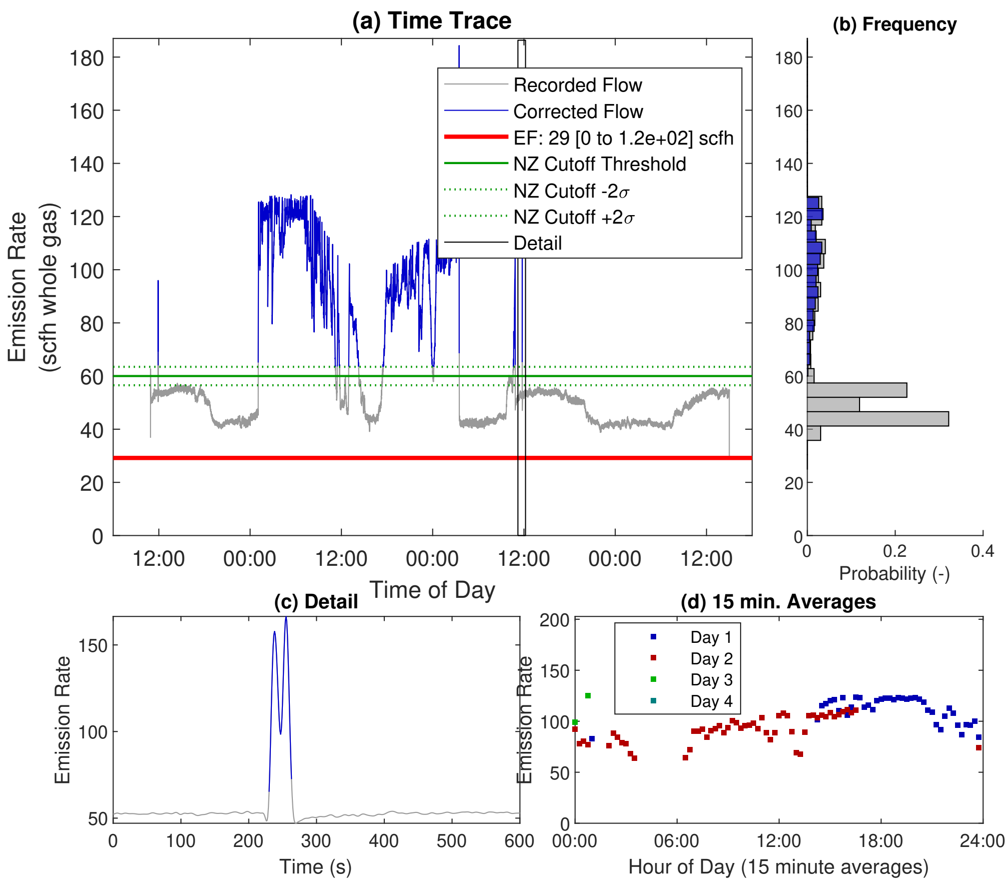

Figure A.70: Device V-2

Device V-3

Site Class: II	NEMS Region: Rocky Mountain
Install Location: Inline	Measurement Duration: 78.1 hrs
Controller Location: Yard Piping	Avg. Gas Temperature: 21.1 $^\circ F$
Process Controlled: Pressure	Avg. Supply Pressure: 48.1 psia
Controller Model: Fisher C1	Gas Methane Fraction: 75%
EPA Bleed Type: Low Bleed	Emission Factor: 1.1 [0 to 20]
Non-zero Correction:	NZ Cutoff: 16.7 scfh
Samples Remaining: 4.7%	Emissions Remaining: 6.5%
Evaluation: Normally Operating	

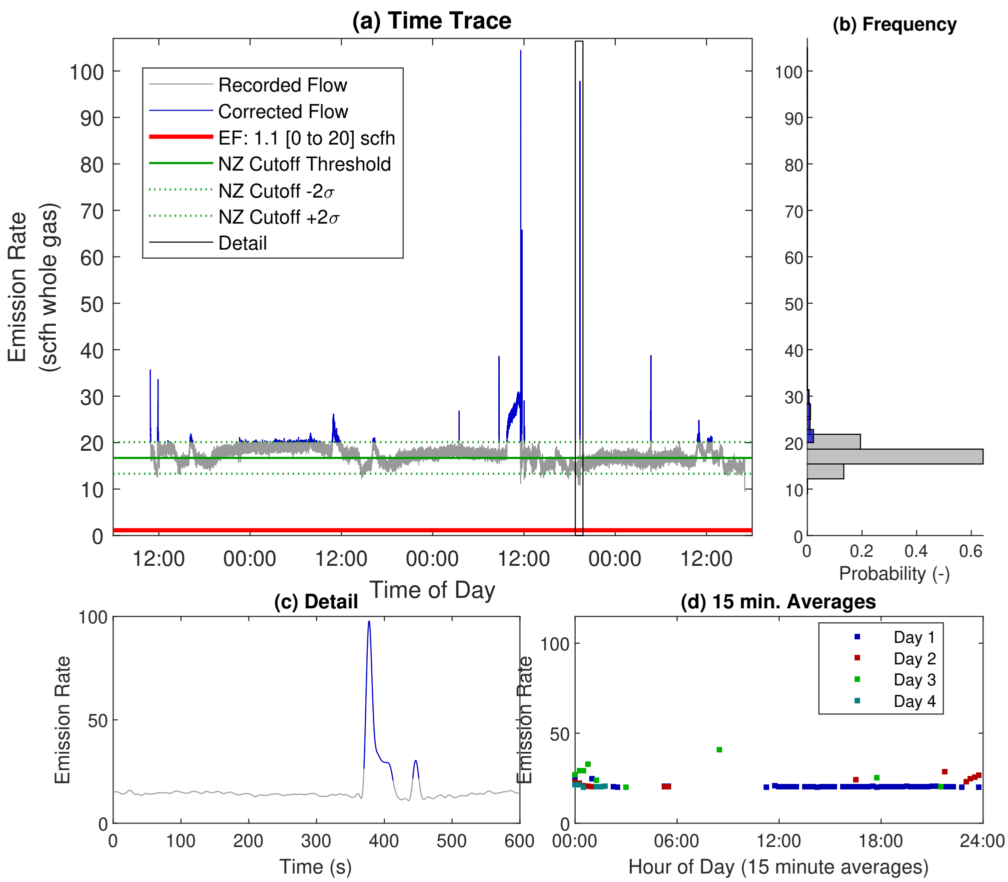

Figure A.71: Device V-3

Device V-5

Site Class: II	NEMS Region: Rocky Mountain
Install Location: Inline	Measurement Duration: 78.3 hrs
Controller Location: Yard Piping	Avg. Gas Temperature: 16.6 °F
Process Controlled: Pressure	Avg. Supply Pressure: 37.3 psia
Controller Model: Fisher C1	Gas Methane Fraction: 75%
EPA Bleed Type: Low Bleed	Emission Factor: 0.71 [0 to 13]
Non-zero Correction:	NZ Cutoff: 8.27 scfh
Samples Remaining: 5.5%	Emissions Remaining: 16%
Evaluation: Normally Operating	

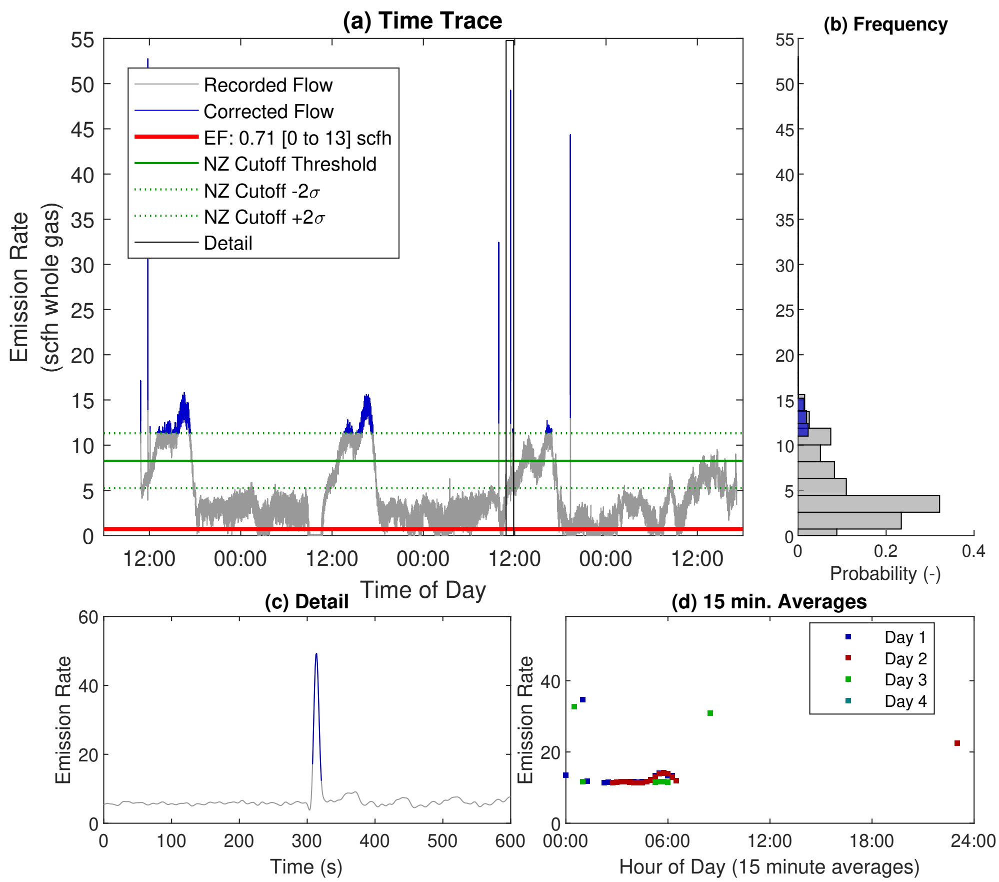

Figure A.72: Device V-5

A.4 Discarded

This section contains recordings that were effectively zeroed after applying the NZ correction. Because the recordings in this section do not contain measurements that are distinguishable from the NZ meter error, they will not be used for any further analysis.

Device A-5

Site Class: II	NEMS Region: Southwest
Install Location: Inline	Measurement Duration: 69 hrs
Controller Location: Compressor	Avg. Gas Temperature: 51.1 °F
Process Controlled: Liquid Level	Avg. Supply Pressure: 35.1 psia
Controller Model: Murphy LS200N	Gas Methane Fraction: 92%
EPA Bleed Type: Intermittent	Emission Factor: 0.93 [0 to 11]
Non-zero Correction:	NZ Cutoff: 6.17 scfh
Samples Remaining: 9.1%	Emissions Remaining: 14%
Evaluation: -	

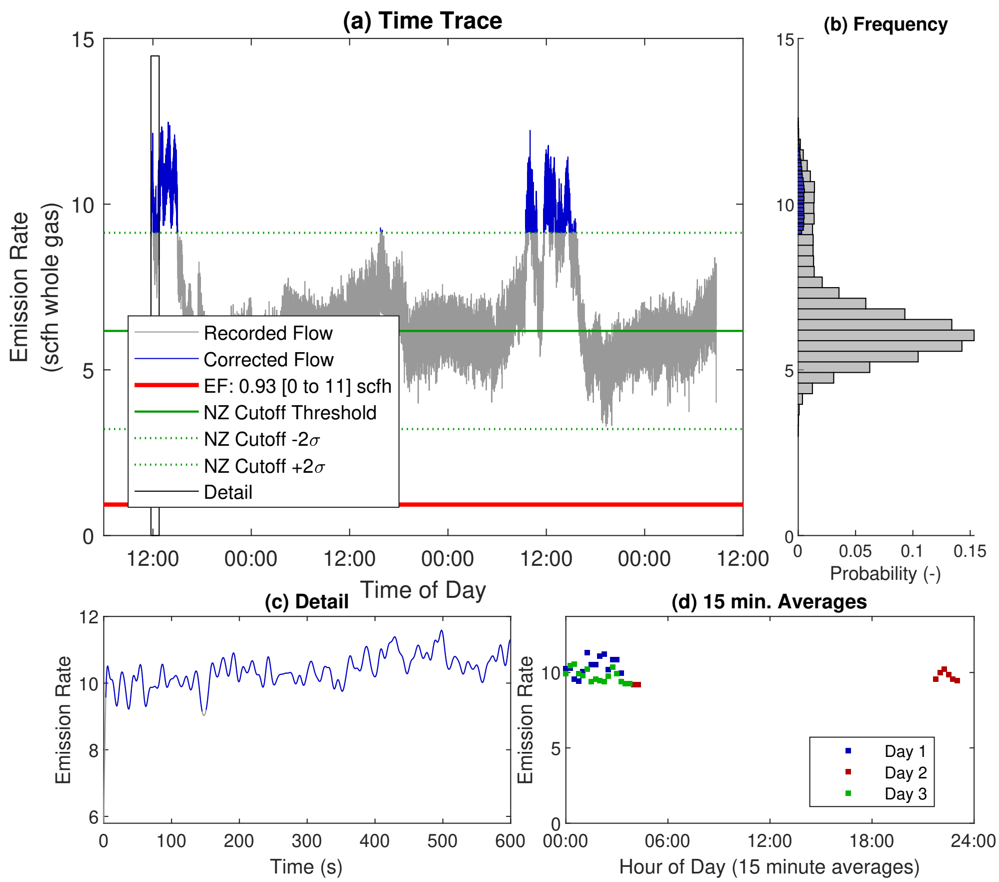

Figure A.73: Device A-5

Device D-5

Site Class: I	NEMS Region: Rocky Mountain
Install Location: Inline	Measurement Duration: 91.1 hrs
Controller Location: Compressor	Avg. Gas Temperature: 42.9 $^\circ F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 32.8 psia
Controller Model: Mallard, 3100-P1	Gas Methane Fraction: 99.2%
EPA Bleed Type: Intermittent	Emission Factor: 0.0013 [0 to 0]
Non-zero Correction:	NZ Cutoff: 4.06 scfh
Samples Remaining: 0.018%	Emissions Remaining: 0.038%
Evaluation: -	

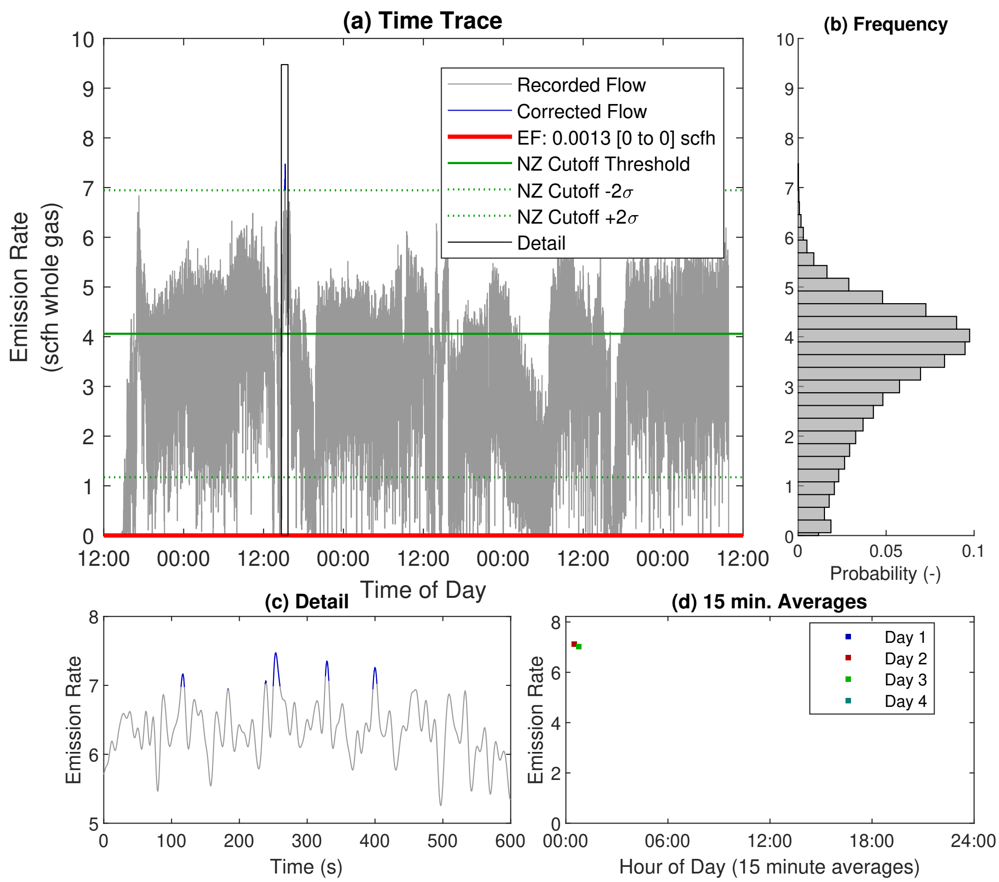

Figure A.74: Device D-5

Device H-2

Site Class: I	NEMS Region: Southwest
Install Location: Inline	Measurement Duration: 88 hrs
Controller Location: Compressor	Avg. Gas Temperature: 67.7 $^\circ F$
Process Controlled: Pressure	Avg. Supply Pressure: 39.9 psia
Controller Model: ABB, Type 22/06	Gas Methane Fraction: 70%
EPA Bleed Type: Low Bleed	Emission Factor: 0 [0 to 0]
Non-zero Correction:	NZ Cutoff: 11.5 scfh
Samples Remaining: 0%	Emissions Remaining: 0%
Evaluation: -	

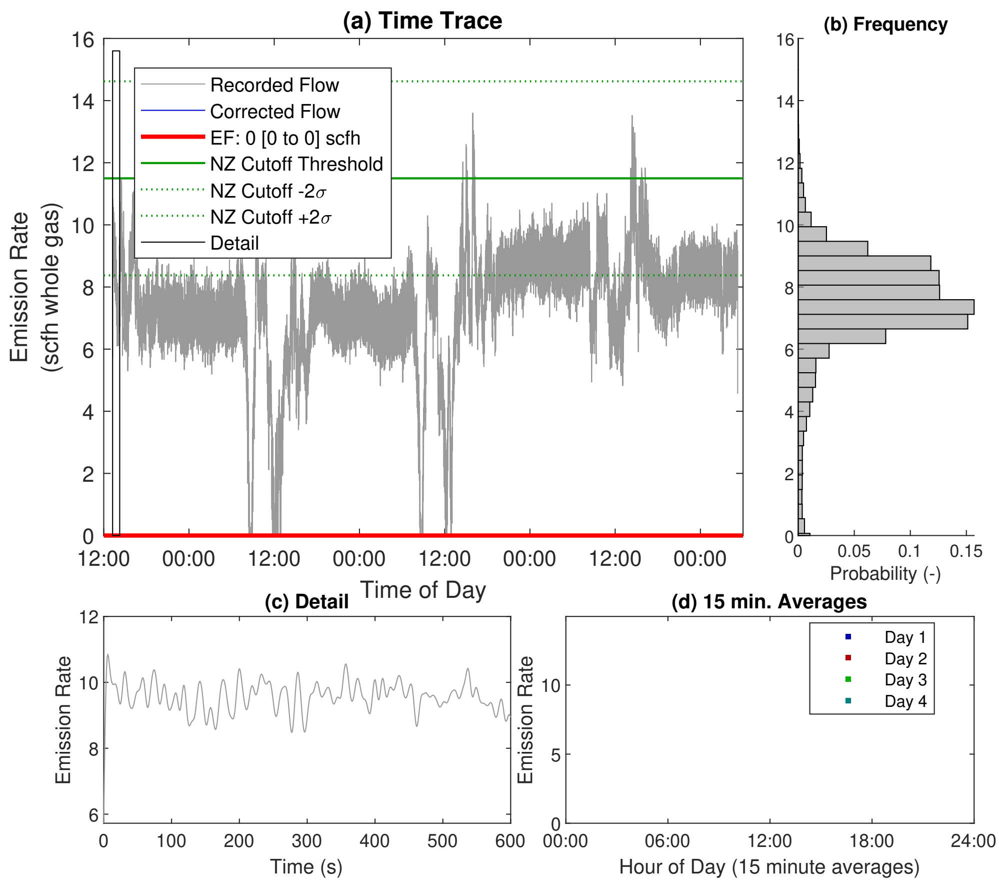

Figure A.75: Device H-2

Device H-3

Site Class: I	NEMS Region: Southwest
Install Location: Inline	Measurement Duration: 89.9 hrs
Controller Location: Compressor	Avg. Gas Temperature: 71.5 °F
Process Controlled: Pressure	Avg. Supply Pressure: 37.7 psia
Controller Model: Ronan X55-600 I/P	Gas Methane Fraction: 70%
EPA Bleed Type: Low Bleed	Emission Factor: 1.1 [0 to 9.9]
Non-zero Correction:	NZ Cutoff: 4.25 scfh
Samples Remaining: 13%	Emissions Remaining: 20%
Evaluation: -	

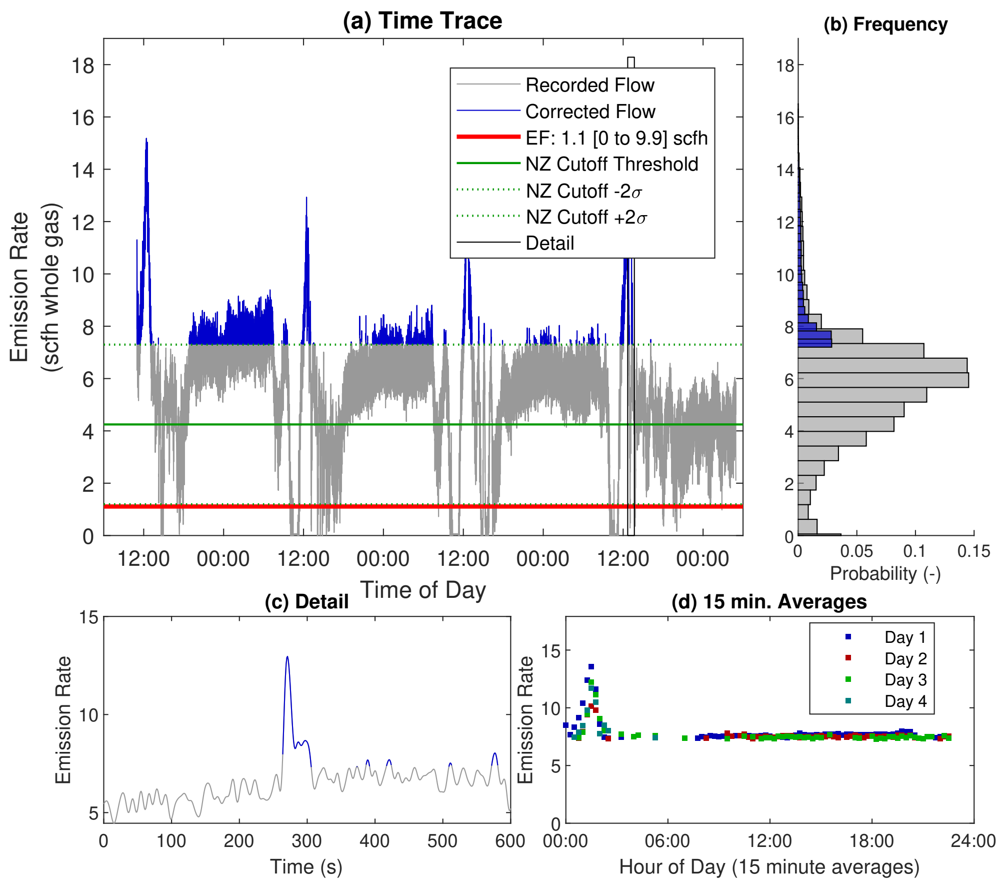

Figure A.76: Device H-3

Device H-5

Site Class: I	NEMS Region: Southwest
Install Location: Inline	Measurement Duration: 91.8 hrs
Controller Location: Compressor	Avg. Gas Temperature: 67.9 $^{\circ}F$
Process Controlled: Pressure	Avg. Supply Pressure: 47.8 psia
Controller Model: Solenoid Operated	Gas Methane Fraction: 70%
EPA Bleed Type: Low Bleed	Emission Factor: 0.0015 [0 to 0]
Non-zero Correction:	NZ Cutoff: 18.3 scfh
Samples Remaining: 0.0067%	Emissions Remaining: 0.017%
Evaluation: -	

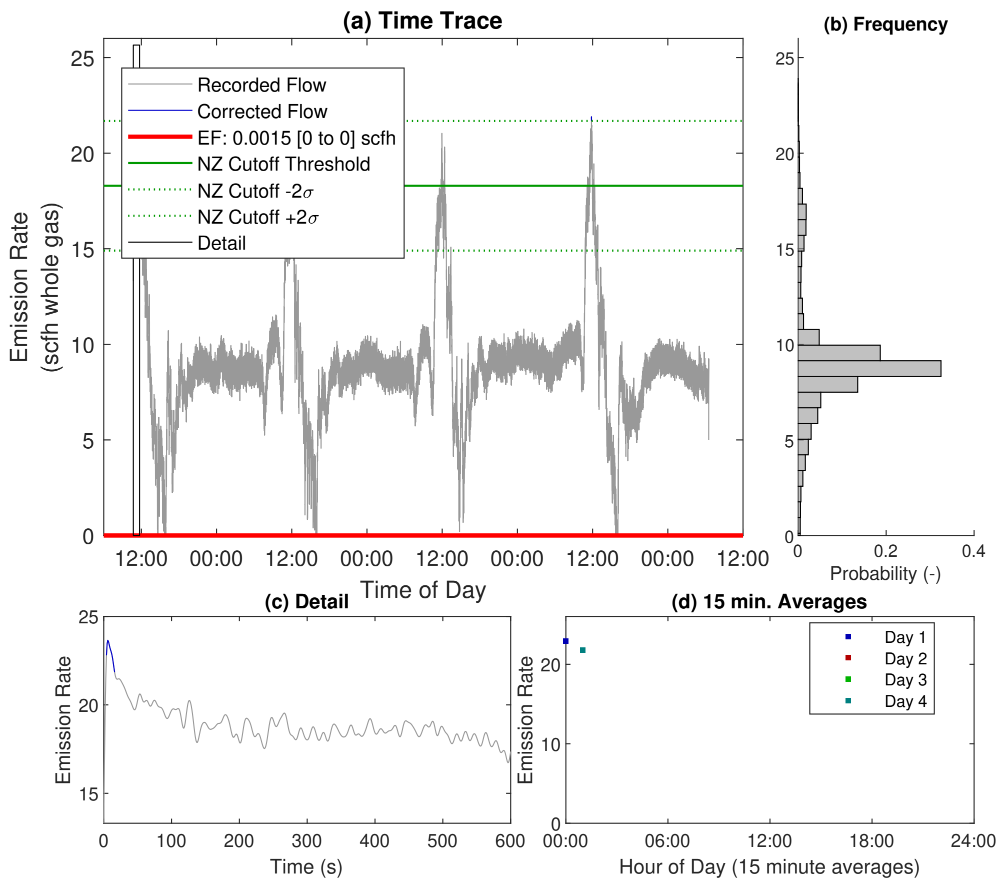

Figure A.77: Device H-5

Device L-5

Site Class: III	NEMS Region: Gulf Coast
Install Location: Inline	Measurement Duration: 90.2 hrs
Controller Location: Yard Piping	Avg. Gas Temperature: 24.2 °F
Process Controlled: Pressure	Avg. Supply Pressure: 46.6 psia
Controller Model: Fisher 546	Gas Methane Fraction: 94.5%
EPA Bleed Type: High Bleed	Emission Factor: 0.21 [0 to 1.2]
Non-zero Correction:	NZ Cutoff: 17.1 scfh
Samples Remaining: 1%	Emissions Remaining: 1.2%
Evaluation: -	

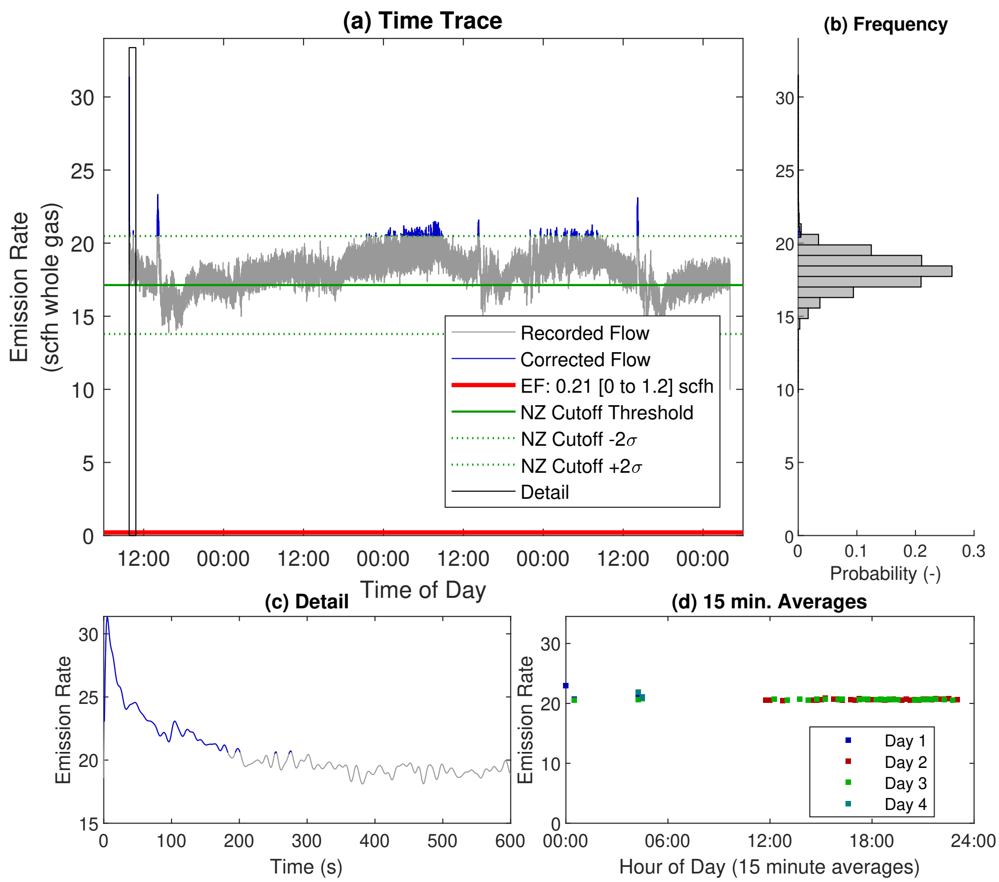

Figure A.78: Device L-5

Device L-6

Site Class: III	NEMS Region: Gulf Coast
Install Location: Inline	Measurement Duration: 89.9 hrs
Controller Location: Yard Piping	Avg. Gas Temperature: 32.6 °F
Process Controlled: Liquid Level	Avg. Supply Pressure: 46.4 psia
Controller Model: Mallard 3100P1	Gas Methane Fraction: 94.5%
EPA Bleed Type: Intermittent	Emission Factor: 0.00035 [0 to 0]
Non-zero Correction:	NZ Cutoff: 19 scfh
Samples Remaining: 0.0015%	Emissions Remaining: 0.0026%
Evaluation: -	

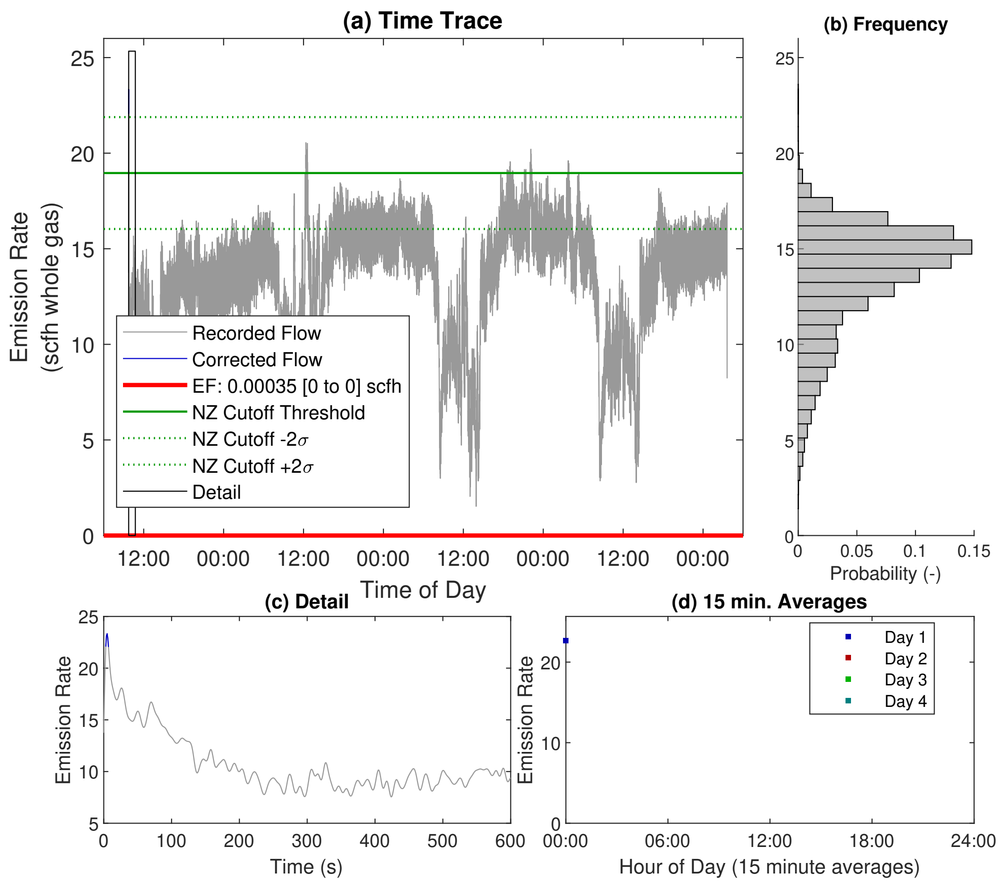

Figure A.79: Device L-6

Device O-4

Site Class: II	NEMS Region: Rocky Mountain
Install Location: Inline	Measurement Duration: 73.5 hrs
Controller Location: Compressor	Avg. Gas Temperature: 71.6 $°F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 37.4 psia
Controller Model: Mallard 3200	Gas Methane Fraction: 89.5%
EPA Bleed Type: Intermittent	Emission Factor: 0.28 [0 to 2.7]
Non-zero Correction:	NZ Cutoff: 3.66 scfh
Samples Remaining: 4%	Emissions Remaining: 4.9%
Evaluation: -	

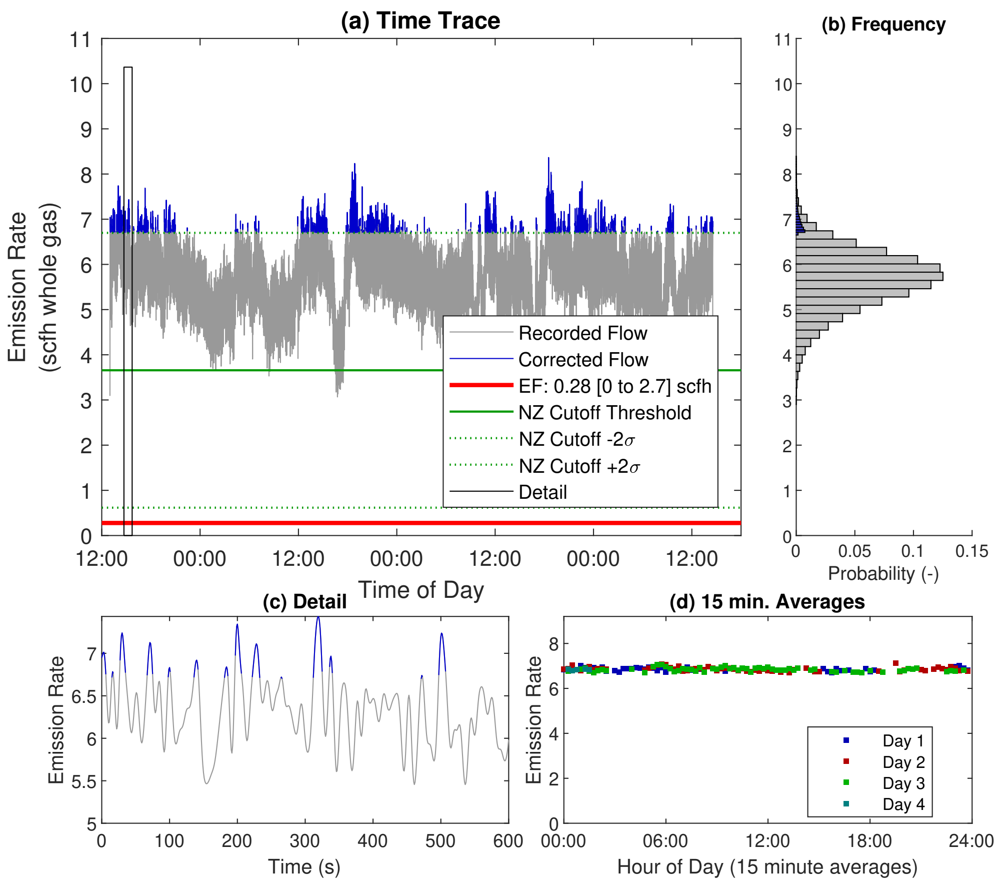

Figure A.80: Device O-4

Device O-5

Site Class: II	NEMS Region: Rocky Mountain
Install Location: Inline	Measurement Duration: 28.8 hrs
Controller Location: Compressor	Avg. Gas Temperature: 57.1 $°F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 41.9 psia
Controller Model: Mallard 3200	Gas Methane Fraction: 89.5%
EPA Bleed Type: Intermittent	Emission Factor: 0 [0 to 0]
Non-zero Correction:	NZ Cutoff: 12.7 scfh
Samples Remaining: 0%	Emissions Remaining: 0%
Evaluation: -	

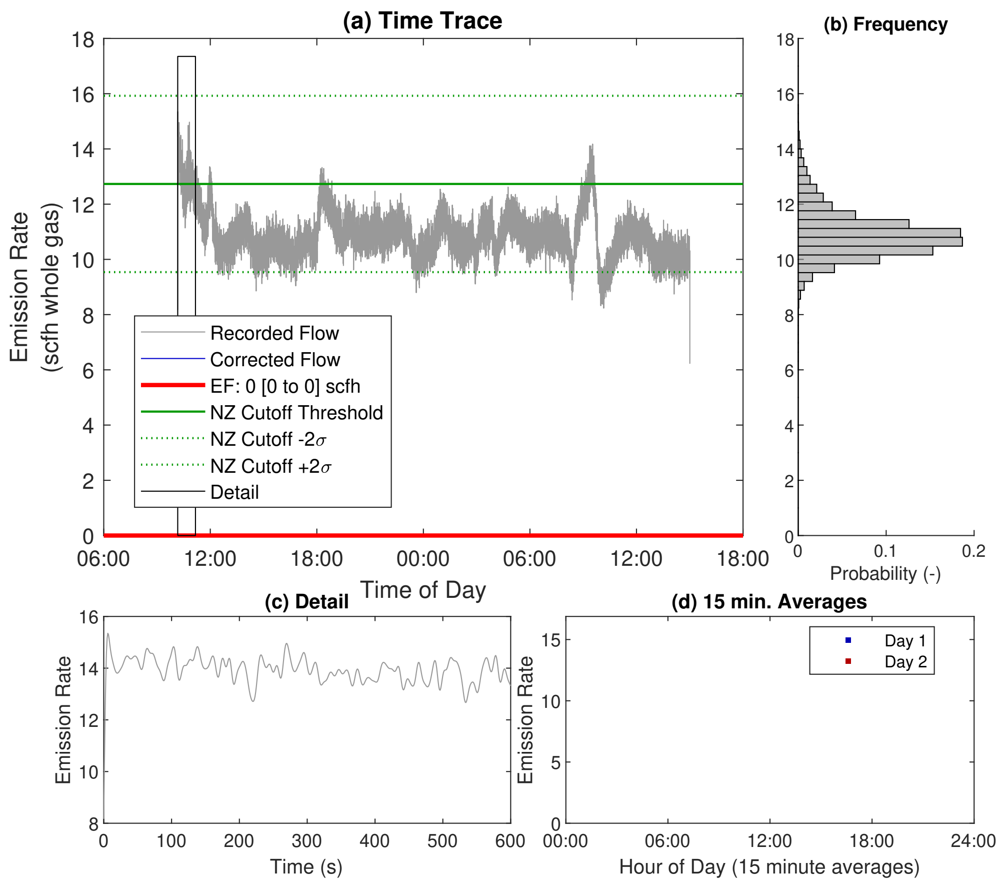

Figure A.81: Device O-5

Device P-3

Site Class: III	NEMS Region: Gulf Coast
Install Location: Inline	Measurement Duration: 68.6 hrs
Controller Location: Compressor	Avg. Gas Temperature: 49.7 $^{\circ}F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 39.5 psia
Controller Model: Norriseal 1001A	Gas Methane Fraction: 94.5%
EPA Bleed Type: Intermittent	Emission Factor: 0.00048 [0 to 0]
Non-zero Correction:	NZ Cutoff: 6.37 scfh
Samples Remaining: 0.0049%	Emissions Remaining: 0.007%
Evaluation: -	

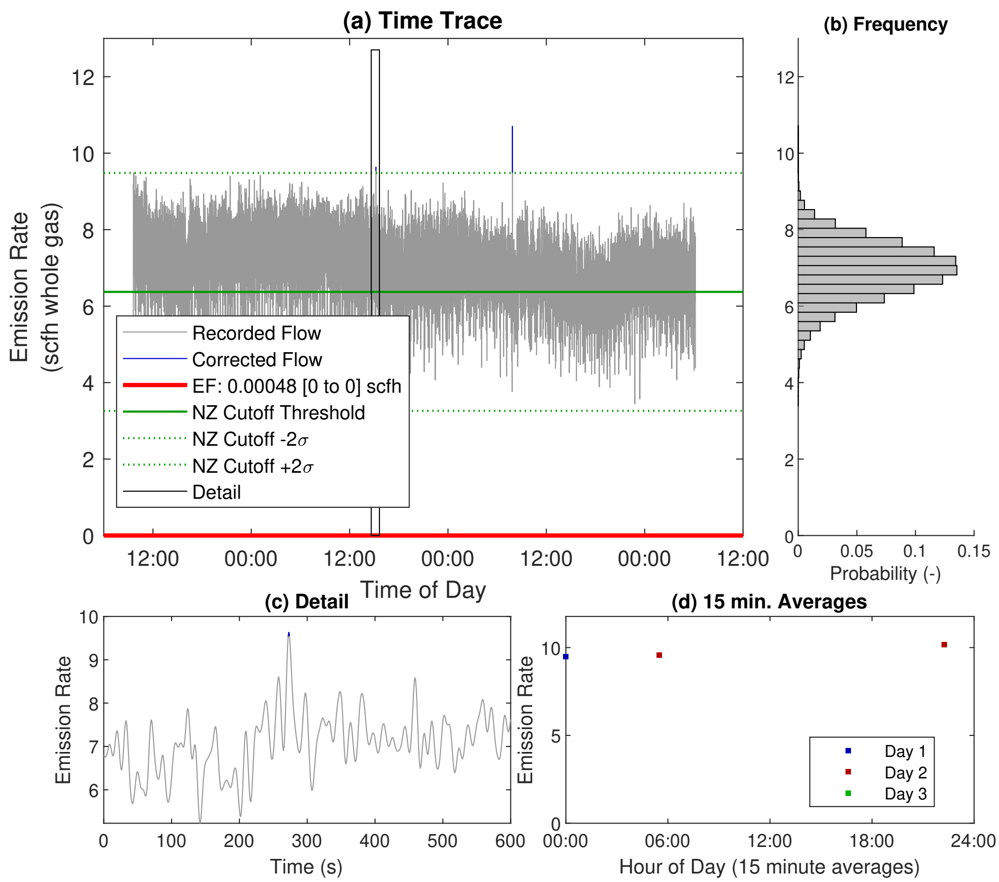

Figure A.82: Device P-3

Device P-4

Site Class: III	NEMS Region: Gulf Coast
Install Location: Inline	Measurement Duration: 68.7 hrs
Controller Location: Compressor	Avg. Gas Temperature: 45.9 $^\circ F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 68.5 psia
Controller Model: Norriseal 1001A	Gas Methane Fraction: 94.5%
EPA Bleed Type: Intermittent	Emission Factor: 0 [0 to 0]
Non-zero Correction:	NZ Cutoff: 25.8 scfh
Samples Remaining: 0%	Emissions Remaining: 0%
Evaluation: -	

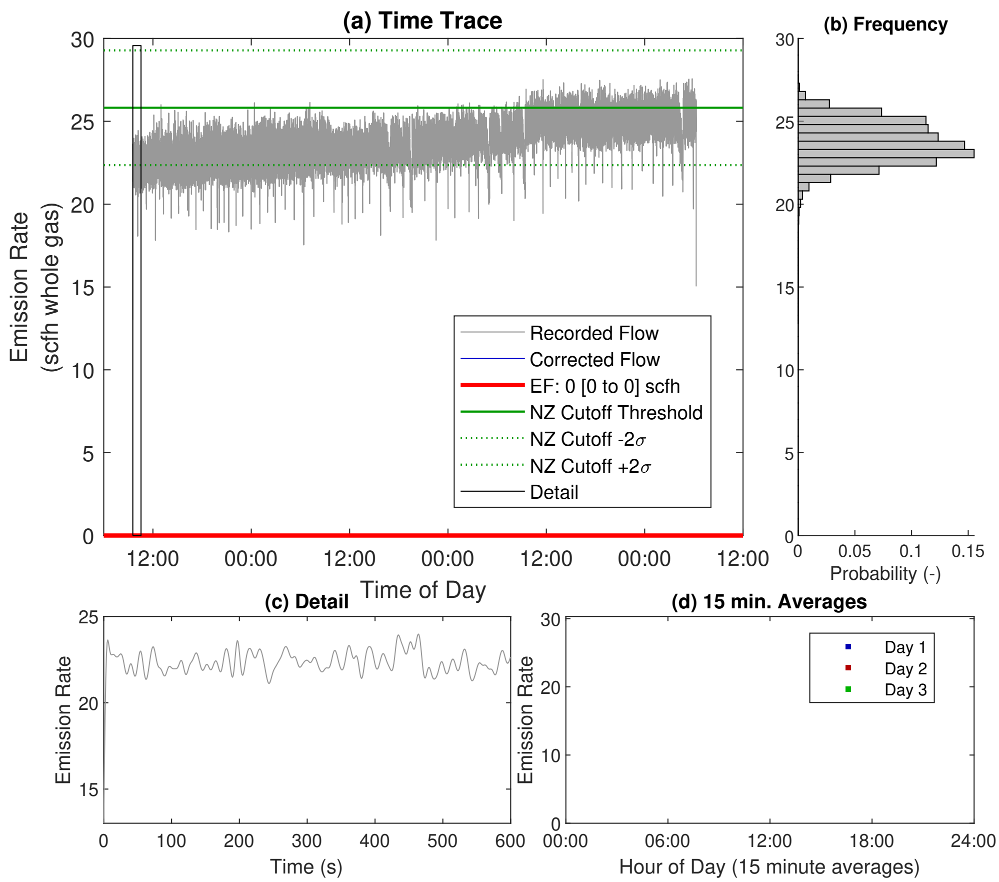

Figure A.83: Device P-4

Device T-1

Site Class: III	NEMS Region: Rocky Mountain
Install Location: Inline	Measurement Duration: 69.4 hrs
Controller Location: Separator	Avg. Gas Temperature: 4.89 $^{\circ}F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 35.8 psia
Controller Model: Solenoid Operated	Gas Methane Fraction: 89.5%
EPA Bleed Type: Intermittent	Emission Factor: 0.0085 [0 to 0.009]
Non-zero Correction:	NZ Cutoff: 1.66 scfh
Samples Remaining: 0.18%	Emissions Remaining: 0.53%
Evaluation: -	

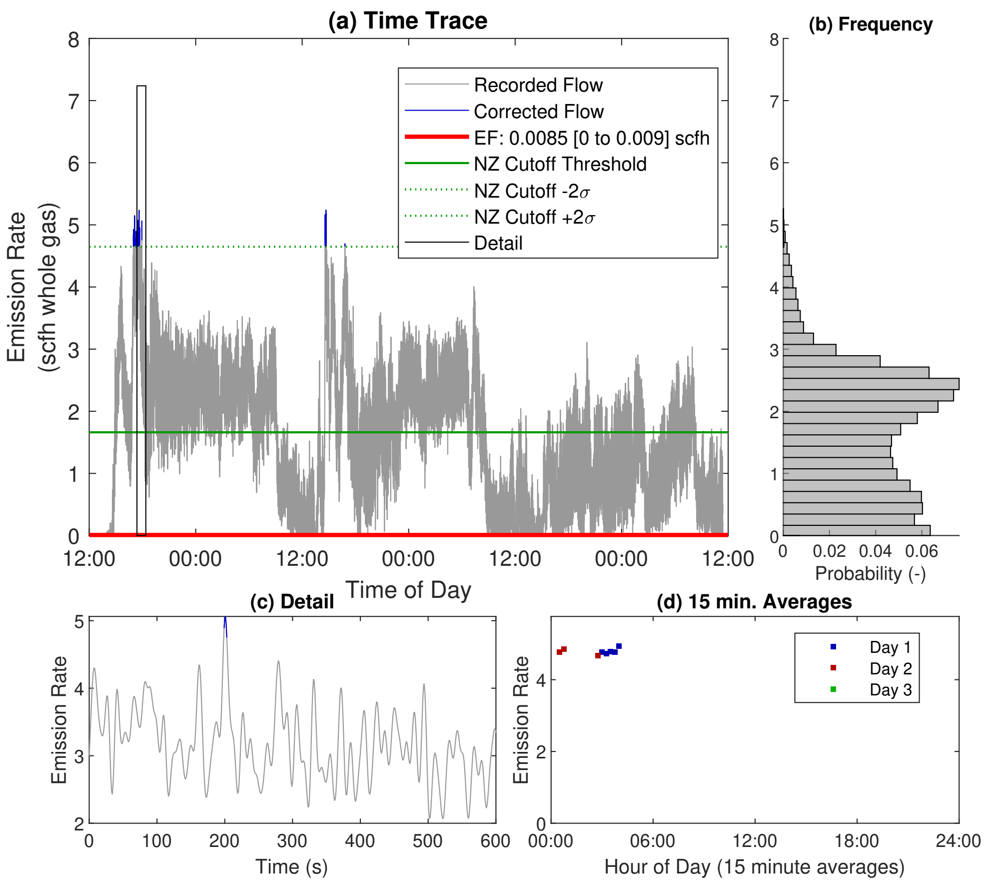

Figure A.84: Device T-1

Device U-1

Site Class: III	NEMS Region: Rocky Mountain
Install Location: Inline	Measurement Duration: 76.3 hrs
Controller Location: Separator	Avg. Gas Temperature: 16 $°F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 50.6 psia
Controller Model: Unknown	Gas Methane Fraction: 89.5%
EPA Bleed Type: Intermittent	Emission Factor: 0 [0 to 0]
Non-zero Correction:	NZ Cutoff: 11.4 scfh
Samples Remaining: 0%	Emissions Remaining: 0%
Evaluation: -	

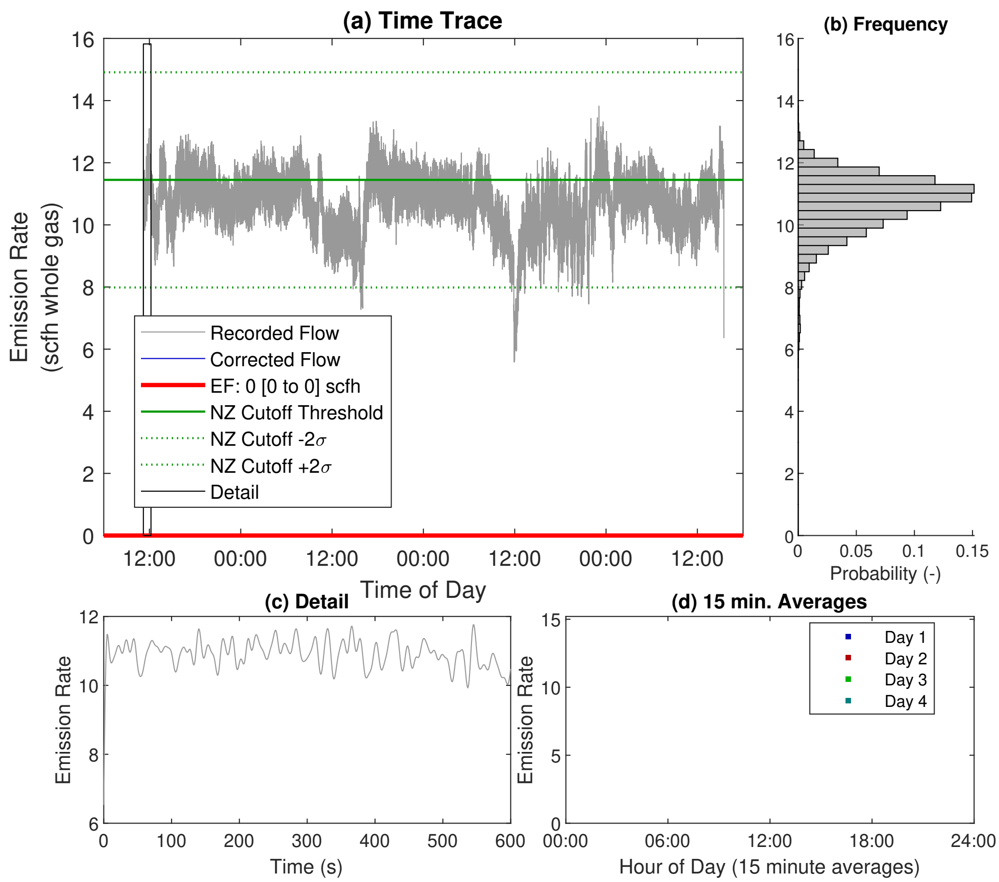

Figure A.85: Device U-1

Device U-4

Site Class: III	NEMS Region: Rocky Mountain
Install Location: Inline	Measurement Duration: 76.8 hrs
Controller Location: Compressor	Avg. Gas Temperature: 54.2 $°F$
Process Controlled: Liquid Level	Avg. Supply Pressure: 44.8 psia
Controller Model: Mallard 3200	Gas Methane Fraction: 89.5%
EPA Bleed Type: Intermittent	Emission Factor: 0 [0 to 0]
Non-zero Correction:	NZ Cutoff: 8.89 scfh
Samples Remaining: 0%	Emissions Remaining: 0%
Evaluation: -	

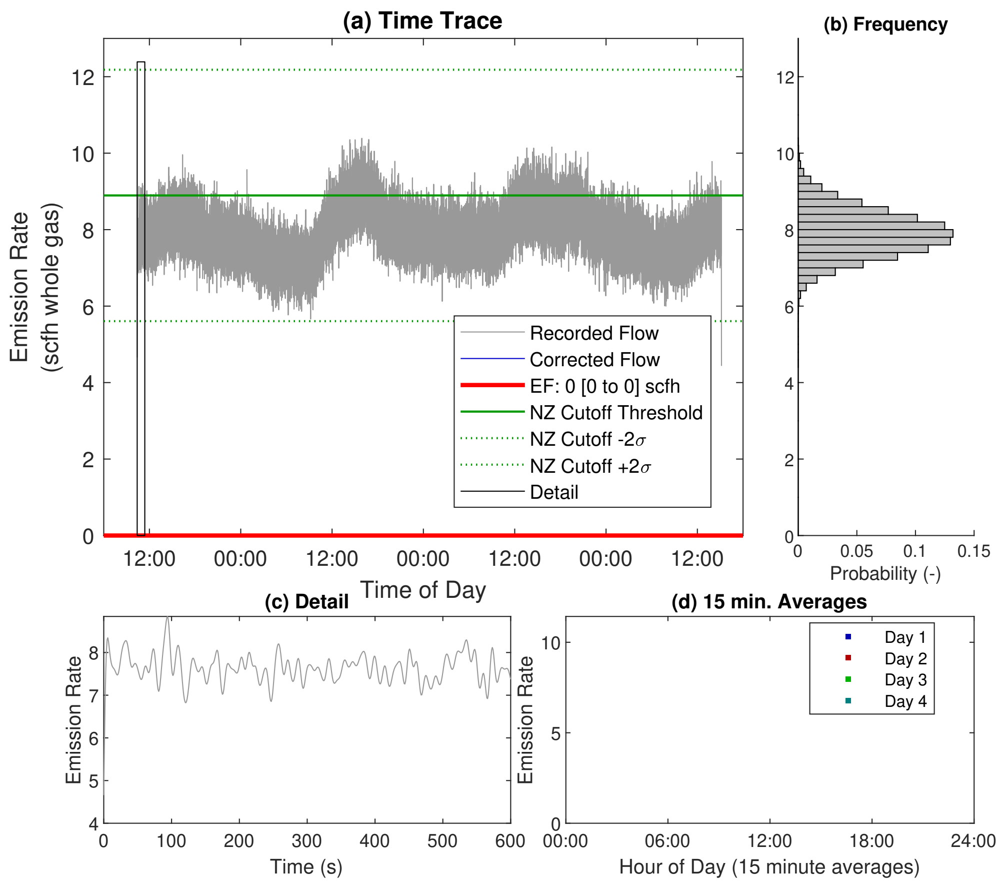

Figure A.86: Device U-4