Performance Assessment of Loci Controls Automated Landfill Gas Collection System

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Executive Summary

Loci Controls manufactures and operates automated control and measurement devices for active gas collection systems at municipal solid waste (MSW) landfills. The Loci system is mounted to individual landfill gas (LFG) collection wells or along the header system (which are larger pipes carrying gas from multiple wells), takes measurements (gas composition, flow, temperature, and pressure), and makes automated adjustments according to a programmed logic system with user-specified setpoints. Loci Controls contracted with PTP Informatics, LLC to examine operational and performance data of the Loci system at four operating landfill sites, each of which have a LFG-to-energy project (three Renewable Natural Gas, or high-BTU projects and one electricity generation project). The data and performance assessment covered three areas: (i) standalone review of the operation and performance of the Loci system, (ii) operation of the Loci system relative to *status quo* operation of manual landfill gas wellfield management, and (iii) orientation of gas system performance at the four Loci system sites within the larger population of US MSW landfills with active landfill gas collection systems.

Key observations are as follows:

1. **Number of Well Adjustments**

   The Loci system makes a far greater number of adjustments to individual LFG collection wells compared to manual wellfield tuning. Standard practice for manual wellfield tuning normally follows US federal regulatory minima, which require once monthly measurement of individual LFG wells. Our analysis of measurement and adjustment records at one site where the Loci Controls system was installed found wells underwent 4.96 valve adjustments per day (95% confidence interval: 4.64 – 5.28, n = 120 wells), which is approximately 15,000% greater than the standard, manual practice of one adjustment per well per month. These results are generally consistent with operation of the Loci system in general and are not particular to the site analyzed. The collective effect of establishing setpoints that limit air intrusion, frequent measurements, and frequent adjustments toward setpoint, result in more effective CH_4 collection and reduces the amount of air introduced into the LFG collection system.

2. **Methane Flow: Individual Landfill Gas Collection Wells**

   Individual operating records of gas collection wells indicate moderate to strong increases in methane flow after the installation and operation of the Loci system. This observation is based on an evaluation of 124 wells across two sites with substantive historical records. Further, the Loci system was shown to avoid extended periods where little or no gas is collected from a given well, an outcome attributable to the algorithm-based automated well adjustment system that increases or decreases vacuum applied to the collection well on the basis of frequent measurement of gas concentration and other parameters.

3. **Methane Flow: System Wide**

   Totalized methane flow rate (representing cumulative flow from a landfill's entire wellfield) showed a marked increase at each site following wide-scale deployment (approximately defined as controlling 75% or more of available landfill gas flow[1]) and operation of the Loci system. The near-term performance improvement after Loci system installation generally ranged from a 13% to 24% increase in methane flow or associated energy plant output, which is the most useful measure of performance improvement. Totalized data exhibited variability consistent with normal wellfield conditions (e.g., well damage, wells filling with liquid, seasonal weather changes, and other factors), but the Loci system further enabled stable and increasing performance over time, even when controlling for the installation of new gas collection wells. These performance improvements were attributed to the greater degree of control enabled by the system, the increased "visibility" of well conditions that enable near-real-time adjustments, and the automated, 24 hour per day, well adjustment capability on an individual and whole-wellfield basis.

4. **Operational Downtime**

   Operating data from one site with substantial, historical energy production plant records showed a marked decline in the number of operating hours lost because of poor inlet gas quality after installation of the Loci system. In the 18 months prior to

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[1] This definition derives from available data reviewed in this four-site evaluation. Section 3 provides additional, relevant discussion.

the first major Loci system installation, the plant experienced 59.1 hr of downtime attributable to poor inlet gas quality ($\mu \approx 3$ hr of monthly downtime) and in the 30 months after the first major Loci system installation, the plant experienced 30.3 hr of downtime ($\mu \approx 1$ hr of monthly downtime). The first full year of extensive Loci system installation (year 2019) showed even better performance ($\mu \approx 0.5$ hr of monthly downtime).

5. **Maintenance of Anaerobic Conditions (CH_4:CO_2 Ratio)**

   Operating data at wells with the Loci system were found to consistently maintain levels of CH_4 relative to CO_2 consistent with normal, "healthy" anaerobic waste decomposition conditions, which substantially reduces a site's risk profile (e.g., risk associated with "overpulling" on the wellfield, leading to aerobic conditions and subsurface heating events) compared to manual operation, provided there is extensive wellfield coverage with the Loci system.

6. **Collected Methane Quality Compared to 800+ GCCS in the US**

   Annual (year 2018) average site-wide CH_4 concentrations at the three sites with the Loci system installed in year 2018 were in the top decile when compared to total average CH_4 concentrations at 844 other operating MSW landfills in the US with active gas collection systems, indicating high performance relative to the broader population of operating landfill sites in terms of total collected gas quality.

Based on the data reviewed for four operating sites and assessing a range of evidence (inherent nature of the Loci system's operation, individual well data, totalized gas collection data, and comparison to the broader population of MSW landfills), the Loci system provides both direct and indirect performance improvements compared to manual gas wellfield operation. Using an accumulation of evidence approach, the data showed an increase in CH_4 collection both in individual well data and total system flow and energy plant data. Further, data from one site exhibited a substantial reduction in plant downtime caused by inlet gas quality. Further, the large volume and granularity of data, coupled with feedback mechanisms that enable rapid problem identification and system adjustment, reflects a mix of operating quality and performance that cannot be matched by standard manual monitoring and operation of a landfill gas wellfield.

1 Analytic Purpose and Report Scope

Loci Controls contracted with PTP Informatics, LLC[2] to analyze available data from four sites at which Loci's automated landfill gas control system operates and review these data against historical site performance to assess if (and by how much) performance at its sites differs compared to standard, manual site operating conditions that were present before the Loci system was installed. The analysis here necessarily relies on data collected by and provided by others, and all site data were taken "as is" and were assumed to be collected using accepted methods with calibrated instruments. In addition to reviewing data from Loci sites, PTP Informatics collected, analyzed, and synthesized additional, relevant data sets related to landfill gas collection systems and their performance, both for comparative analysis with Loci system data but also to provide context around the topics of landfill gas production, collection, and emissions. The analytic work reported here was performed between December 2019 and April 2020.

2 Introduction: Landfill Gas Production and Collection Basics

2.1 Regulatory Overview – US Federal Rules and Standards

Municipal solid waste (MSW) landfills are one of the largest anthropogenic sources of methane (CH_4). Landfill gas (LFG, which principally includes CH_4, CO_2, and small amounts of a wide mix of other gases) is principally produced from anaerobic decomposition of degradable organic materials (Figure 1) and volatilization of other chemicals contained in deposited waste. Although the amount and composition of LFG production changes over time, the bulk of a landfill's lifetime reflects methanogenic (methane-forming) conditions.

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[2] This analysis and report were prepared by Jon Powell, Ph.D., P.E., CEO of PTP Informatics, LLC. See Section 6.

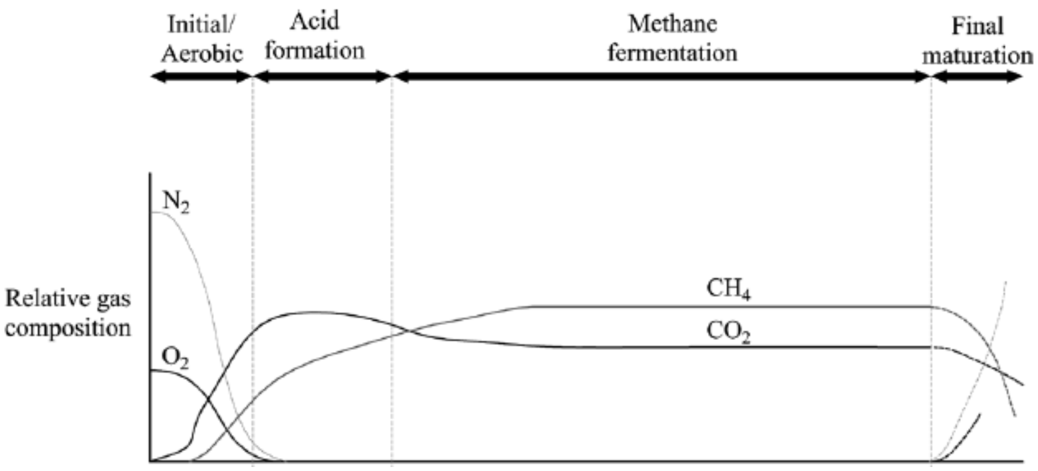

Figure 1. Generalized Figure of Landfilled Waste Decomposition and Stabilization Phases (adapted from Townsend, Powell et al. 2015). The scale is not uniform – the initial/aerobic and acid formation stage normally occur at a landfill over several months, with methane fermentation occurring over a period of many years.

Four sets of key federal regulations directly relate to LFG migration, production, collection, measurement, and destruction, as summarized in Table 1.

Table 1. Summary of Four Key Federal Regulations Related to LFG from MSW Landfills

Federal Rule Name	**Code of Federal Regulation Section**	**Brief Description of Applicability to Landfills and Landfill Gas**
Resource Conservation and Recovery Act, Criteria for Municipal Solid Waste Landfills	40 CFR Part 258	Limit odors and lateral migration of CH_4 into structures and beyond the property boundary
New Source Performance Standards	40 CFR Part 60 Subpart XXX[3]	Design and operational standards for LFG collection systems
National Emission Standards for Hazardous Air Pollutants	40 CFR Part 63 Subpart AAAA	Destruction, startup, and shutdown procedures for LFG collection and control systems

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[3] Section for current NSPS shown for brevity; Emission Guidelines have similar structure as NSPS

Federal Rule Name	**Code of Federal Regulation Section**	**Brief Description of Applicability to Landfills and Landfill Gas**
Greenhouse Gas Reporting Program	40 CFR Part 98 Subpart HH	Estimation, measurement, and reporting of LFG production and (as applicable) collection and destruction

Of note in Table 1 are the New Source Performance Standards (NSPS) for MSW landfills (analogous rules exist for landfills that existed prior to promulgation of the rule), which in part explicitly spell out (i) design standards that active LFG collection systems (hereafter referred to as gas collection and control systems (GCCS)) must meet, and (ii) operational standards for GCCS after they are constructed, which include monitoring requirements to assess system performance and ensure the GCCS is operating as intended by the rule. Although an extensive discussion of the nuances of the NSPS rules is beyond the scope of this discussion, relevant components of design, operation, and monitoring requirements as specified in the rule are as follows:

1. Individual collectors (usually vertically-constructed or horizontally-constructed wells, see Section 2.1) must be designed and specified to provide sufficient coverage of the entire landfill. The rule specifies timelines indicating how soon new areas of waste must be “covered” by the GCCS.
2. Individual wells must be operated under a pressure vacuum, in a manner to avoid elevated temperatures (which can lead to subsurface oxidation, aerobic conditions, and/or subsurface fires), and in a manner to avoid the intrusion of ambient air into the landfill.
3. Individual wells must be monitored at least monthly and the monitoring event must collect data that portrays the operational condition of each collector that is part of the permitted GCCS.
4. LFG that is collected by the GCCS must be destroyed (i.e., combusted or converted into less-harmful products), which can be accomplished with flare systems or energy conversion systems that utilize or otherwise meet the rule definition of destruction.

The design of well systems in a GCCS are established as part of a formal GCCS design plan, which incorporates necessary calculations and assumptions to demonstrate a system comports with rule requirements. The “coverage” of the landfill is demonstrated at the design stage by making a series of engineering judgments and assumptions to show the designed system will effectively collect LFG that is produced. Design criteria for wells normally include:

1. Expected production rate of LFG
2. Hydraulic characteristics of the waste
3. Assumed operating conditions (e.g., applied pressure at the well)

Standard practice for estimating LFG production rates assumes first-order decomposition kinetics as shown in the following equation:

$$G_{CH4} = \left[\sum_{x=S}^{T-1} \left\{ W_x \times MCF \times DOC \times DOC_F \times F \times \frac{16}{12} \left(e^{-k(T-x-1)} - e^{-k(T-x)} \right) \right\} \right]$$

Where S is the start of the calculation year; MCF is the methane correction factor, DOC is degradable organic carbon, DOC_F is the fraction of DOC dissimilated, F is the fraction of CH_4 present in the LFG; k is a decomposition rate constant, and W_x is the quantity of waste disposed of in a given year.

A designer will use the equation above (or some variant) to predict the amount of LFG produced on an annual basis. Usually, the only measured value available for the equation is the quantity of waste disposed of at the landfill, which is based on historical scale records from the landfill site and expected future amounts. Even when site-specific weight records are used, the amount of modeled LFG production depends on the specific materials within the waste and the characteristics of the materials – Figure 2 displays compositional data for MSW landfilled in the US as of 2018. As the figure shows, a wide range of materials are disposed of into landfills, each of which has variable ability or tendency to decompose and generate LFG (e.g., food waste is generally quickly degradable, paper is moderately degradable, and soil/inert material and metals will not appreciably degrade). The composition going into a specific landfill will vary from the values shown in Figure 2 and will change over time, which directly influences both the DOC and DOC_F variables in the LFG production equation. Further, the other factors influencing the estimate of LFG production are usually taken from the grey literature (e.g., technical papers, government reports, and the like) or peer-reviewed literature, rather than site measurements. Thus, accurately predicting the amount of LFG produced for a given point in time can be challenging and is subject to a wide amount of error. Despite these limitations, the approach described above reflects the state-of-the-practice for GCCS design, and the proximity of the design's specifications to accommodating actual site conditions after system construction directly affects the quality of the GCCS operation and overall LFG collection and emission outcomes.

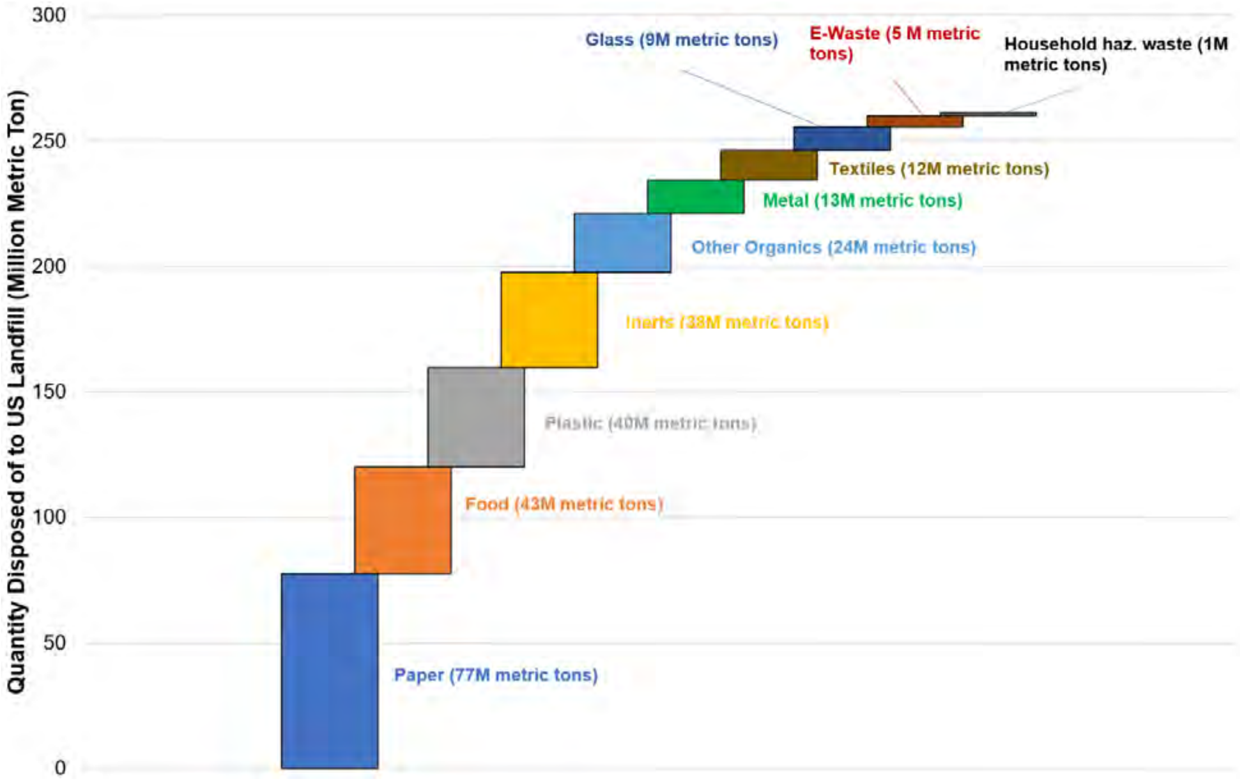

Figure 2. Breakout of Landfilled Components of MSW, Year 2018[4].

The design process also must use assumptions regarding the hydraulic characteristics of waste, which (along with assuming an applied vacuum pressure at the well) directly influences the apparent area or radius of influence of a given collector. When the designer establishes these values, wells are placed on a map of the landfill and this becomes the basis for how the GCCS wellfield is built. Just as the variable amounts and types of waste influence characteristics like degradability, the hydraulic characteristics are also influenced and can vary widely over time and space in the landfill. Figure 3 portrays an illustration of this concept, which shows extensive

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[4] Powell (2020). Research Brief: Materials Landfilled in the United States and Opportunities to Increase Materials Recovery, 2018 Update. Incorporates methods and data from Powell and Chertow 2018.

measurements of air permeability (a measurement of how readily a gas can move through a defined cross-sectional area) at a full-scale operating landfill. The figure shows that air permeability substantially decreases – by two orders of magnitude – as the landfill gets deeper, which can be attributed to greater overburden pressures at depth and a greater moisture content relative to areas of the landfill closer to the surface. These observations are critical, as substantial differences in hydraulic characteristics of waste – namely, the ease with which gas produced surrounding a well can be pulled into the well and into the GCCS – should be expected in real-world conditions. As demonstrated, design tools can only be made to guard against these differences, therefore the actual operating conditions (i.e., degree of applied pressure at the well, the removal of flow impediments like built-up liquid) serve as a critical hedge against poor GCCS performance.

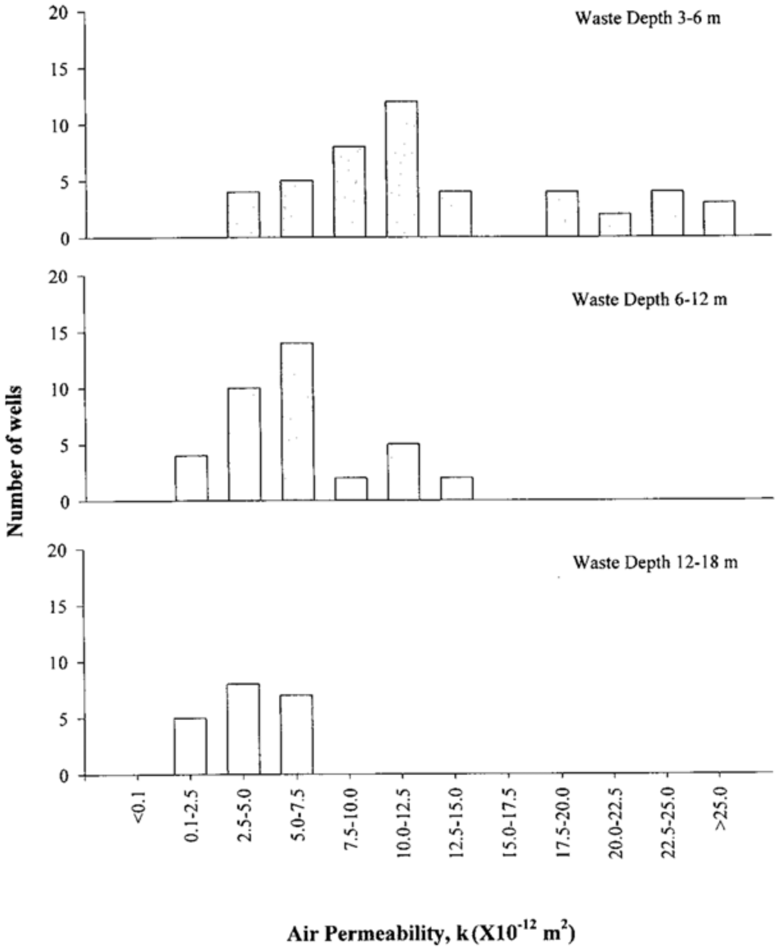

Figure 3. Relationship Between Waste Depth and Air Permeability of Compacted MSW (adapted from Jain et al. 2005).

2.2 GCCS Components and Performance Characteristics

GCCS designs share a common principle: placing individual collection points, networking the collection points together, and routing the collected gas to one or more points where the gas is destroyed or otherwise converted. Figure 4 gives a simplified cross-section of an MSW landfill showing the major collection components. When a GCCS is initially built, standard practice is to build out the wellfield consistent with the design plan, covering the areas that must undergo active collection per the site's permit. As a landfill continues operating, new wells are added to collect LFG from newer areas of the site, and typically older wells can be extended or otherwise replaced, the degree to which is based on the amount and frequency of damage incurred by the system during operations and on the landfill's sequence of filling waste.

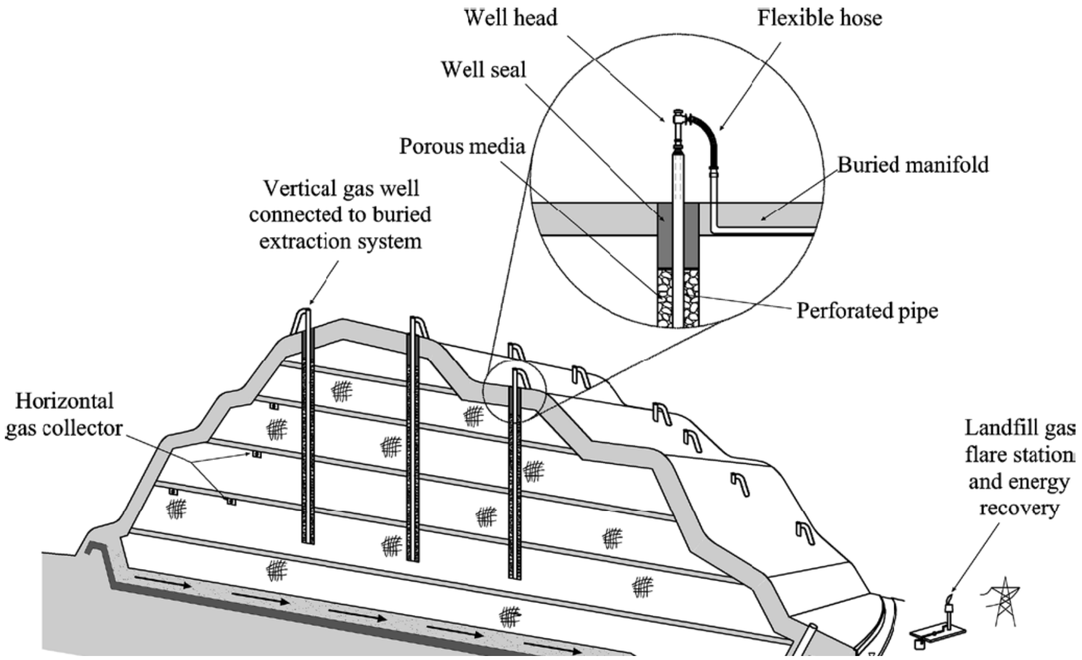

Figure 4. Schematic of Typical GCCS Components at MSW Landfills (Adapted from Townsend, Powell et al. 2015)

A closer view of a typical vertically-oriented LFG collection well is provided in Figure 5. As shown in the figure, vertical wells have protective rock surrounding a perforated section of pipe, which transitions to solid pipe closer to the surface to reduce the potential for air intrusion through the landfill surface and into the waste. Above the surface, a wellhead assembly provides the opportunity to collect regulation-required monitoring data, which can be done through measurement with a specialized LFG monitoring instrument. With few exceptions, every well connected to the GCCS must be operated according to federal NSPS operational standards, which includes operating under a vacuum with an oxygen concentration <5% and a temperature <131 °F.

Monitoring wells at a GCCS must be done once monthly (per Federal NSPS rules) and is normally accomplished manually by a human operator and a calibrated instrument. Taking a measurement from one well normally takes at least a few minutes with industry standard equipment like a GEM-5000. Once a measurement is complete, the wellfield operator can make an adjustment to the well (e.g., increase or decrease vacuum pressure depending on the information gleaned from the measurement) and moves on to the next measurement point on foot or by vehicle. The time to complete the regulatory-required monthly wellfield measurement in this manner may take one or more days depending on the size of the wellfield and other factors.

The performance of GCCS in strict quantitative terms is not well understood. Although the literature has reported on individual studies of efficiency (taken as the amount of gas collected compared to the total gas produced), such measurements can be subject to large error, principally because of challenges in creating accurate predictions of LFG production (see Section 2.1 for further discussion). Additionally, measuring LFG *emissions* (which would be a useful component of a total site mass balance and give a clearer understanding of likely efficiency) is only sparingly done quarterly, and the regulatory-required fashion of measuring surface emissions only covers a relatively small fraction of the total landfill surface, and normally takes several hours or more to complete, thereby missing critical dynamics of gas migration through the landfill surface. Additional methods of measuring emissions through the cover have been developed, but have mostly been deployed in research contexts.

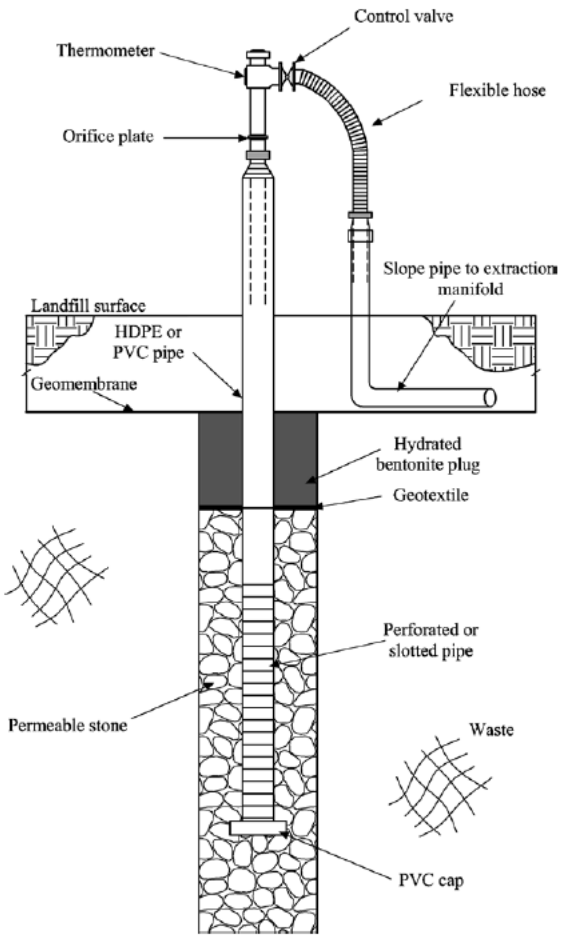

Figure 5. Detail Cross-Section of Vertical LFG Collection Well Components (Adapted from Townsend, Powell et al. 2015). Note that this reflects a well installed at a landfill with a closure cap in place – at a landfill that is open, the surface would contain cover soil but likely no geosynthetic cap.

The best measurement of landfill performance comes from data reported to the US EPA's Greenhouse Gas Reporting Program. In brief, MSW landfills sites required to report to the program (i.e., those exceeding a CO_2-equivalent emissions threshold, reflecting about 90% of operating MSW landfills) submit data indicating the total area of landfill surface covered by a gas collection system and the total area not covered by a gas collection system – in all, the program uses five unique surfaces with a different assigned default value of gas collection efficiency. The assigned default values were established by US EPA during the development of the Greenhouse Gas Reporting Rule and reflect a combination of literature-reported values and public feedback. Once information about the area of each surface type is entered by an individual site, a weighted-average LFG collection efficiency is computed and reported. Figure 6 summarizes the reported LFG collection efficiency for 847 landfills reporting to this program in 2018.

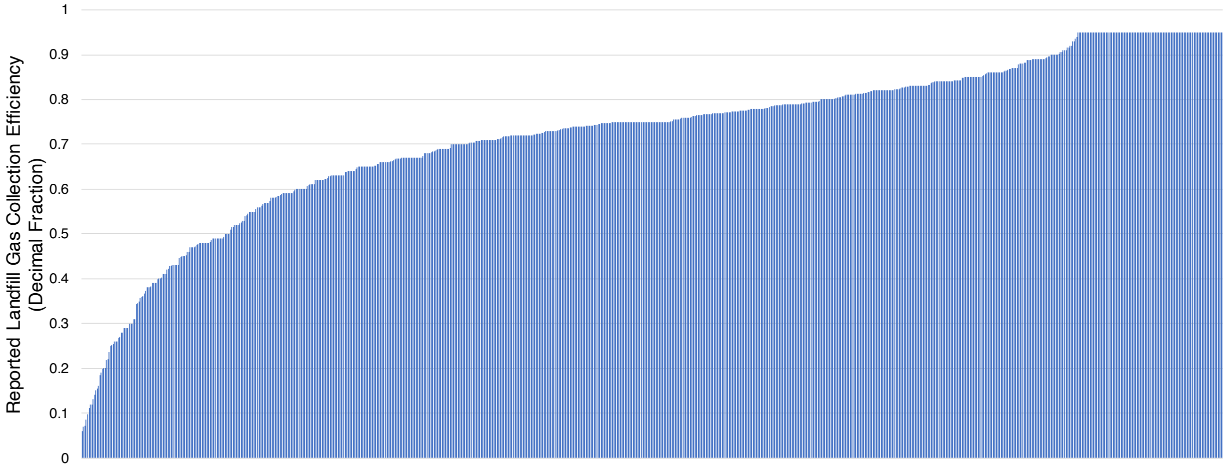

Figure 6. Reported Gas Collection Efficiency at Landfills Reporting to the US Greenhouse Gas Reporting Program, Year 2018 (n = 847 Landfills)

The figure shows a wide range of reported, calculated LFG collection efficiencies, ranging from less than 10% to 95%. There is a cluster of sites showing 95% efficiency, which reflects landfills that are closed and have GCCS infrastructure covering the entire landfill area. The data in Figure 6 can be a useful benchmark – in principal, LFG collection efficiency is expected to be better at closed landfills (in Figure 6, μ = 86%, n = 154), as the surface has a low-permeability cap per federal MSW landfill regulations, and GCCS coverage is complete. Open (i.e., actively-operating; in Figure 6, μ = 69%, n = 693 sites) landfills tend to have a lower LFG collection efficiency because there are often areas which have newly-placed (and more quickly degradable) waste without any companion GCCS infrastructure. Although not ideal from an emissions perspective (and, as applicable, an energy production perspective), such a phased approach for open landfills is consistent with allowable practice in the federal NSPS regulations.

We further gathered information on well characteristics – Figure 7 displays a histogram summarizing the number of landfills with a given range of installed LFG collection wells. Nearly two-thirds of landfills with active GCCS have fewer than 100 wells installed. A substantial number of sites have more than 200 individual collectors. The differential in number of wells will principally be a function well type well installed (which is usually constrained by the surface area containing waste – a common design rule-of-thumb is approximately 30-m spacing between wells) and (or) the use of horizontal collectors, which tend to be spaced closer together than vertical wells.

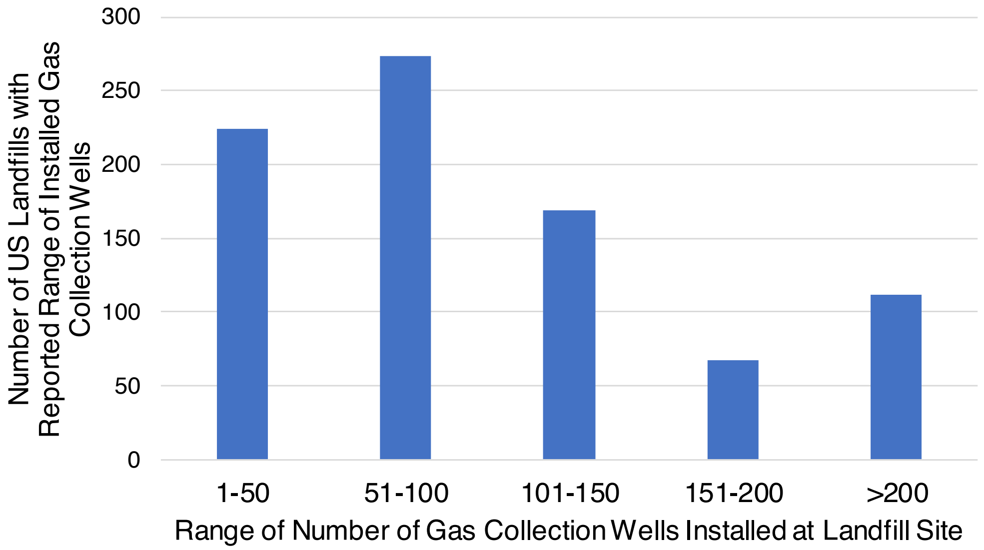

Figure 7. Number of Gas Collection Wells Installed at Landfills with Active Gas Collection Systems in the US, Per the US Greenhouse Gas Reporting Program, Year 2018.

The typical performance of active LFG collection wells, as measured by the total mass of methane collected in a given year, is presented in Figure 8. The methane flow for the average well at active landfills far outstrips that at closed landfills, owing to the relatively weaker rates of gas production observed in older waste. Here, the difference in median CH_4 collection rates is about 50 Mg of CH_4 per well per year. The figure also shows a far wider distribution of CH_4 recovery rates at open landfills, which is expected in view of the kinetics of LFG production and the potential for some sites to (at least temporarily) display outsize recovery amounts during the initial years following waste placement.

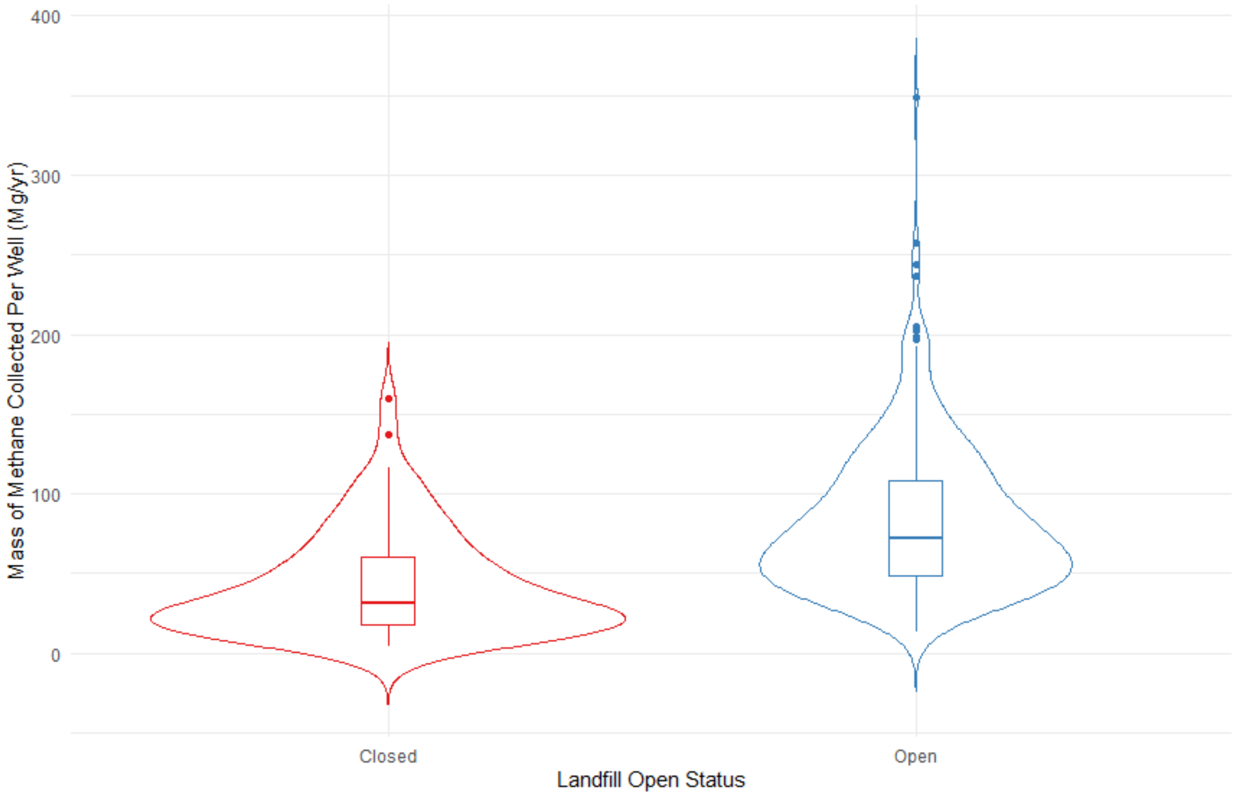

Figure 8. Comparison of Collected Methane, Mass Basis, at Closed and Open Landfills in the US. The Violin (Outer) Plots[5] Represent the Overall Distribution of Data, While the Box-and-Whisker (Inner) Plots Show the Median, 25th and 75th Percentiles (i.e., the interquartile range (IQR)), and the whiskers represent 1.5 times the IQR

2.3 Loci System Overview and Description of Operating Sites Analyzed

Loci Controls manufactures two types of products (sentry, intended for header monitoring, and controller/guardian, an integrated product that is installed on individual collection wells that includes monitoring and control capability). Loci's products are intended to be deployed at individual wells and can be deployed at one or more locations in GCCS header systems. Fundamental aspects of the Loci system include the following:

1. Optical sensors to measure LFG composition

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[5] The violin plots show a probability density via a kernel density plot – the display less than zero is simply an outcome of how these types of displays are visualized at values near 0, but to be clear all methane collection flow data are greater than zero.

2. Flow measurement device (in-device or coupled with a flow meter – orifice plate or pitot tube)
3. Remotely-activated valve controller coupled with algorithm-driven automation with site-specific LFG quality setpoints
4. A cellular-connected online platform for data compilation and real-time performance evaluation
5. Batteries and solar panels
6. Real time text, or e-mail alert system to accelerate detection, and corrective action for mechanical or gas collection system problems.
7. Remote automatic and on-demand calibration, with NIST-traceable calibration gas

An image of an installed Loci system is provided in Figure 9. Although its development has evolved over time, as of this writing there are two algorithms used to automate valve adjustments that dictate LFG extraction conditions at each well. The first (referred to as a "Fine Tuning" Algorithm) is a well-by-well automation that collects a well gas composition measurement at a defined interval (a common interval is every 1 hour[6]), then makes an adjustment to the well's valve on the basis of the result of the reading (a common interval is every 3 hours). A common example is that if a reading for a well has a CH_4 concentration less than the system set point, the valve will be closed a small amount. The automation continues in this fashion, adjusting the valve position up and down, to keep the well's operation within the desired operating limits. A second automation (referred to as the Aggregate Gas Composition algorithm, which is an optional deployment at a Loci installation) can create batch adjustments to many wells on the basis of aggregate LFG quality characteristics at an hourly frequency. A simple example here is if measurement at a header pipe (e.g., at a point just prior to entering an energy conversion plant) shows less-than-desired LFG quality, multiple valves may be incrementally throttled to reduce vacuum pressure to help bring the BTU content back above the site's specified threshold.

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[6] Per personal communication with Loci Controls, April 2020.

Figure 9. View of Vertical Landfill Gas Collection Well Equipped with the Loci System (image source: Loci Controls).

Four US-based sites where Loci operates volunteered to provide data as part of this effort. The data request was initiated in mid-December 2019 and we worked iteratively with Loci and indirectly with its site partners and the data collection phase was considered complete on 25 February 2020. We were provided multiple years of operating data including manual well measurements, total gas flow (including composition and other information), Loci operating data, and variable amounts of site information (e.g., design plans, drawings, etc.).

The four sites and their information has been de-identified as part of a confidentiality request – here, use a consistent, anonymous set of names for each site (Site A, Site B, Site C, and Site D). Three of the four sites (A, B, and D) are “high-BTU” LFG-to-energy projects that upgrade the collected gas to nearly 100% methane, and these three also incorporate the Loci Aggregate Gas Composition algorithm. Site C is a LFG-to-energy project that converts the collected LFG into electricity and does not incorporate the Aggregate Gas Composition algorithm.

3 Results and Discussion

3.1 Individual Well Measurement and Adjustment

The first evaluation of individual well operation includes assessing the frequency of well adjustments at individual wells. Figure 10 displays a summary of historical average adjustment data at Site D.

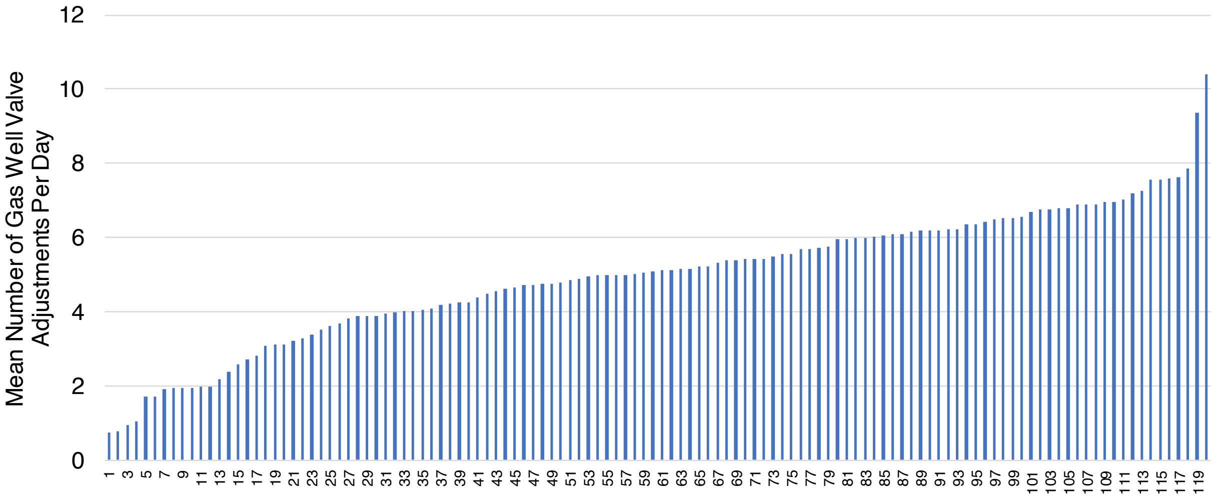

Figure 10. Average Number of Daily Well Valve Adjustments By the Loci System at Site D. Each bar represents a unique gas collection well, and the y-axis represents the average number of valve adjustments made to the well per day during the well's full operating period since installing the Loci system.

On average, wells shown in Figure 10 had 4.96 valve adjustments (95% confidence interval (CI): +/- 0.32) per day, with the average number of days in operation for the Loci system of 455. As a point of comparison, on average a well with the Loci system made approximately 15,000% more adjustments on a monthly basis compared to standard wellfield operating practice with one measurement and one adjustment per month.

As described in Section 2, the Loci system collects an LFG composition reading at a defined interval and, depending on the result of the reading, automatically adjusts the well's valve to bring the well closer to a defined setpoint. Thus, if the concentration of CH_4 drifts away from the set point in successive readings, the valve will be closed a small amount (0.5% per adjustment[7], based on a 0% (fully closed) to 100% (fully open) scale). The valve adjustment frequency data indicates a few important implications: (i) LFG concentration on a per-well basis is dynamic and non-uniform over time – some wells require more or less adjustment depending on a host of factors, (ii) more frequent measurement and adjustment, tied to a defined setpoint that maximizes CH_4 and minimizes atmospheric air intrusion, should result in steadier LFG composition compared to less frequent measurement and adjustment, and (iii) more frequent measurement and adjustment should unearth well issues more quickly, resulting in shorter periods of poor performance.

3.2 Individual Well Performance Comparison

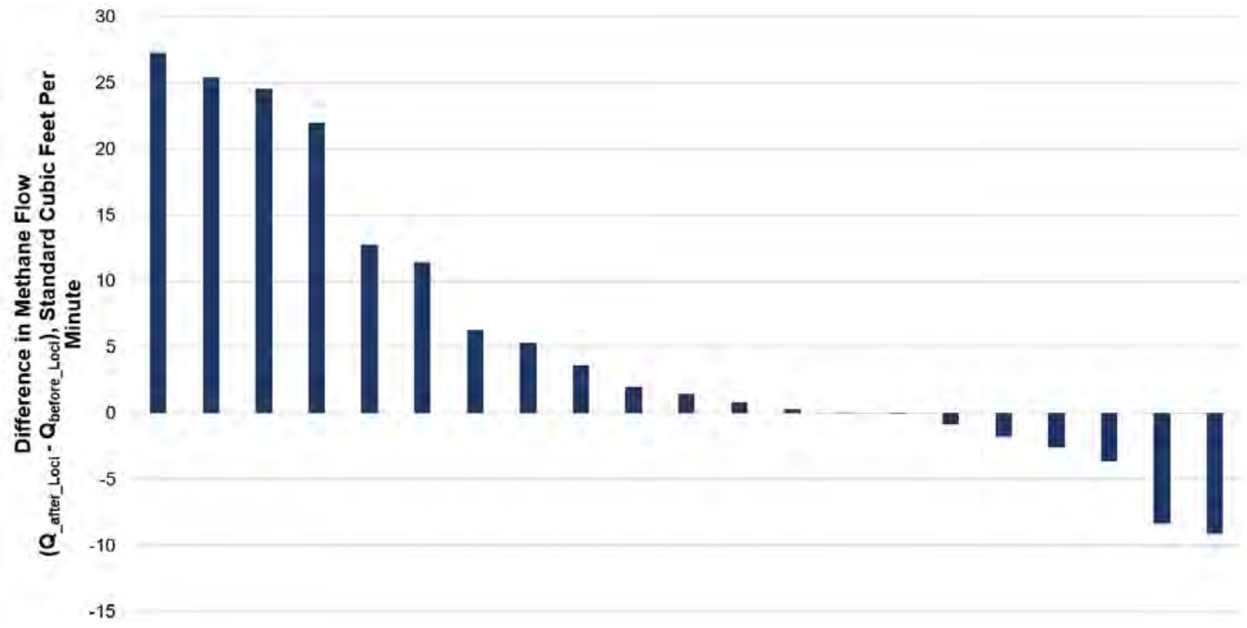

Figure 11. Difference in Per-Well Mean CH_4 Flow Rate. Each Bar Represents the Difference in Average CH_4 Flow Rate After Installation of the Loci System and Before Installation of the Loci System. Data Represents Wells with At Least 5 "Before" Measurements and 5 "After" Measurements, and All Data Reflect GEM Measurements.

Two of the four sites analyzed (Site A and Site B) had sufficient historical (before Loci) and contemporary (after Loci) data to enable a comparison of individual well performance before

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[7] Personal communication with Loci Controls, 26 March 2020.

and after Loci installation. Here "sufficient historical data" means at least five measurements before and 5 measurements after installation with a common measurement device (in this case, a GEM analyzer or equivalent).

Figure 11 shows a comparison of manual measurements at 21 wells operating at Site A. All 21 wells are outfitted with the Loci system, and the figure compares the difference in average CH_4 flow after installing the Loci system compared with the average CH_4 flow at the well before installing the Loci system. Data for each bar reflects manual measurements with a hand-held LFG monitoring device. Fourteen of 21 wells showed an average CH_4 flow increase (range: 0.1 – 27.3 scfm). Of the fourteen, four wells had a historical CH_4 flow of zero, implying the use of the Loci system enabled more frequent measurement to enable a consistent amount of LFG flow as intended in the system design. The remaining wells had a wide range of increases (min: 3% increase in average CH_4 flow, max: 547% increase). The seven wells that had a reduced CH_4 flow rate had more modest absolute values when compared to the observed increases (largest decline: -43%, smallest decline: -7%). These data point toward an overall, sustained increase in CH_4 flow following the installation of the Loci system. An important point to note is the infrequent measurements with the hand-held instruments paint an incomplete picture – additional observations on this phenomenon are presented later in this section.

Figure 12 presents a before and after comparison of individual well performance for Site B. A total of 93 wells are represented in the figure – of the 93 wells, 48 showed an average increase and 45 wells showed an average decrease. As the figure shows, the magnitude of change in both directions appear to be near parity, with a few exceptions at the left end. As with Figure 11, we note that the use of manually-collected GEM data as the sole basis to gauge relative performance has its limitations, principally in the small number of available measurements with which to compare central tendencies.

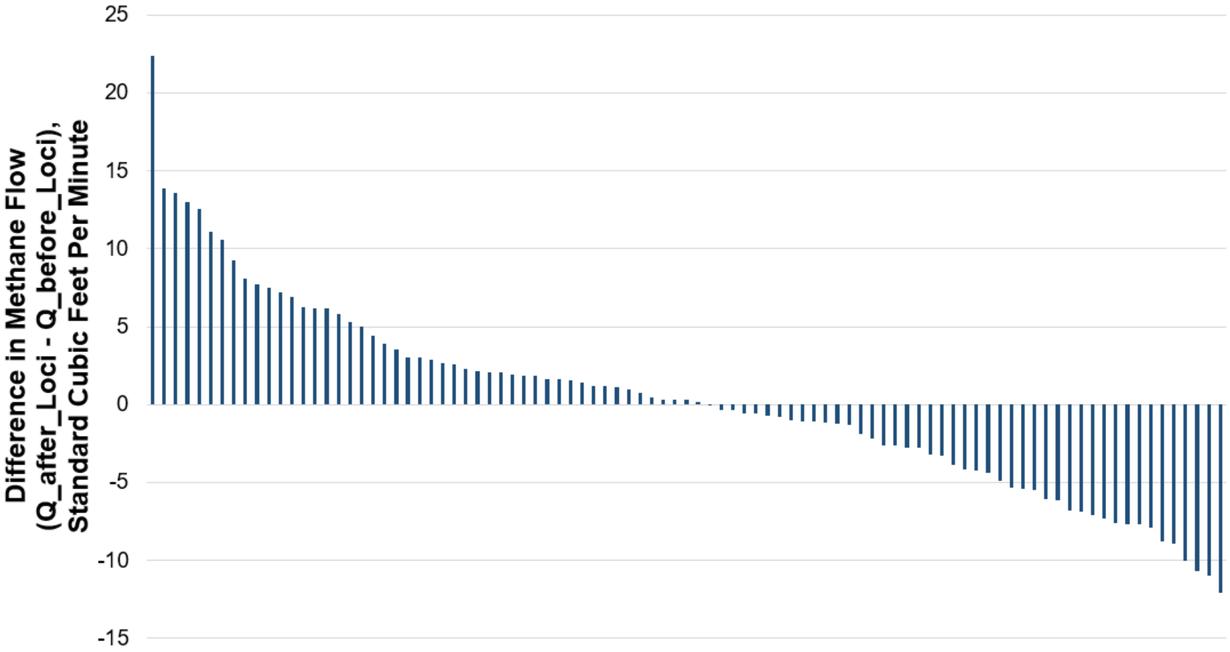

Figure 12. Comparison of Mean CH_4 Flow After and Before Loci System Installation at Site B. The figure represents individual gas collection wells with at least five measurements before and five measurements after. Data only represent GEM measurements.

We developed Figure 13 to illustrate the difference that frequent measurement and adjustment can have on well performance, and how this paradigm compares to the status quo scenario of monthly measurements. The figure portrays historical performance of one collection well at Site B. The top portion of the figure reflects manual, monthly readings, and the bottom portion of the figure reflects output from the Loci system after its installation at the well. Several observations are evident from the figure. First, we can see that, in general, the magnitude of CH_4 flow measured by the portable instrument is consistent with the Loci output at a couple of points in time – initially, just after Loci system installation, and for the period after March 2019. A more comprehensive view of day-to-day operation of the well is evident upon examining the Loci data. Further, more insight into macro trends is evident – first, it can be seen that the historical CH_4 flow in the well was around 10 scfm, but the well maintains a flow for an extended period around 60 SCFM. A few cases are evident when the CH_4 flow dipped, which could be attributable to issues at or adjacent to the well (e.g., the well filling with liquid[8]), but the continuous measurement enabled remediation and restoration of flow to a range from around 30 SCFM to 60 SCFM through the end of 2019.

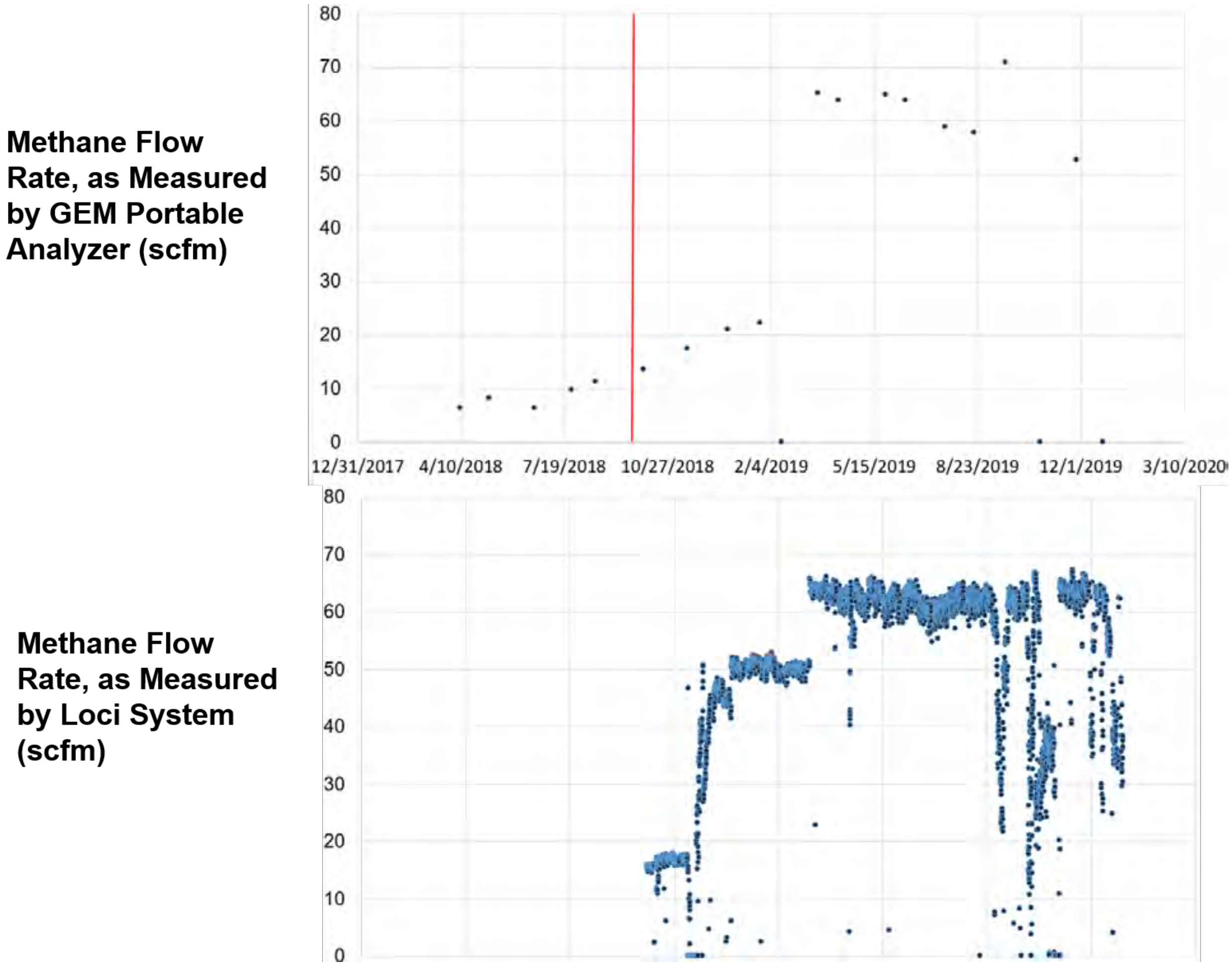

Figure 13. Comparison of Instantaneous CH_4 Flow Rate as Measured by Portable GEM Analyzer (top) and Loci System (bottom), Site B. The Red Vertical Line in the Top Figure Reflects the Time at Which the Loci System was Installed.

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[8] Liquid could be condensation from saturated landfill gas cooling once it is above the surface, resulting in condensation draining back into the well. Liquid could also be landfill leachate, which is liquid that is present in the waste when it is delivered to the landfill or rainfall that percolates into the waste during operations.

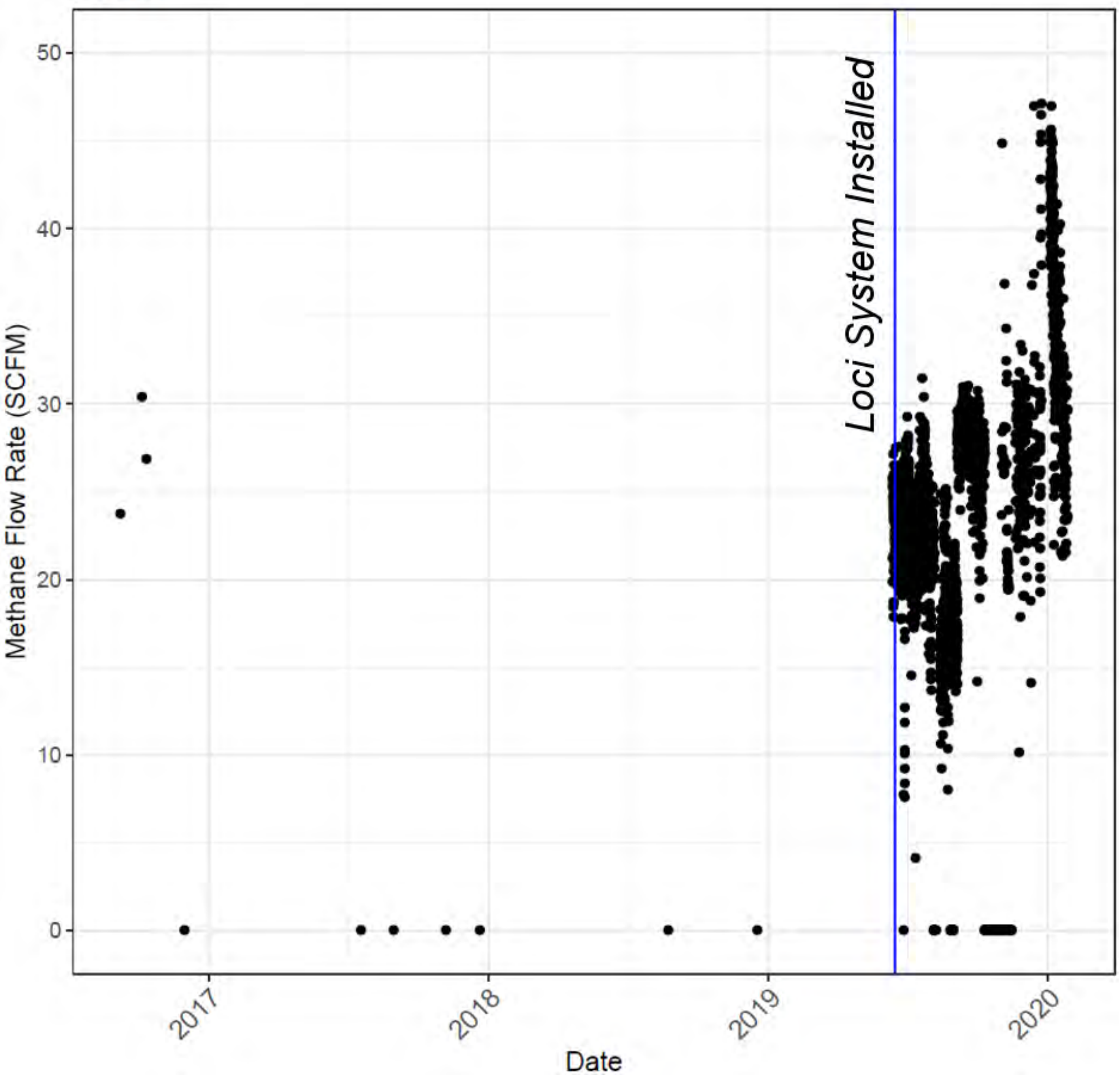

Figure 14. Historical CH_4 flow at a selected well from Site C before and after Loci system installation.

The improvement in CH_4 flow is further illustrated in Figure 14, which displays a historical trend at a well from Site C. The data shows that, except for the initial few measurements, CH_4 flow readings at this site historically showed 0 SCFM. The well was newly-installed in 2017, so the data shown in Figure 14 reflect the entire history of the well. The consistent readings of zero suggest one or a combination of issues with the measurement device, (1) sub-optimal well valve adjustment, and/or (2) system clogging (e.g., liquid build-up inside of the well). Regardless of the case, the figure shows dramatic improvement in CH_4 flow – although there are still occasional zero readings after Loci system installation, the well maintains over time (as supported by frequent measurements) an average flow rate of about 30 SCFM. The data in Figure 14 further bolster the benefit provided by frequent measurement and system adjustment, as this well that was apparently unproductive for months at a time, was immediately transitioned into elevated production after installation of the Loci system. The results in Figure 14 are not unique to that well – of 37 wells at the site, we observed 25 cases where a well had historically low flow that was immediately improved after operating the Loci system.

3.3 Operation Within NSPS Guidelines

As described in Section 2, there are concerns regarding air intrusion into landfills causing aerobic conditions, subsurface oxidation, and subsurface fires. Such conditions can lead to serious consequences in the form of rapid, isolated settlement, substantial and sustained damage to key infrastructure, excessive emissions, and difficult-to-control reactions. This section examines the consistency of operation for wells equipped with the Loci system with specific regard to gas composition. Prior to discussing the data, a brief bit of background on air intrusion, subsurface oxidation, and landfill fires is presented.

The federal NSPS operational requirements in part limit the concentration of certain gases at individual wellheads to avoid air intrusion and its concomitant effects. A useful indicator of "healthy" anaerobic conditions is the ratio of CH_4 to CO_2 at individual wells. In theory (and as indicated in Figure 1), anaerobic decomposition of waste should yield a proportion of CH_4 to CO_2 at about a ratio of 1.2 to 1.5. Active GCCS that are operated in a manner that "over-pulls" with uneven and/or excessive vacuum pressure can lead to undesirable aerobic conditions and the negative effects described above.

For illustration of the deleterious effects of wellfield over-pulling, Figure 15 summarizes published research at an MSW landfill that sustained substantial damage and a series of challenging consequences resulting partly from subsurface oxidation of waste. The figure shows the relationship between the ratio of CH_4 to CO_2 at a select group of wells, and the trend of measured temperature as a function of this ratio is evident: as CH_4:CO_2 declines, temperature increases sharply.

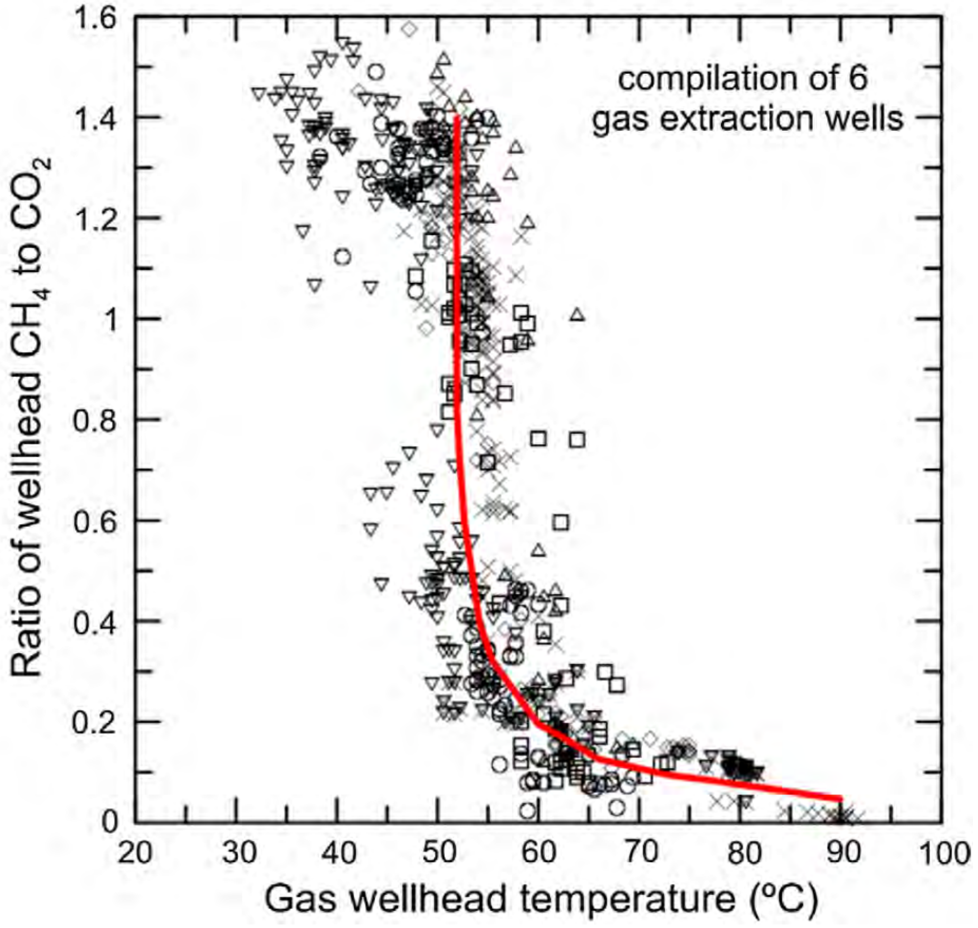

Figure 15. Relationship Between Landfill Gas Wellhead Temperature and the Ratio of CH_4 to CO_2 Concentration. Figure adapted from Jafari et al. 2017.

A companion concern regarding subsurface oxidation, aerobic conditions, and increased waste temperatures is the fact that fires at landfills are somewhat common. Figure 16 summarizes the number of reported fires at MSW landfills in a 7-year period from 2004 through 2010 – as the figure shows, of the 869 landfills with operating GCCS during this time frame, 402 also had at least one reported fire. Of these sites, 151 had more than one reported fire. Evidence suggests that although landfill operators have standard methods to deal with fires, which normally involve suppressing the fire with dirt, aerobic conditions and increased temperatures can re-heat the area, and dissipating the heat can be quite challenging and expensive.

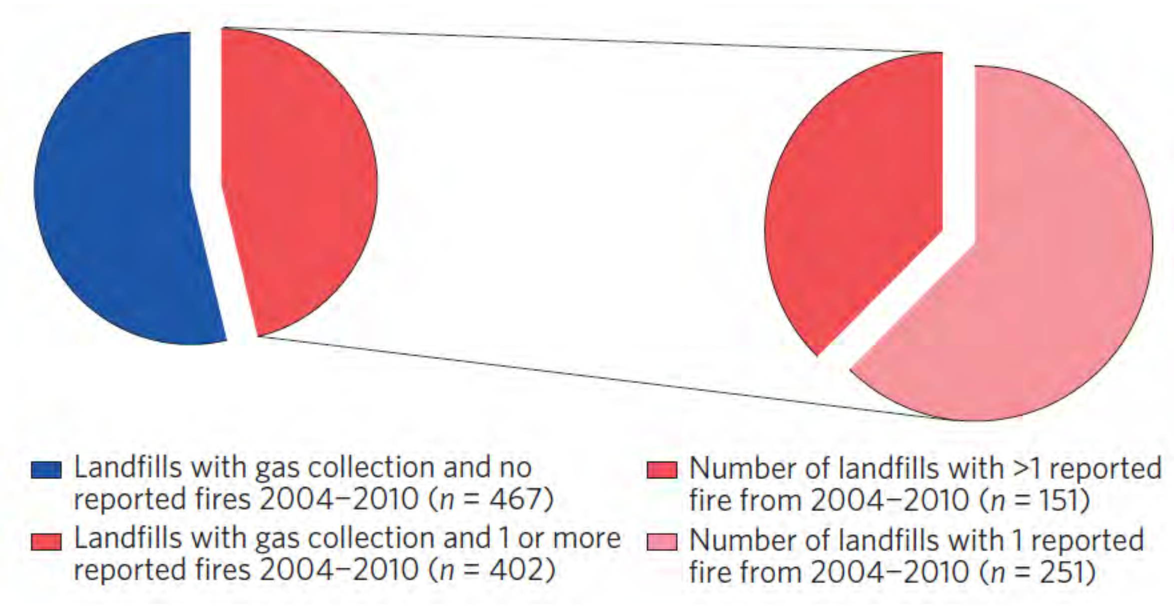

Figure 16. Summary of Reported Fires at US MSW Landfills With and Without Active Gas Collection Systems (adapted from Powell et al. 2016).

Figure 17 presents a summary of historical operational data at 146 wells installed at Site B taken from Loci system data. A few observations are evident from the figure. First, in every case, the CH_4:CO_2 ratio is between 1.2 and 1.5. Although most of the data appear to be points, each mark represents the mean plus the 95% CI – thus, all wells fall within the ideal anaerobic range for operating gas wells, and do so quite consistently over time. The pooled mean CH_4:CO_2 ratio across all wells is 1.34, and Figure 17 reflects approximately 1.1 million measurements for the 146 wells during the Loci system's operation. These results are broadly consistent with previously-displayed individual well results that reflect the rapid opening and closing of valves in response to specified setpoints. In all, these results provide evidence that frequent measurement and automated operation to force wells to operate within a target range would reduce the risk of operating one or multiple wells for extended periods in a manner leading to air intrusion. By contrast, the limited measurements of manual operation, coupled with evident occurrence that dynamic conditions within the landfill can necessitate easing back of vacuum pressure for a short time, suggests the relative risk in this regard is far less with the Loci system compared to manual wellfield operations. Put another way, if a well begins over-pulling, an operator may not become aware of this situation for up to 30 days, as the over-pulling may not be evident in totalized flow data and the operator in this case has no mechanism to know if over-pulling is occurring until her or his next set of well measurements are collected.

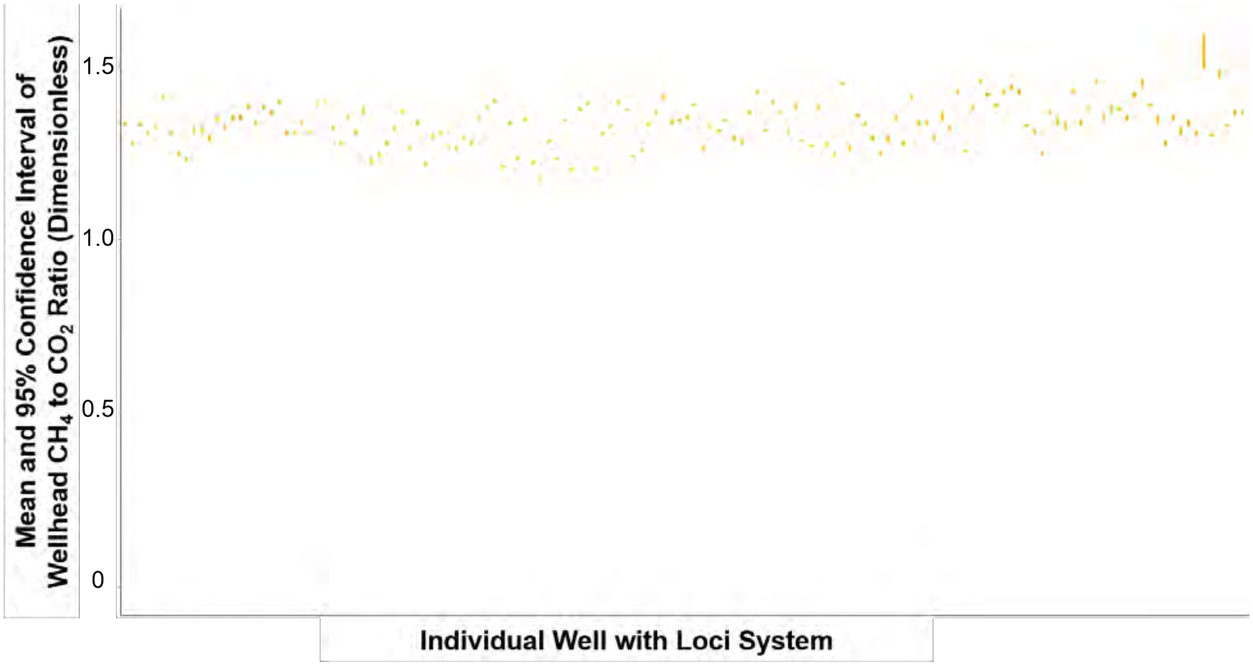

Figure 17. Computed Average and 95% Confidence Interval of the Mean for Measured CH_4 to CO_2 for 146 Gas Collection Wells Site B.

3.4 Totalized System Flow and Performance Assessment

In this section, GCCS performance is observed through the lens of total flow from the wellfield and companion trends. Because landfills are dynamic systems, changes in total gas flow may vary for a variety of reasons:

- Differences in barometric pressure, which increase or decrease the differential pressure between the landfill and the atmosphere, results in a differential pressure gradient making it easier or more difficult to extract gas
- Changes in ambient temperatures, as colder temperatures can slow down the activity of methanogenic bacteria that are decomposing organics within the waste mass

- Addition of new waste, as more waste directly adds to the potential methane production rate as described in Section 2
- The installation of new gas collection wells
- The damage to or declining performance of individual wells

Although as described above there are multiple factors influencing total LFG flow at a landfill, we examined data from multiple Loci sites to assess trends on overall performance (i.e., CH_4 flow) and related factors.

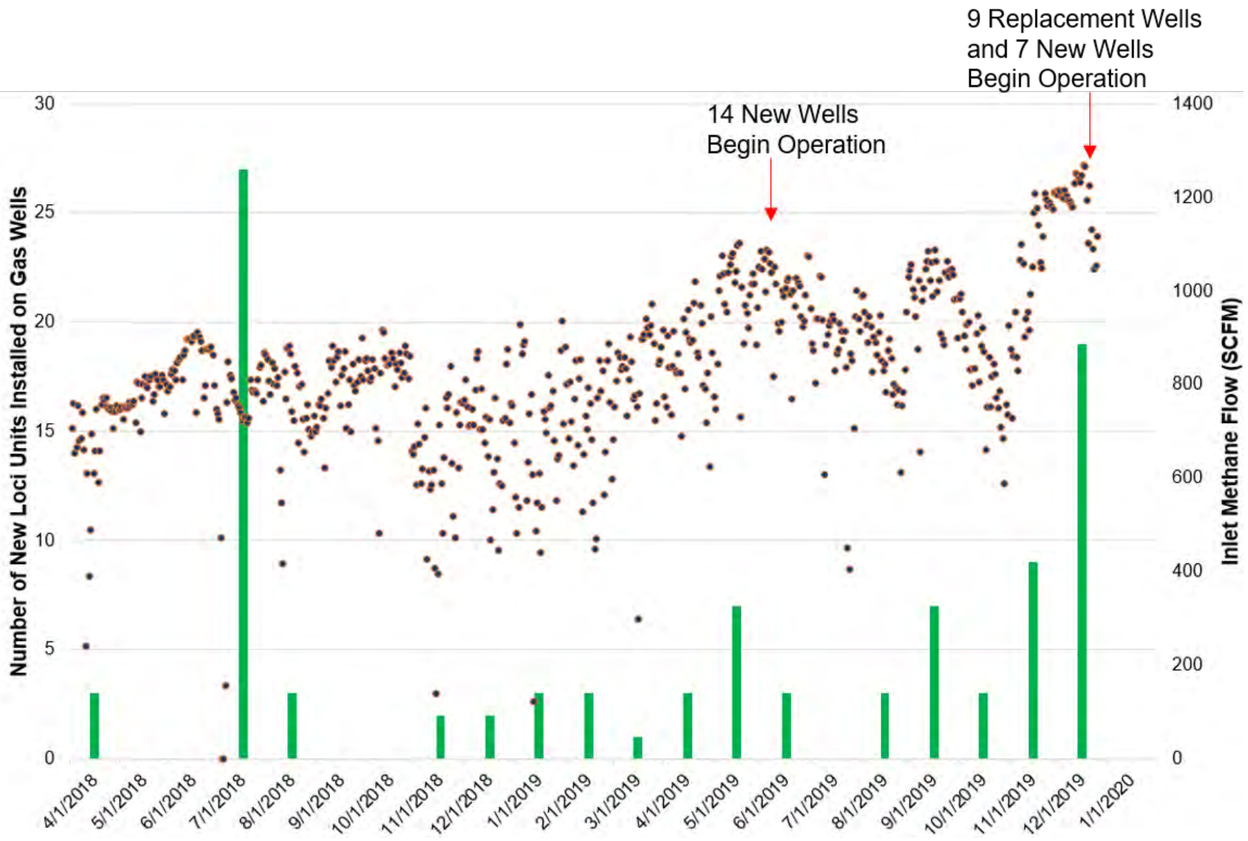

Figure 18. Plot of Instantaneous Daily Total GCCS CH_4 Flow Rate Measurements Over Time (Points), New Loci Units Installed (Bars), and New/Replacement Gas Collection Well Installation (Notations) at Site D.

Figure 18 shows the temporal trend of total methane flow and the progressive deployment of the Loci system, along with new and replacement gas collection wells. The GCCS was relatively new in April 2018, and a steadily increasing trend is shown at first, although the increase likely cannot be attributed to the Loci system as only a few installations were operating. A substantive Loci system deployment occurred in July 2018, with progressive installations coming online in subsequent months. One key trend is the steady, but erratic, increase in flow from late 2018 through mid-2019, which occurred despite no new well additions to the GCCS. The increase can be attributed both to the progressive installation of the Loci system and to the deployment of Loci's Aggregate Gas Composition algorithm that enables batch wellfield adjustment based on totalized flow inlet specifications. After mid-2019, there continued to be progressive Loci system installations (including a large installation in December 2019) along with the addition of new gas wells (14 in May 2019 and 7 in December 2019 began operation) and 9 replacement gas collection wells (December 2019). The new and replacement well installations make discerning a specific trend attributable to the Loci system difficult. However, the Figure shows a series of declining flows – despite installation of several new wells – in July and August 2019, and again in September and October 2019. Following this period, however, is a sharp increase to flow rates not reached previously. There appears to be two clear instances (December 2018 through May 2019 and November 2019 through December 2019) where increases appear to be mostly attributable to the operation of the Loci system. In these cases, the magnitude of flow increase was approximately 25% and 14%, respectively, compared to previous highs.

Figure 19 provides another view of the totalized flow at Site D, but with the Loci installation schedule removed and a trendline in its place. The trendline shows the best-fit linear model, along with a shaded area reflecting the 95% CI of the mean throughout the period of measurement shown. The figure clearly shows that, although peaks and troughs are evident from time to time, the overall trend is a steady increase, which as established can be specifically attributed to the Loci system in at least two distinct periods, with the remaining factors influencing flow increase attributable to the addition of new waste, the installation of new wells, and replacement of low-performing wells.

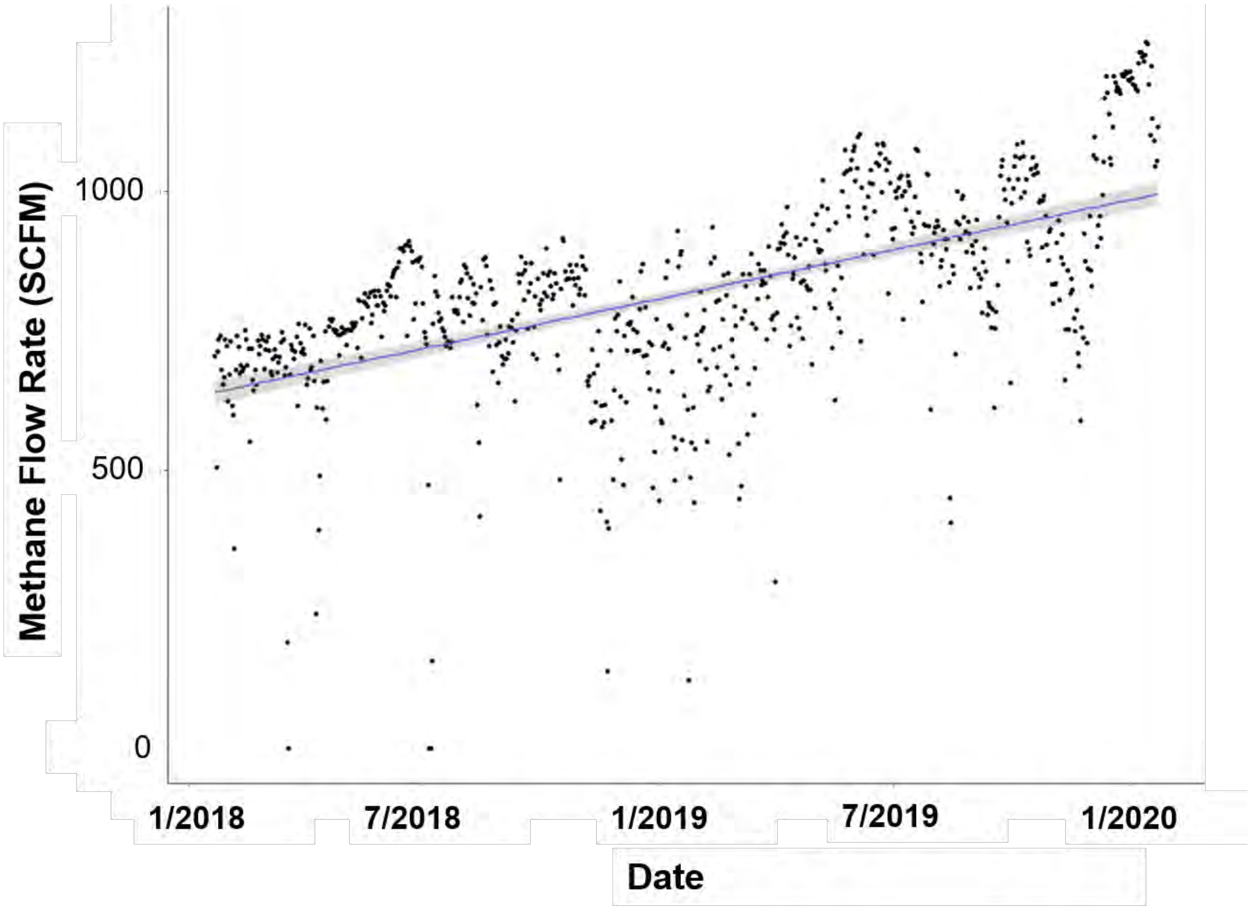

Figure 19. Instantaneous Daily Total GCCS Flow Rate Measurements Over Time, Site D. The best-fit linear regression line is represented with a blue line, and the gray shading reflects the 95% confidence interval of the mean over time.

Figure 20 presents a temporal trend of totalized flow at Site C. In contrast to the Site B depicted in Figures 18 and 19, Site C had the Loci system installed at every well, with the bulk of Loci systems installed in June 2019 and all installs completed by August 2019. No new or replacement gas collection wells were installed after 2016, so because of the batch installation schedule of the Loci system and the lack of new wells added, specific trends with respect to the Loci system impacts on overall performance can be better pinpointed, compared to Site B. Displayed in the figure are the average measured monthly CH_4 flow and the net plant output (Site C has a LFG-to-electricity system). The figure shows that, expectedly, the net plant output and CH_4 flow follow a similar pattern. The data show that in the month immediately following Loci system installation, CH_4 flow increased approximately 9%, with a similarly-large increase in net plant output. Two months later, CH_4 flow is approximately 14% greater than the month just prior to the Loci system installation.

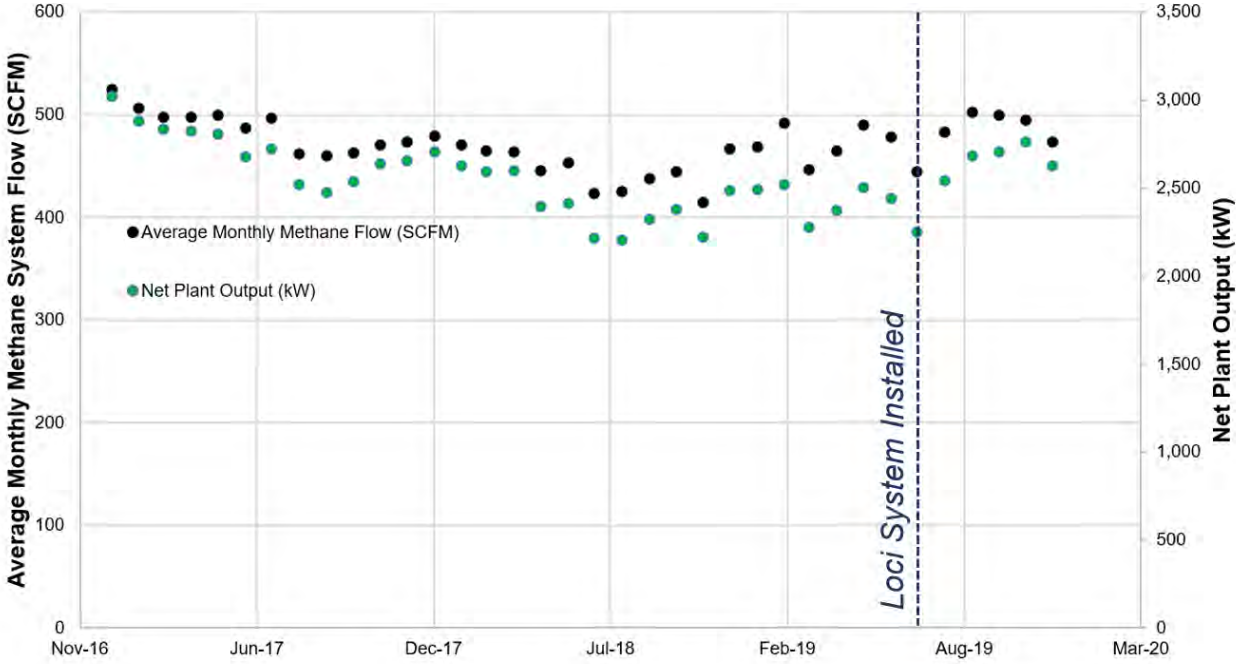

Figure 20. Temporal Trend of Monthly Average Methane Flow and Net Plant Output at Loci Site C. The Loci System was Installed to Cover the Entire Gas Collection System Wellfield in Late June 2019[9].

Figure 21 presents net plant output data for Site C, but in a manner enabling month-wise comparisons for each year data are available. All six months showed a year-over-year increase from 2018 to 2019, from a low of 1.6% to a high of 24.3% and four out of six months showing more than a 13% increase. In both cases (the review of instantaneous increase in flow and plant output and the month-to-month comparison across years), a consistent increasing trend is observed, and in more cases than not, approximately on the order of nearly 13% to 24%. Note that the first data points in early 2017 reflect the start-up of the GCCS – the performance in early 2017 is relatively strong because the GCCS infrastructure is in its most pristine condition. Over time, GCCS components undergo normal wear-and-tear (e.g., shifting of header pipes,

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[9] Based on personal communication with Loci Systems and available operating records for the Loci system at this site.

breakdown of adhesive compounds, clogging of wells), the effects of which are identified and addressed as part of ongoing GCCS management.

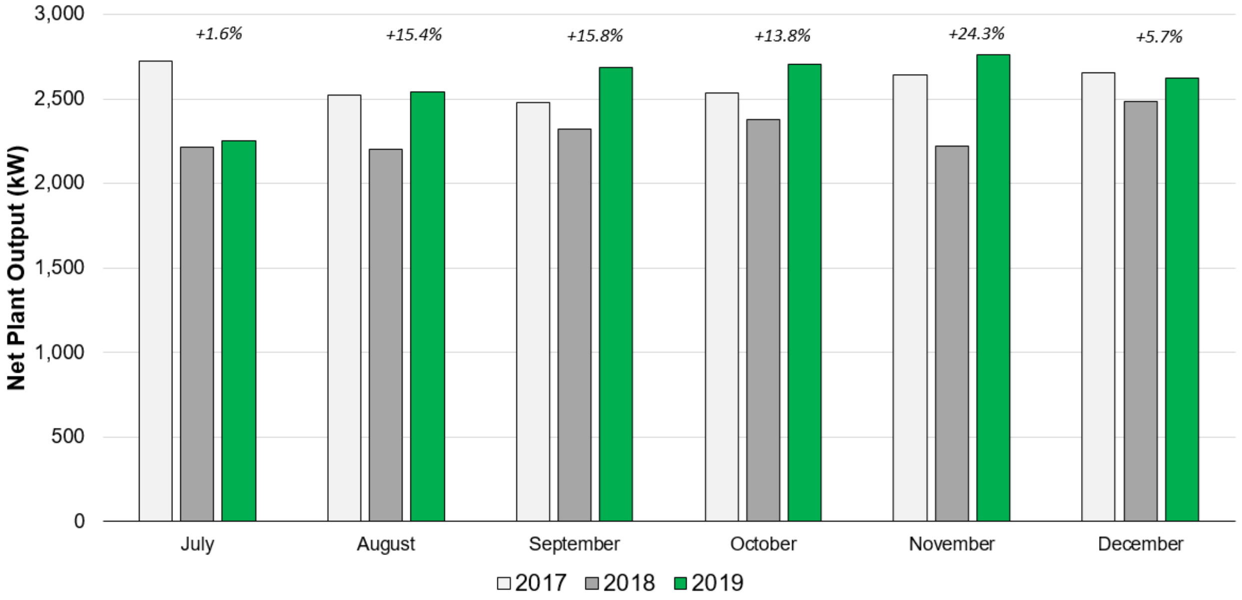

Figure 21. Month-to-Month Trend of Net Plant Output at Loci Site C, Years 2017 through 2019.

Another approach to assess the effect of the Loci system lies in a review of energy conversion plant downtime. As discussed previously, LFG-to-energy projects have strict specifications that must be met – which are more stringent in high-BTU applications than electricity generation applications – thus, the quality of inlet LFG is critical. We reviewed operating records of the LFG energy plan system at Site B (a high BTU LFG-to-energy project), which included daily values of gas composition, plant uptime as a percentage of a 24-hr day, and written comments on each date on which the plant experienced a planned or unplanned outage. We isolated all instances where the plant shutdown cause was a non-damage-related wellfield gas quality issue – representing but one of several reasons for the plant shutdown (others include routine maintenance, new well installation, gas compressor issues, scrubber system repairs, and others). We further reviewed operating records of Site B to evaluate plant downtime, with a focus on causes associated with out-of-specification inlet LFG quality. In our review, we noted "inlet LFG quality" causes of downtime falling into two different categories: (i) those caused by a major wellfield construction effort or explicitly-identified damage to a well or header line, and (ii) those caused by an unacceptable increase in O_2, N_2, or a decline in CH_4 concentration. We removed type (i) from consideration and only focused on causes of shutdown that were not associated with any construction or damage, which we take to be a proxy for overall wellfield management and quality of gas absent any major event.

Figure 22 portrays an accumulation of downtime hours dating back to 2016, and Table 2 summarizes the specific downtime amounts. Two critical events are shown in Figure 22: the installation of an initial tranche of 60 Loci system units in July 2017 and the installation of an additional 140 Loci units in December 2018. Further, December 2018 also marked the roll-out of Loci's Aggregate Gas Composition algorithm that enables batch adjustment to wellfield valves based on inlet flow measurements. Figure 22 shows a decline in the magnitude and frequency of downtime events after the initial installation of 60 Loci units and an even more dramatic decrease after the second batch of Loci units. As summarized in Table 2, the plant experienced 59.1 hours of downtime because of inlet gas quality in the period between January 2017 and July 2017, and 30.3 hr of downtime from July 2017 through December 2018. Importantly, only 6.7 and 6.2 hr of downtime were observed in 2018 and 2019, respectively. These data suggest that the Loci system stabilized overall gas quality from the wellfield and led to a substantial reduction in the amount of plant downtime.

As shown in Table 2, Site B experienced a monthly average plant downtime (again, caused by poor inlet gas quality that was not the result of physical damage) of 3.28 hours. Since the initial installation of the Loci System in July 2017, Site B has experienced a monthly average plant downtime of 1.01 hours. Note that the initial installation in July 2017 represented approximately 20% of the total site LFG flow – the December 2018 Loci System expansion controlled flow of the bulk of the wellfield (approximately 75%). Considering plant downtime since December 2018, Site B has experienced an average monthly plan downtime of 0.5 hr.

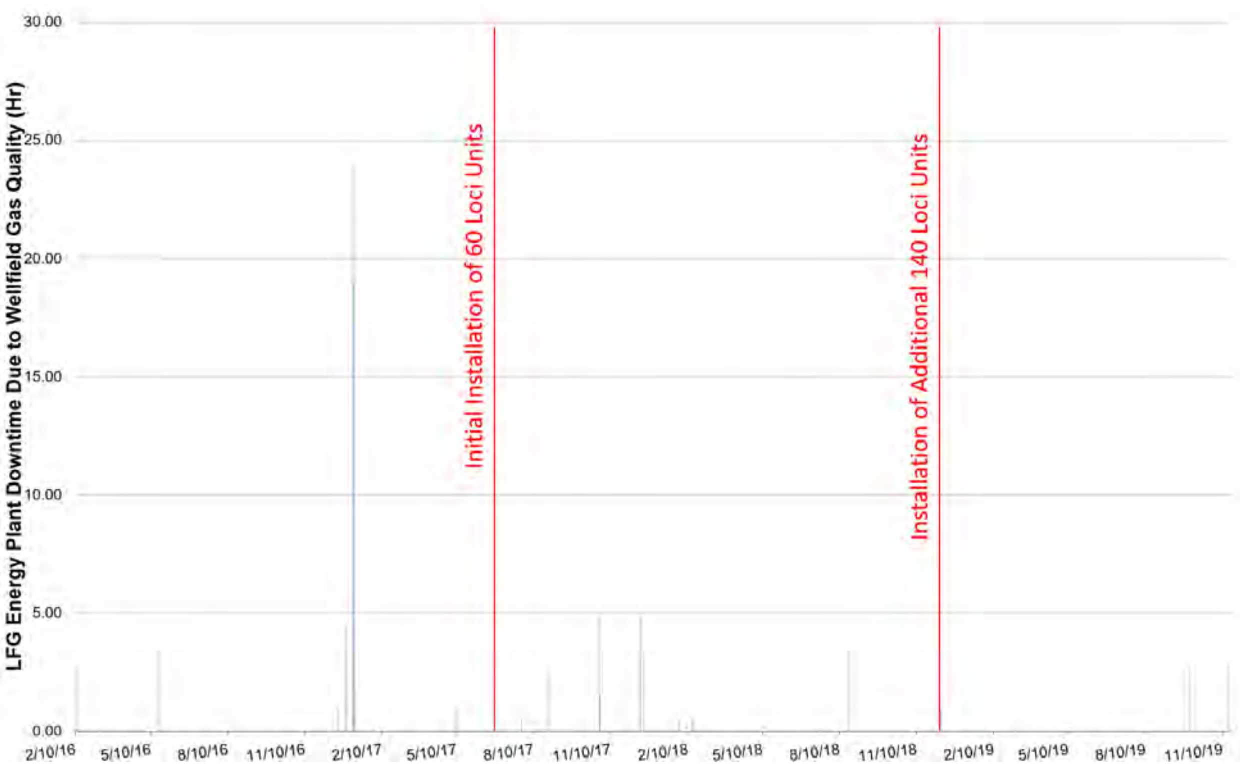

Figure 22. Site B LFG Energy Plant Downtime Caused by Non-Damage-Related Poor Inlet LFG Quality. Red Lines Indicate Time Period of Major Loci System Installations. Total Loci System Count as of Late 2018 was 200, Representing Approximately 75% of All Wellfield Flow[10].

Table 2. Summary of Site B LFG-to-Energy Plant Downtime, By Year

Year	**Hours of LFG-to-Energy Plant Downtime Because of Inlet Gas Quality**
2016	12.8
2017 (Through July 1, 2017)	46.3
2017 (July 1, 2017 (Initial Loci system installation occurred at 60 wells) through December 31, 2017)	17.4

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[10] Loci Systems, Personal Communication

Year	Hours of LFG-to-Energy Plant Downtime Because of Inlet Gas Quality
2018 (time period after installation of Loci system on an additional 140 wells)	6.7
2019	6.2

Although the energy plant data we reviewed for Site D covered the period of January 1 2019 through December 31 2019, thus precluding a detailed assessment akin to Site B, we did review a publication detailing year-over-year downtime statistics of winter 2018 and winter 2019[11]. The manuscript reported total energy plan downtime attributable to out-of-specification inlet LFG concentration as being reduced 93% when doing pairwise comparisons of October through February in these years. This reported result is broadly consistent with that seen at Site B, whereby downtime changes were observed when the Loci system installation coverage comprised most the wellfield. As displayed in Figure 18, 70 of 98 wells had a Loci system installed by the end of October 2019, and the entire wellfield had Loci coverage by the end of December 2019.

3.5 Comparing CH_4 Quality at Loci Sites to Other Operating Landfills with GCCS in the US

The CH_4 concentration in 2018 measured at 847 MSW landfills with active GCCS in the US is shown in Figure 23. These data derive from data submitted by landfill operators to the Greenhouse Gas Reporting Program and reflect the average CH_4 concentration of total collected gas flow measured in the year 2018. Overlain on the data are the positions of the three landfills with the Loci system analyzed here (one site did not have the Loci system installed until 2019), shown as red dots. The figure shows the measured CH_4 concentration of the three Loci system sites are well above the median value across all open landfills in the year 2018 (n = 693 landfills). In fact, the measured CH_4concentration places all three sites in the top decile (i.e., top

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[11] Technical presentation at Solid Waste Association of North America, February 2019, and supplemental white paper.

10%) of all open landfills. Although data and installation timeframes preclude additional years of comparison, these results demonstrate that the concentration of CH_4 as a percentage of LFG collected by GCCS with the Loci system are among the highest-performing sites on the basis of methane content.

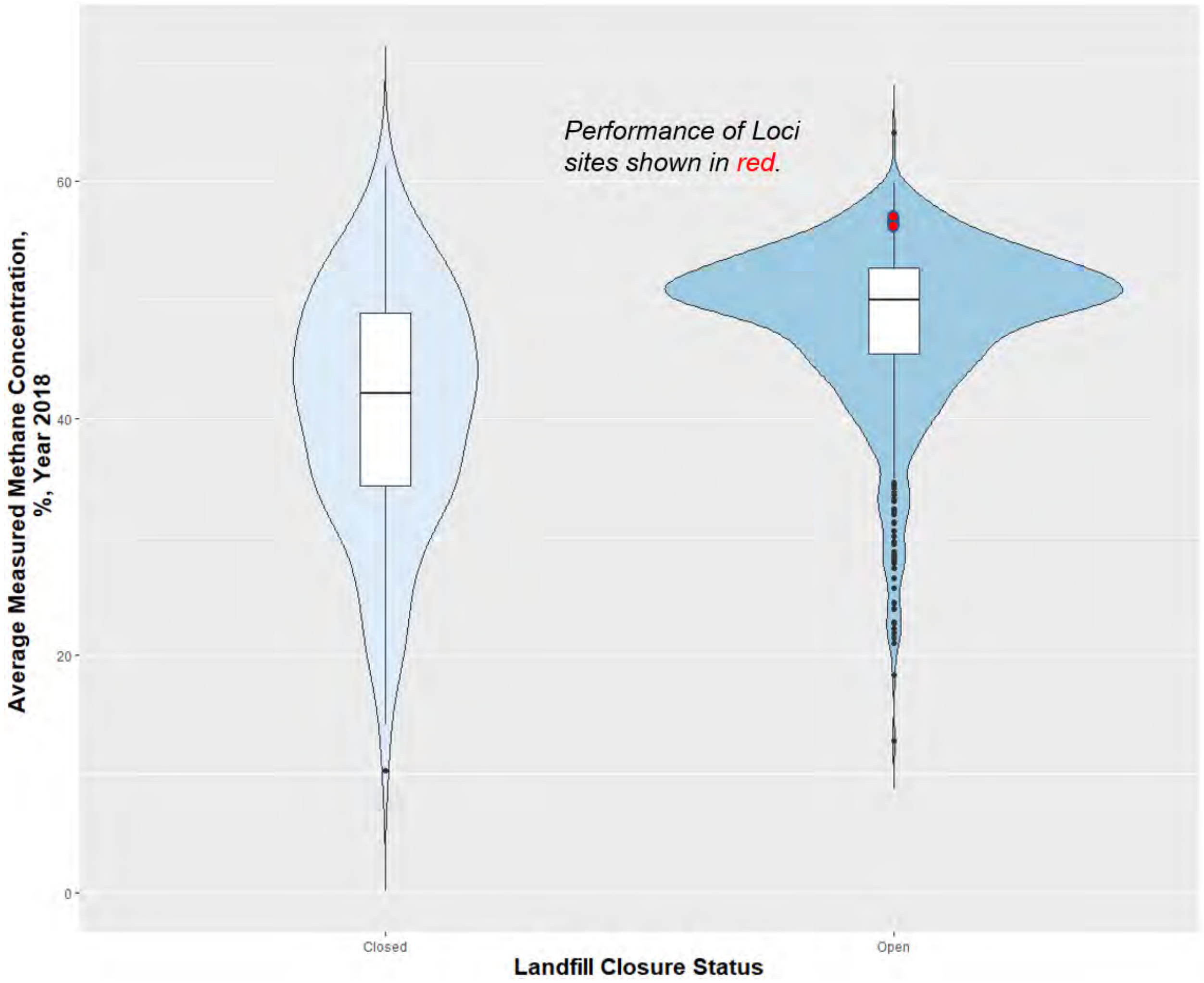

Figure 23. Collected Methane Concentration, Annual Average (Year 2018) for 847 MSW Landfills Reporting to the Greenhouse Gas Reporting Program. The Violin (Outer) Plots Represent the Overall Distribution Density of Data, While the Box-and-Whisker (Inner) Plots Show the Median, 25th and 75th Percentiles (i.e., the interquartile range (IQR)), and the whiskers represent 1.5 times the IQR. The Red Dots on the Figure Reflect Average CH_4 Concentration Measured at Three Sites with the Loci System (Two Points are Nearly Identical So they Appear to Overlap).

4 Conclusions

The principal focus of this analysis and report was to compare the performance of GCCS with the Loci system to the status quo of manual operations. We used an accumulation of evidence approach to examine data at the individual well and total system level. Further, we put results from the four sites examined in this study in the context of the broader population of more than 800 operating GCCS in the US. The following conclusions are provided:

1. **Number of Well Adjustments**
   The Loci system makes a far greater number of adjustments to individual LFG collection wells compared to manual wellfield tuning. Standard practice for manual wellfield tuning normally follows US federal regulatory minima, which require once monthly measurement of individual LFG wells. Our analysis of measurement and adjustment records at one site where the Loci Controls system was installed found wells underwent 4.96 valve adjustments per day (95% confidence interval: 4.64 – 5.28, n = 120 wells), which is approximately 15,000% greater than the standard, manual practice of one adjustment per well per month. These results are generally consistent with operation of the Loci system in general and are not particular to the site analyzed. The collective effect of establishing setpoints that limit air intrusion, frequent measurements, and frequent adjustments toward setpoint, result in more effective CH_4 collection and reduces the amount of air introduced into the LFG collection system.
2. **Methane Flow: Individual Landfill Gas Collection Wells**
   Individual operating records of gas collection wells indicate moderate to strong increases in methane flow after the installation and operation of the Loci system. This observation is based on an evaluation of 124 wells across two sites with substantive historical records. Further, the Loci system was shown to avoid extended periods where little or no gas is collected from a given well, an outcome attributable to the algorithm-based automated well adjustment system that increases or decreases vacuum applied to the collection well on the basis of frequent measurement of gas concentration and other parameters.
3. **Methane Flow: System Wide**

Totalized methane flow rate (representing cumulative flow from a landfill's entire wellfield) showed a marked increase at each site following wide-scale deployment (approximately defined as controlling 75% or more of available landfill gas flow[12]) and operation of the Loci system. The near-term performance improvement after Loci system installation generally ranged from a 13% to 24% increase in methane flow or associated energy plant output, which is the most useful measure of performance improvement. Totalized data exhibited variability consistent with normal wellfield conditions (e.g., well damage, wells filling with liquid, seasonal weather changes, and other factors), but the Loci system further enabled stable and increasing performance over time, even when controlling for the installation of new gas collection wells. These performance improvements were attributed to the greater degree of control enabled by the system, the increased "visibility" of well conditions that enable near-real-time adjustments, and the automated, 24 hour per day, well adjustment capability on an individual and whole-wellfield basis.

4. **Operational Downtime**

   Operating data from one site with substantial, historical energy production plant records showed a marked decline in the number of operating hours lost because of poor inlet gas quality after installation of the Loci system. In the 18 months prior to the first major Loci system installation, the plant experienced 59.1 hr of downtime attributable to poor inlet gas quality ($\mu \approx 3$ hr of monthly downtime) and in the 30 months after the first major Loci system installation, the plant experienced 30.3 hr of downtime ($\mu \approx 1$ hr of monthly downtime). The first full year of extensive Loci system installation (year 2019) showed even better performance ($\mu \approx 0.5$ hr of monthly downtime).

5. **Maintenance of Anaerobic Conditions (CH_4:CO_2 Ratio)**

   Operating data at wells with the Loci system were found to consistently maintain levels of CH_4 relative to CO_2 consistent with normal, "healthy" anaerobic waste decomposition conditions, which substantially reduces a site's risk profile (e.g., risk

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[12] This definition derives from available data reviewed in this four-site evaluation. Section 3 provides additional, relevant discussion.

associated with "overpulling" on the wellfield, leading to aerobic conditions and subsurface heating events) compared to manual operation, provided there is extensive wellfield coverage with the Loci system.

6. **Collected Methane Quality Compared to 800+ GCCS in the US**

   Annual (year 2018) average site-wide CH_4 concentrations at the three sites with the Loci system installed in year 2018 were in the top decile when compared to total average CH_4 concentrations at 844 other operating MSW landfills in the US with active gas collection systems, indicating high performance relative to the broader population of operating landfill sites in terms of total collected gas quality.

5 Limitations to Analysis

PTP Informatics prepared this analysis and report under contract to Loci Controls and the report's contents are intended for the sole use of Loci Controls. We necessarily relied on third-party collected and supplied data (Loci Controls and its client landfill sites) and based our observations, analyses, and conclusions based on these data "as is". No warranties, express or implied, are made regarding the validity of the aforementioned data, and PTP Informatics relied on this information "as is".

Although we used a series of approaches to evaluate the performance of the Loci system based on our experience and information gleaned from the supplied site data, some additional limitations must be noted which could have an effect on the direction and magnitude of evidence regarding gas collection system performance. Notably, well-specific data can greatly influence the performance of a given collection point. Key factors include, but are not limited to, types of waste near the well; age of waste near the well; conditions relevant to the prevalence of bacterial consortia (e.g., moisture, temperature, nutrient mix and availability, and others); liquid build-up in the well; hydraulic conditions near the well including conductivity and permeability of waste and any associated cover materials. Additionally, the full mass balance considering all available gas (i.e., gas produced), gas captured, and gas emitted, is not available. In most cases, detailed and accurate data on most of these factors is either unknowable, impossible or impractical to measure, thus these are not limitations of the specific sites here but a general limitation in evaluating all conditions influencing small- and large-scale factors influencing the performance of landfill gas recovery systems.

Further, as with most operating MSW landfills, the sites analyzed here were not necessarily operated with strict research goals or protocols in mind (e.g., establishing strict “control” and “effect” conditions), which necessarily constrains comparative analyses. However, the author has experience with some of the most heavily-controlled, full-scale MSW landfill research experiments in the US and notes that even purpose-built research project landfill sites share many of the same limitations described above. It is for these reasons that, in this and future evaluations, an accumulation of different evidence should be used to draw inferences regarding reasonable bands of performance differential between systems (e.g., manual versus automated systems), as confounding factors will exist in most cases regardless of the system set and scale analyzed.

6 Author Biosketch

The analysis presented in this report was prepared by Jon Powell, Ph.D., P.E., CEO of PTP Informatics, LLC. Jon’s experience spans 17 years in the waste and materials management space as an entrepreneur, engineer, designer, and educator. He has led more than 250 technical projects spanning waste facility design, material flow modeling, GCCS design, GCCS operation, assessments of subsurface oxidation/heating events, life-cycle analysis, law and policy review, and many others for a variety of public- and private-sector organizations. He has authored or co-authored 20 peer-reviewed papers on an assortment of waste and materials topics including hydraulic properties of waste, aerobic and anaerobic decomposition kinetics and air emissions, liquids addition design and performance, GCCS performance, dynamic disposal models, groundwater impacts, municipal and industrial byproduct reuse, and life-cycle analysis of various waste processes. He is the co-author of Sustainable Practices for Landfill Design and Operation (Springer Nature), holds a Ph.D. in Chemical and Environmental Engineering (Yale University) and an M.E. and B.S. in Environmental Engineering Sciences (University of Florida), and is a licensed Professional Engineer in Florida (Active), Connecticut (Inactive), and Puerto Rico (Inactive).

This report was subject to external peer review by Mr. Judd Larson, P.E. He is an environmental engineer with more than 15 years of research and practice spanning a range of environmental- and waste-related areas including bioreactor landfill design and operation, solid and hazardous waste design and engineering, wastewater treatment plant design and engineering, air quality analysis, groundwater remediation, and environmental life cycle analyses. He earned his B.S. and M.E. from the University of Florida and will complete his Ph.D. at the University of Wyoming in 2020.

ATTACHMENT

EXTERNAL PEER REVIEW MEMO
AND COMMENT-RESPONSE MATRIX

memo

1 Independent Contractor: Judd Larson, P.E.

To: Jon Powell, Ph.D., P.E., Chief Executive Officer, PTP Informatics
From: Judd Larson, P.E.
Date: April 22, 2020
Re: Technical Peer Review of “Draft Loci Controls System Performance Assessment”

This memo is submitted as partial fulfilment of the following scope of work:

Provide technical support to include peer review of the draft document: “Draft Loci Controls System Performance Assessment”.

The primary objectives of the peer review are to confirm that the approach taken to analyzing and presenting the information is scientifically valid and that the results are technically sound.

The deliverables include:

1) a brief memorandum summarizing the review and any general and/or critical comments along with recommendations.

2) a track-changes (Word) version of the document markup including any additional comments.

(3) if provided, a completed Client specified peer reviewer form addressing the content & scope, apparent validity of analytical technique(s) used, and soundness of conclusions.

This memo is Deliverable 1. Deliverable 2 is likewise attached within the same e-mail correspondence. The contents of a Deliverable 3 are presented within this memo, however, if provided by the Client, a peer review form will also be completed and submitted.

The following is my review and any general or critical comments, as well as recommendations:

Assessment of Content and Scope

According to this report, the scope of the authors was the following:

"Loci Controls contracted with PTP Informatics, LLC to examine operational and performance data of the Loci system at four operating landfill sites, each of which have a landfill gas-to-energy project (three high-BTU and one electricity generation). The data and performance assessment covered three areas standalone review of the: (i) operation and performance of the Loci system, (ii) operation of the Loci system relative to status quo operation of manual landfill gas wellfield management, and (iii) orientation of gas system performance at the four Loci system sites within the larger population of US MSW landfills with active landfill gas collection systems."

This report met the scope requested.

Organization and Presentation:

The report was well organized and well written with few grammatical corrections. Graphs and tables were neatly presented.

Quality of data and validity of analytical techniques:

To the extent that the data quality could be assessed without access to the raw data, the data quality and analytical techniques appear to be sound.

Soundness of Conclusions:

All major conclusions appear to be supported by the data. There are a few minor instances where I ask the author to consider adding qualifying remarks regarding some interpretations of the data. These are outlined in the table of comments below.

Editorial Quality:

The report was well written with few grammatical errors.

Peer Review Table of Comments

The following table of comments are only those reflective of significant modifications and/or suggestions that would impact the author's presentation or conclusions of the report material. Comments regarding corrections or potential improvements of grammar or report organization have been left out of the table of comments, however, they reside in the Track Changes version of the MS Word document. A response column has been included for later inclusion of the author's responses. These comments are best viewed along with the Track Changes version of this report (Deliverable 2).

Page	**Judd Larson, P.E. Comment**	**PTP Informatics Response**
1	Regarding point 1 of key observations from this analysis: I calculated 15,086.7% (~15,000%) greater valve adjustments per month: [(4.96*365)/(1*12)]*100%	We modified all references to be 15,000% - our previous figure of 14,800% was based on a simplified 30-day month.
2	Regarding point 3 of key observations from this analysis: Consider changing 25% to 24% to better reflect the information provided in the body of the report. Specifically: Per the paragraph immediately following Figure 20, the stated near-term performance improvements were 13% to 24%.	We changed this value to reflect actual (24%, not 25%).
3	Regarding point 3 of key observations from this analysis: Consider adding, "or associated energy plant output" to better reflect what data this observation was based on (per Figure 21).	We added language reflecting this comment.

Page	Judd Larson, P.E. Comment	PTP Informatics Response
8	Regarding the author’s discussion of how operation of gas collectors is a key factor in gas collection performance and that gas collector design is limited in bettering gas collection performance due to an abundance of environmental variables: The following comment is a bit of a reach at this point, as it is too early to say, but an assemblage of optimized operational data, from such a control system as Loci Controls, along with LFG collector attributes could potentially be used to determine better LFG collector designs. (not changes necessary here, just (hopefully) a helpful insight)	Although we don’t necessarily disagree with the reviewer’s assertion that far better data (such as that provided by the Loci Controls system) could inform better GCCS design, this question was not explored in detail and including this comment would be speculative at this point. This could be an area of exploration for Loci Controls or its partners in the future.
11	For the paragraph immediately after Figure 5, consider adding the phrase, “, the latter based on models” to clarify that the total produced gas is determined from model equations.	We address the use of models in Gas production later in the report, so we left this section unchanged.
12	Figure 6 is missing a citation.	This figure was developed by PTP Informatics during this project from data reported to the GHGRP and is referenced as part of the text.
13	Total N for closed + open landfills is 847 (i.e., 154 + 693). This is slightly short (17) of the 864 total landfills noted in the caption of Figure 6. This is not a big issue, but wanted to bring attention to it, in case this discrepancy may point to a slight error.	We modified the numbers in the report to reflect this discrepancy.

Page	Judd Larson, P.E. Comment	PTP Informatics Response
13	Figure 7 is missing a citation.	This figure was developed during this project from data reported to the GHGRP.
14	The caption of Figure 8 appears to be incomplete.	We added language to complete the figure caption.
15	The paragraph following the bulleted list of fundamental aspects of the Loci system reads, "A simple example here is if measurement at a header pipe (e.g., at a point just prior to entering an energy conversion plant) shows less-than-desired LFG quality, multiple valves may be closed to bring the BTU content back above the site's specified threshold." Consider adjusting the wording to "partially closed" (i.e., throttled to reduce flow). This may be an important clarifying modification. As it currently reads, a potential client may get concerned that the Loci system may cause a landfill to be out of compliance with regulations by shutting gas collector well valves to reach a BTU goal.	We added language to clarify that "closed" doesn't mean "fully closed", but is rather an incremental adjustment/throttling.
17	Same comment as in the Executive Summary on page 1: I calculated 15,086.7% (~15,000%) greater: [(4.96*365)/(1*12)]*100%. However, if you assume 30 days/month, then the 14,800% is mathematically accurate. If you assumed 30.42 days/month (365/12), 15,000% is mathematically accurate. Either way, it is splitting hairs.	We modified all references to be 15,000%.

18	Consider adding an additional analysis with these data that take into account the variability of the 5 pre and 5 post Loci installation LFG well methane flow rates. A difference in mean values based on a sample may or may not represent a true difference in performance. A pre and post-installation t-test (with or without assuming homoscedasticity – depending on an F-test) would better tell if these differences in means are indeed significant differences (typically conducted at 95% confidence). Such an analysis may also show that the seven wells that had reduced average CH_4 flow rates, may have not had significant differences (meaning there may not have been any difference in performance). Note: There would be no need to run a t-test on the four wells that had pre-installation CH_4 flow rates of zero since there would be no variation in pre-installation measured flow and therefore any post-installation positive flow would be considered different. Additionally, reading this section as a skeptic, I'd be interested in knowing what the other GEM readings were as well. Did adjusting the CH_4 flow rates by the Loci system result in any other notable changes in GEM readings (e.g., oxygen, carbon dioxide, balance gas)? Further, what was the range of time that the 5	The pre- and post-evaluation data reflect various points in time – thus, t-test construction would only tell part of the story and regardless of whether 'statistical significance' is identified, would carry little practical significance given the aforementioned shortcomings with infrequent (monthly) well measurement. We deliberately focused discussion on methane and did not explore effects of other non-methane gases in this part of the analysis (evident effects on collected gas stability within anaerobic range, for example). We stated previously in the report that the data reflect approximately monthly GEM readings, so the time period reflects at least (approximately) four months of data, which reflects/encompasses five total individual readings at a minimum.

Page	Judd Larson, P.E. Comment	PTP Informatics Response
	measurements were taken over, pre and post-installation. Was it 5 months?	
19	Same comments as above (for page 18), regarding the application of a t-test for each well comparison (pre and post-installation), only for the data presented in Figure 12.	See comment above.
20	Consider modifying the description, "watering out" for a less ambiguous term.	We modified language to indicate well filling with liquid rather than the jargon term.
21	For the Figure 13 caption: Consider adding a note about what the red line in the top graph represents (installation of the Loci system).	Added definition of red line in the figure caption.
24	The paragraph immediately following Figure 16 reads: "Although most of the data appear to be points, each mark represents the mean plus the 95% CI – thus, all wells fall within the ideal anaerobic range for operating gas wells, and do so quite consistently over time." If accepting my recommendation regarding Figure 17 to adjust the y-axis scaling to make more visible the data points and 95% confidence bars, revise the sentence accordingly.	The presentation of data was chosen to illustrate the tight range of many individual data points, so the figure was unaltered.

Page	Judd Larson, P.E. Comment	PTP Informatics Response
24	The paragraph immediately following Figure 16 reads: "These results are broadly consistent with previously-displayed individual well results that reflect the rapid opening and closing of valves in response to specified setpoints." If accepting my recommendation regarding Figure 17, to add the average valve adjustments per month as a secondary y-axis, I recommend discussing that data here to more explicitly make this point.	See comment above – no adjustments were made to the figure. Discussion earlier in the text documents the number of well adjustments (including the figure for one of the sites), so addition of the secondary axis as suggested is extraneous as the point had already been made.

Page	**Judd Larson, P.E. Comment**	**PTP Informatics Response**
25	Consider the following adjustments to Figure 17: 1) Use a darker color for the points and 95% confidence interval bars. 2) If wanting to make the 95% confidence interval bars more visible, consider adjusting the y-axis to start at 1.0 at the x-axis intersection with the same upper bound to effectively zoom in on the data. 3) To better make the point, in the relative text, that use of the Loci System caused these methane to carbon dioxide ratios, consider adding a secondary y-axis to plot the average valve adjustments per month for each well such that the secondary data can be clearly seen (in a different color and/or use a different style – e.g., bars, and should lie above or below the methane to carbon dioxide ratio data to not obstruct it). 4) Consider adding the average timeframe that the methane to carbon dioxide ratios are measured over within the caption.	Again, see responses above. We added language to the text to indicate the total number of measurements reflected in the data set in this figure.

Page	Judd Larson, P.E. Comment	PTP Informatics Response
26	For Figure 18, the caption reads, “Plot of instantaneous daily cumulative methane flow rate measurements over time and indication of Loci System installation (Site D) and new/replacement gas collection well installation.” Consider the following caption modifications for clarity, “Plot of instantaneous daily ~~cumulative~~ total GCCS methane flow rate measurements over time (points) ~~and~~, ~~indication of~~new Loci ~~System~~ units ~~installation~~ installed (bars)~~(Site D)~~ and new/replacement gas collection well installation (notations) at Site D.”	We adjusted the language to improve clarity.
28	For Figure 19: For ease of reading, consider darkening the x and y-axes’ numbers and making the font larger. Also consider replacing the words “Cumulative” with “Total GCCS” within the caption for clarity, since “Cumulative” could be misinterpreted as temporally additive instead of spatially additive as it is intended here.	We adjusted the figure to improve aesthetics and clarity as suggested, along with caption.

Page	Judd Larson, P.E. Comment	PTP Informatics Response
29	In the paragraph immediately following Figure 20, consider adding the qualifying phrase, “and in more cases than not,” for the claim that “a consistent increasing trend is observed, approximately on the order of nearly 13% to 24%.” I believe adding this phrase is more accurate considering that two of the six months showed (in Figure 21) lower increases in net plant output (based on methane production) of 1.6% and 5.7%.	We inserted language to clarify this point.
30	Regarding Figure 21: I believe this is a more telling graph than the previous figure (Figure 20) since landfill gas generation varies with ambient conditions (i.e., seasons – as noted earlier), so this figure allows you to compare apples to apples (effectively accounting for seasonal variation). Another interesting point is that since no additional waste was placed at this site during the graphed time frame, there would be an expected negative temporal trend of methane production, but after the Loci system was installed there was a positive trend. (No change necessary)	We appreciate the comment, no change needed.
31	Regarding Figure 22: For ease of reading, consider darkening the x and y-axes’ numbers and making the font larger. Also consider making the bars wider and a darker or brighter color.	We adjusted aesthetics as suggested.

Page	Judd Larson, P.E. Comment	PTP Informatics Response
32	Regarding Table 2: Consider adding superscripts at "2017 (July 1, 2017 through December 31, 2017)" and "2017 (July 1, 2017 through December 31, 2017)" with associated footnotes explaining the phased installations of Loci systems.	We added clarifying language as suggested directly within the table.
33	Consider the following changes to Figure 23: 1) Move the figure to appear after the text introducing it. 2) Darken the x-axis and y-axis numbers and make the fonts larger. 3) Use different shape markers for the 3 landfill sites to better show the three points, as it only looks like two points due to overlapping.	We note that two of the three data points are very close to one another, so we added language in the caption reflecting this.
34	Regarding point 1 of the conclusions: If accepting my previously suggested calculation modification (in the Executive Summary and in Section 3.1), make that change here as well. I calculated 15,086.7% (~15,000%) greater valve adjustments per month: [(4.96*365)/(1*12)]*100%	See response above to the adjustment we made to reflect the comment throughout the report.
35	Regarding point 3 of the conclusions: If accepting my previously suggested correction noted in the Executive Summary, change 25% to 24% to better reflect the information provided in the body of the report. Specifically: Per the paragraph immediately following Figure 20, the stated near-term performance improvements were 13% to 24%.	We accepted this comment and revised the text accordingly.

Page	**Judd Larson, P.E. Comment**	**PTP Informatics Response**
35	Regarding point 3 of the conclusions: If accepting my previously suggested modification noted in the Executive Summary, add, “or associated energy plant output” to better reflect the data this observation was based on (per Figure 21).	We accepted this comment and revised the text accordingly.
36 and 37	Regarding the last two paragraphs: I wholeheartedly agree with your assessment here on the limitations and need for an accumulation of different evidence to aid in making strong inferences regarding the impact of landfill technologies. It is the nature of the beast that is field work.	We appreciate the reviewer comment.