2025 Controlled Release Experiment Program – Landfill

Experimental Protocol

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Dave Risk and Rafee Hossain
St. Francis Xavier University
Antigonish, NS, Canada
www.fluxlab.ca

Contents

1. Purpose

This testing will assess the performance of survey methods which perform leak detection and quantification (LDAQ) under Single-Blind Controlled Release testing over a range of environmental conditions and emission rates at a landfill. Testing will evaluate system-level performance measures including probability of detection, accuracy, precision of localization and quantification estimates as applicable. The project is being managed by St. Xavier University and the Environmental Research & Education Foundation (EREF).

2. History

This protocol borrows heavily on a previous methane testing protocol methodology for oil and gas methane detection systems, built by the Methane Emissions Technology Evaluation Center (METEC) at Colorado State University. Like oil and gas operations, landfill sites emit methane. Where oil and gas sites generally emit from one or more specific component point sources on a Facility whose footprint is generally less than 10s of metres, a landfill will emit from a multiplicity of point sources and area sources separated by sometimes more than one kilometre. A typical landfill can emit as much methane as hundreds of oil and gas production sites. The nature of emissions at landfill sites are different and larger than we see for oil and gas and it is with these considerations that this protocol has been adapted from the original, with METEC's understanding. The original protocol is called the Controlled Test Protocol: Survey Emission Detection and Quantification Revision 0.0 5 July 24, 2020.

3. Definitions

Controlled Release (CR) – A type of experiment where Emissions are intentionally created for the purpose of evaluating Emission Detection and/or quantification systems. During a Controlled Release, the emission rate and location are known to the Test Center within well understood accuracy.

Area-Source Emission – An Emission of methane or natural gas that is spread across an area. Using an individual leg of CR tubing, or a collection of CR tubing legs located nearby one another, lying on the surface, buried, or elevated,

methane or natural gas is released from a multiplicity of perforations along each leg, where each leg of tubing might measure up to 50m in length.

Background Emission Points – A release of methane or natural gas from a source outside the defined controlled release area from either landfill or other source to the ambient environment. Since the tests are being conducted on a closed landfill, Background Emission Points may be present on the landfill surface and the Test Centre will seek to identify and characterize these including an estimate of emission rate, on an ongoing basis, using walking surveys and/or other techniques. These additional pre- existing Emission Points will not be identified with labelling and their locations and emission rates will not be shared with Performers.

Detection – An alert provided by an Emission Detection System to the Facility operator that an Emission is present. An elevated gas concentration measurement alone does not constitute a Detection, but instead must be accompanied by analytics to attribute the elevated concentration to an Emission within the Facility. This attribution must be established with a high enough confidence to warrant providing a Detection alert to the Facility operator.

Emission – A release of methane or natural gas from a system to the ambient environment.

Emission Detection System – A system including the sensor(s), deployment platform, auxiliary equipment, and analytics capable of detecting Emissions and attributing them, at minimum, to a Facility. Emission Detection Systems may include analytics to estimate emission rate and/or the location of the Emission source.

Emission Point – A location from which an Area Source Emission or Point Source Emission is released by the Test Centre from the Emission System. Since all constructed Emission Points will be visible to participants due to ground disturbance or surface infrastructure, they will be labelled on maps provided to

Performers.

Emission Survey – An inspection performed within the Facility using an Emission Detection System to detect, localize, and or quantify emissions during the survey.

Emission System – A collection of individual Emission Points (area-source, and diffuse source)

Experimental Design (a test matrix) – A set of Experimental Design Points designed to investigate correlation between variation in a dependent variable and variation of one or more independent variables.

Experimental Design Point (an experiment) – A single combination of settings for the independent variables of a Controlled Release experiment. Independent variables include both the emission rate of the Controlled Release(s) and Environmental Conditions.

Facility – The defined boundaries for Emission Surveys, laid out by the Test Centre in which the Emission Points are located. For most Experimental Design Points, the Facility will be a sub-domain of the landfill comprising 10-20 acres at which the experiment is being conducted, and in other cases the Facility may comprise the entire landfill operation.

False Negative (FN) – A Controlled Release that was not detected by a Performer. See Section 6.1 for Classification of Detections.

False Negative Fraction (FNF) – The number of False Negative Controlled Releases relative to the total number of Controlled Releases. See section 6.2.3 for False Negative Fraction.

False Positive (FP) – A Detection reported by a Performer that cannot be attributed to a Controlled Release. See section 6.1 for Classification of Detections.

False Positive Fraction (FPF) – The number of False Positive Detections relative to

the total number of Detections. See section 6.2.2 for False Positive Faction.

Final Report – A report issued by St. Francis Xavier University FluxLab and EREF after the conclusion of testing. See section 8 for Final Report.

Localization Accuracy (LA) – A measure of the distance between the location of an emission estimated by a Performer and the location where a Controlled Release occurred. In this protocol Localization Accuracy is 2D. Localization Accuracies may be calculated based on a single latitude-longitude coordinate pair, or a set of coordinates indicating a bounding box reported by the Performer. See section 6.3.5 for Localization Accuracy (Single Coordinate) and section 6.3.6 for Localization Accuracy (Bounding Box).

Localization Precision (LP) – A measure of the area to which an Emission source is attributed by a Performer. Localization Precision may be calculated based on a single latitude-longitude coordinate pair, or a set of coordinates indicating a bounding box reported by the Performer. See section 6.2.5 for Localization Precision (Emission Point) and section 6.3.8 for Localization Precision (Bounding Box).

Performer – A single participant in the testing, under this protocol. The Performer includes the personnel and an Emission Detection System.

Point-Source Emission – An Emission from a small orifice on or near the ground, expressing as elevated concentration in the air over metres, and mimicking an emission from a concentrated ground level source like membrane tear, separation of collection well casing and surface membrane, or a leak in gas collection system pipework, or a well where the vacuum draw pipework has been damaged.

Probability of Detection (PD) – The fraction of Controlled Releases, over an extended test period, that the Performer reported as Detections. The Probability of Detection may vary across Survey Protocol independent

variables, such as the emission rate and/or the meteorological conditions, resulting in a Probability of Detection curve or surface. See section 6.2.1 for Probability of Detection.

Quantification Accuracy (QA) – A measure of the difference between the emission rate estimated by a Performer and the metered emission rate of a Controlled Release. Quantification Accuracy may be represented as an absolute difference, or as a percentage difference relative to the metered emission rate. See section 6.3.1 for Quantification Accuracy (Absolute) and section 6.3.2 for Quantification Accuracy (Relative).

Quantification Precision (QP) – A measure of the difference between the upper and lower confidence limits reported by a Performer for an emission rate estimate. See section 6.3.3 for Quantification Precision (Absolute) and section 6.3.4 for Quantification Precision (Relative).

Single-Blind – An experimental procedure in which the controlled testing Facility knows the location and emission rate of all Emissions, but operators of the systems being tested (i.e. the Performers) do not.

Survey Solution – A Survey Solution document/report includes the Emission Detection System, personnel, and methodology to perform an Emission Survey by the Performer

Survey Time – The time required by a Performer to complete an Emission Survey measured as the difference between the time of arrival at a Facility and time of departure from the Facility.

Test Center – The location at which testing is performed under this protocol. The term 'Test Center' includes the larger physical facilities, the personnel performing the evaluation, and any supporting software or analysis.

True Positive (TP) – A Detection reported by a Performer that can be attributed to a Controlled Release. See Section 6.1 for Classification of Detections.

4. Variables and Subscripts

The variables listed in Table 1 are used in equations throughout the protocol: Table 1:

Variable	Description
N	Total number across all experiments
n	Number during a single experiment or subset of all experiments
t	Time
FP	False Positive Detection(s)
FN	False Negative Detection(s)
PD	Probability of Detection
FPF	False Positive Fraction
FNF	False Negative Fraction
OF	Operational Factor
QA	Quantification Accuracy
QP	Quantification Precision
LA	Localization Accuracy
LP	Localization Precision
DT	Detection Time

The abbreviations in Table 2 are used in equations throughout the protocol: Table 2:

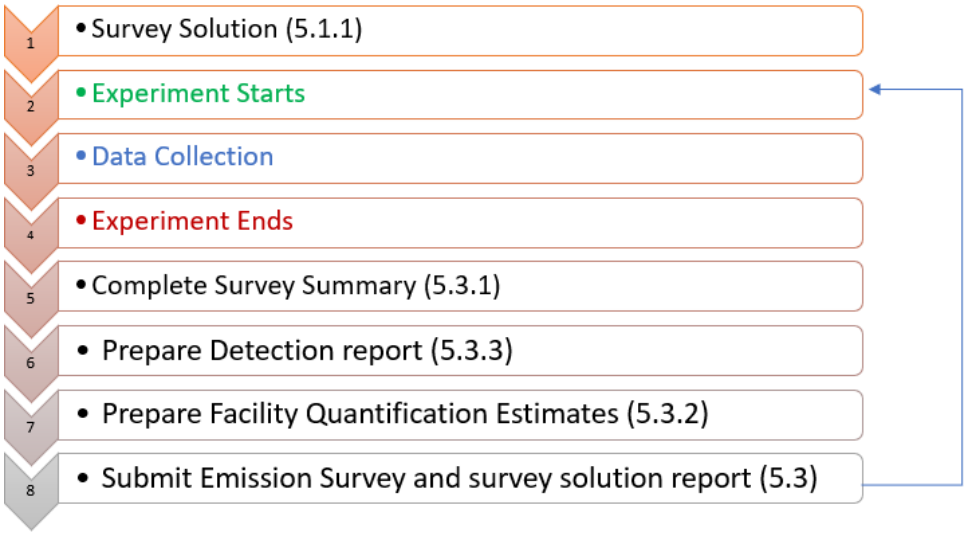
Abbreviation	Description
CR	Controlled Release(s)
RD	Reported Detection(s)
TP	True Positive Detection(s)
FP	False Positive Detection(s)

FN	False Negative Detection(s)
ASE	Area Source Emission
PSE	Point Source Emission
ASR	Area Source Release
PSR	Point Source Release

5.0 Test Method

Testing consists of three activities – Documentation of System Under Test, Emission Surveys, and Reporting. Steps illustrated in Figure 1 will be the usual flow for Performers to follow for each experiment. A sample survey summary document can be found in Appendix B

Figure 1: Performer protocol flow diagram



5.1 Documentation of System Under Test

The configuration of the Performers' Survey Solutions under test shall be documented and reported. Documentation must be sufficient for a reviewer to fully identify the as tested revision and configuration of the Survey Solution.

5.1.1 Documentation Requirements

At a minimum, documentation from the participant Survey Solution shall include:

1. Detailed description of system configuration and primary components including the sensor and deployment platform. Additionally, the location (latitude, longitude, height) of auxiliary components such as meteorological station or any other equipment installed at or near the Test Center must be recorded.
2. Model number of each component in (1).
3. Revision number of software installed in each component in (1) that includes Performer-specific software components, revisions, or customizations.
4. Revision number of any software analytics installed offsite.
5. Detailed description of the methodology used by the Performer during Emission Detection surveys.
6. Confidence level at which Emission Detection data are reported.
7. Personnel are considered part of the deployed Survey Solution and should match typical deployment in field use. The number of people participating in surveys and their roles must be documented. Additional Performer personnel may not interact with the survey team during the experiments, either onsite or via remote contact methods. Any remote personnel participating in the survey in any fashion should be documented as part of the survey team in this section. Installation documentation should be considered public information, and Performers should not include proprietary information (e.g. algorithmic details, reasons for locating sensor in specific locations, performance data of sensors, etc.) as part of this documentation.

5.1.2 Testing Cautions

Performers should recognize results are applicable only to the system as tested and documented. Future reviewers of results will be interested in whether systems proposed for field deployment include the same quality of sensors, deployment platform, and methodology as were tested under the protocol. Deploying more sensors, higher cost-performance sensors, more extensive analytics, or more human intervention than would be typical in field deployments may render the results produced in these tests inapplicable to future field deployments, regulatory applications, or other uses of the test results. Appendix B contains a sample survey solution form that performers can use to document preliminary system data.

5.2 Emission Surveys

Performer personnel will be present at the Test Center to perform Emission Detection. For each experiment, the following process will be followed:

1) A Facility boundary will be defined by the Test Center for the experiment. In detection and localization experiments the facility boundary will be defined by coordinates, and will constitute a <20 acre search area. For Survey Solutions that provide total site quantification, the Facility boundary will be defined as the landfill perimeter road (some of which will be accessible to Performers).

2) An Experimental Design Point including a predetermined number of Controlled Releases on the designated Facility will be established by the Test Center. An Experimental Design Point may include zero Controlled Releases. Controlled Releases in an Experimental Design will be steady, although the Test Center reserves the right to turn off Emission Points that have already been surveyed by the Performer, in order to conserve gas, and where it is unlikely to affect measurement of sources not yet covered. For each Controlled Release, the Test Center will record the location, timing, gas composition, metered emission rate, and uncertainty (95% confidence limit) of the metered emission rate.

3) Performers will complete an Emission Survey of the facility. Emission Surveys must be completed according to the Performer methodology as documented in section 5.1. The Performer will record survey data as described in section 5.3.1 and section 5.3.3.

4) Performers will submit survey data from (3) to the Test Center. The Test Center will record the date and time which Performer Emission Detection reports are received and store them for results analysis.

5) Performers operating drones will be allowed to perform ground verification measurements in most cases.

5.3 Reporting

Experiment and detection data must be reported as described in this section.

Performers are encouraged to submit experiment, and detection reports to the Test Center daily during the testing period, if available. Results must be submitted by Performers within 4 weeks of the end of the testing period. The first round of Emission reports that are submitted will be recorded by the Test Center and used in result analysis.
Some methodologies are required to submit ancillary data in addition to detection reports. Detection reports from satellite-based sensors must be accompanied by corresponding satellite imagery to ensure accurate interpretation and validation of the reported methane detections. The integration of methane concentration data with high-resolution satellite imagery allows for the verification of emission sources, assessment of potential confounding factors such as cloud cover or surface reflectance, and contextualization of observed methane plumes within the broader environmental landscape. This requirement ensures that methane detection reports are supported by visual and spatial information, enhancing the reliability and traceability of the reported emissions.

Performers must commit to submit data for all measurements that they make during the study.

After the all initial reports have been submitted by all Performers, the Test Center will release site-specific data to Performers within two weeks that might be useful in refining their analysis such as atmospheric pressure, humidity, onsite wind and temperature measurements recorded onsite at the peak and bottom of the landfill, by weather stations comprising sonic anemometer and temperature sensor recording at 1-minute frequency, with indications of accuracy . Should Performers wish to revise their estimates following the review of site-specific data, revised results must be submitted in a timely fashion by Performers no less than 1 week from the date that results are provided. Where a performer submits revised results, both the initial and revised estimates submitted by the Performer will be used in result Final Report analysis.

5.3.1 Survey Summary

A survey summary will be reported by all Performers for each experiment completed, as a cover page for their detection or quantification report. Each survey summary will include the data fields listed in Table 3. Where Surveys Summaries are missing fields, those Summaries will not be considered in the analysis. The total Survey Time will be computed by the addition of the Survey Time indicated in the reports.

Table 3: Survey summary data fields

Field	Description	Acceptable Values	Mandatory or Optional

ExperimentID	A unique ID assigned to the individual Experimental Design Point by the Test Centre. Performers that wish to submit multiple measurements within the Experimental Design Point should use a format of ExperimentID_a where the last letter is incremented for every separate measurement repetition.	Integer	Mandatory
FacilityID	Facility that was measured by the Survey Solution (CR Facility OR Total Landfill)	As defined at left	Mandatory
StartDateTime	Time (UTC) which survey was started formatted as *yyyy/mm/dd_hh:mm*	Formatted DateTime in UTC	Mandatory
EndDateTime	Time (UTC) which survey was completed formatted as *yyyy/mm/dd_hh:mm*	Formatted DateTime	Mandatory
SurveyTime	Elapsed time during survey formatted as *hh:mm*	Formatted Time	Mandatory
Repetitions	Number of repeat measurements of the	Integer	

	Facility performed and reported within the SurveyTime		

5.3.2 Facility Quantification Data: (For Performers participating in Quantification Studies)

Most Performers will deliver a single quantification estimate for each Experimental Design Point in which emissions are held constant. Some Performers (e.g. aerial) can conduct multiple quantification estimates within an Experimental Design Point / Testing Block and are encouraged to submit as many repeat measurements as possible.

Table 4: Facility-level quantification estimate data fields

Field	Description	Acceptable Values	Mandatory or Optional
QuantificationReportID	A unique ID assigned by the Performer to the individual quantification report. *This number should be incremented for every detection report sent.* Duplicate numbers will be assumed to be multiple transmissions of the same report; only one (arbitrarily chosen) report will be logged. The increment amount between reports is arbitrary and need not be constant; report ID should never be deincremented.	Positive Integer	Mandatory

ExperimentID	A unique ID assigned to the individual Experimental Design Point by the Test Centre. Performers that wish to submit multiple measurements within the Experimental Design Point should use a format of ExperimentID_a where the last letter is incremented for every separate measurement repetition.	Integer	Mandatory
FacilityID	Facility that was measured by the Survey Solution (CR Facility OR Total Landfill)	As defined at left	Mandatory
FacilityEmissionRate	Estimate of total emission rate from the Facility for the experiment. The units of this field should be kilograms per hour of the gas specified in *Gas.*	Decimal Number ≥0	Mandatory
FacilityEmissionRateUpper	Upper estimate of total emission rate of the Facility. The units of this field should be kilograms per hour of the gas specified in *Gas.*	Decimal number >0	Optional
FacilityEmissionRateLower	Lower estimate of total emission rate of the Facility. The units of this field should be kilograms per hour of the gas specified in *Gas.*	Decimal number ≥0	Optional
MeasurementTime	Time (UTC) of the measurement *yyyy/mm/dd_hh:mm*	Formatted DateTime	Optional

Table 5: Example reporting format for Quantification data fields for Performers doing repeat measurements within short timeframes. For Performers doing single measurements within an Experimental Time Block, the first column can be omitted.

QuantificationReportID: 1
ExperimentID: 1

MeasurementTime	FacilityID	Facility Emission Rate	FacilityEmission Rate Upper (kg/hr)	FacilityEmission Rate Upper (kg/hr)
26/10/2023 09:01:01	Total Landfill	100	120	80
26/10/2023 09:04:01	CR Facility	80	100	60
etc				

5.3.3 Detection Data: (For Performers participating in Detection and Localization Studies)

Each Detection during an experiment should be reported using a tabular format summarizing all detections within a measurement repetition, examples of which are provided in Table 6 for Performers doing a single scan of the facility during an Experimental Design Point, and Table 7 for Performers doing multiple scans of the facility during an Experimental Design Point. Table 6 summarizes the data fields to be reported by all Performers. The Controlled Release Facility has 10 CR Emission Sources, and more source locations may exist outside the defined CR Facility area. Detection reports which are missing mandatory fields will not be considered in the analysis. Optional fields listed in Table 6 may be included if the Performer is able to report these additional data. Performers that are capable of reporting optional data fields are encouraged to do so to support the evaluation of additional metrics under the same series of experiments.

Table 6: Detection data fields

Field	Description	Acceptable Values	Mandatory or Optional
DetectionReportID	A unique ID assigned by the Performer to the individual detection report. *This number should be incremented for every detection report sent.* Duplicate numbers will be assumed to be multiple transmissions of the same report; only one (arbitrarily chosen) report will be logged. The increment amount between reports is arbitrary and need not be constant; report ID should never be deincremented.	Positive Integer	Mandatory
ExperimentID	The experiment during which a detected occurred	Integer	Mandatory
DetectionID	A unique ID assigned by the Performer to an individual Detection.	Positive Integer	Mandatory
FacilityID	Indicate if the Detection is within the CR Facility, or OFF_FACILITY.	Defined by Test Center	Mandatory
Latitude1	If a bounding box for the Detection is reported, the southern-most latitude of the bounding box, in decimal degrees. Otherwise, report the estimated centroid latitude of the Detection location in decimal degrees.	Defined by Test Center	Mandatory

Latitude2	If a bounding box for the Detection is reported, the northern-most latitude of the bounding box, in decimal degrees. Otherwise, this field may be omitted or reported as NULL.	Defined by Test Center	Optional
Longitude1	If a bounding box for the Detection is reported, the eastern-most longitude of the bounding box, in decimal degrees.	Defined by Test Center	Optional
	Otherwise, the estimated longitude of the Emission source in decimal degrees.		
Longitude2	If a bounding box for the Dectection is reported, the western-most longitude of the bounding box, in decimal degrees. Otherwise, this field may be omitted or reported as NULL.	Defined by Test Center	Optional
EmissionRate	If applicable, estimated emission rate of the source. The units of this field should be kilograms per hour of the gas specified in *Gas.*	Decimal number >0	Optional
EmissionRateUpper	Upper estimate of emission rate of the source. The units of this field should be kilograms per hour of the gas specified in *Gas.* If *EmissionRateUpper* is reported, *EmissionRateLower* must also be provided.	Decimal number >0	Optional

EmissionRateLower	Lower estimate of emission rate of the source. The units of this field should be kilograms per hour of the gas specified in *Gas*. If *EmissionRateLower* is reported, *EmissionRateUpper* must also be provided.	Decimal number ≥0	Optional
MeasurementTime	Time (UTC) of the measurement *yyyy/mm/dd_hh:mm*	Formatted DateTime	Optional

Table 7: Reporting format for Detection data fields (showing mandatory and likely fields for most Performers). Owing to the design of the CR Facility with multiple release points, most Performers will identify multiple Detections in any Experimental Design Point. Performers capable of doing multiple repeat scans during the Experimental Design Point should also report the MeasurementTime field similar to Table 5.

DetectionReportID: 1
ExperimentID: 1

DetectionID	FacilityID	Latitude1	Latitude2	Longitude3	Longitude4
1	CRFacility	42.872401	42.872653	-82.120926	-82.121206
2	CRFacility	42.872411	42.872664	-82.120937	-82.121217
etc					

This section concludes performer specific protocols for the experiment. Following sections will cover protocols being utilized by the test center to analyze key performance metrics.

6.0 Performance Metrics (Evaluations Done by the Test Centre)

To evaluate performance metrics, detection reports and Controlled Releases will first be classified as True Positive or False Positive Detections. Results will then be used to evaluate primary and secondary metrics. Primary metrics will be evaluated for all solutions under test; secondary metrics will be evaluated for systems that report

optional data fields.

Caution: Performance metrics and the operational and environmental conditions during the experiment will be reported in the Final Report (see section 8). Performance metrics may only be applicable under the conditions tested and caution should be exercised in extrapolating test results to operational or environmental conditions not encountered during the testing period.

6.1 Classification of Detections

This section applies to experiments involving detection and localization, and any non-zero emission rate quantification experiment.

By default, the classification methodology below will be performed where Controlled Releases and detection reports are sorted by emission rate during Experimental Design Points designed to test quantification, and Localization Accuracy for Experimental Design Points aimed at testing detection and localization.

The Test Center will perform the classification using the following process for each experiment:

1. The list of Controlled Releases performed by the Test Centre within the Facility boundary during the experiment will be sorted by type of Emission Point, then by emission rate, in descending order.
2. The list of all Performer Detections during the experiment will be sorted in the same way as (1).
3. For each Controlled Release in (1), if a Detection in (2) is reported on the same Emission Point, the Detection and Controlled Release will be paired as a True Positive Detection and removed from further matching. True Positives matched in this step will be identified as correct Emission Point Detections. See section
   6.2.5 for Localization Precision (Emission Point).
4. Any Controlled Releases remaining after (3) will be identified as False Negative Detections.
5. Any Detections remaining after (3) will be identified as False Positive Detections.

Figure 2 illustrates the pairing criteria described in section 6.1

Figure 1 True Positive Criteria in Order

This process will classify all Detections attributed to the Facility as either True Positive or False Positive, and all Controlled Releases occurring on the Facility as either True Positive or False Negative, and result in the three possible scenarios illustrated in Table 8 for each experiment. If the number on Controlled Releases, nCR, is greater than the number of reported Detections, nRD, then each reported Detection will be classified as True Positive, and the remaining Controlled Releases will be classified as False Negative. If the number of Controlled Releases is equal to the number of reported Detections, then each reported Detection will be classified as True Positive, and no Controlled Releases will be classified as False Negative. If the number of Controlled Releases is less than the number of reported Detections, then each Controlled Release will be classified as True Positive, and the remaining Detections will be classified as False Positive.

Table 8: Detection classification outcomes for each experiment

Relationship between nCR and nRD	Number of True Positives, nTP	Number of False Positives, nFP	Number of False Negatives, nFN
$nCR > nRD$	nRD	0	$nCR - nRD$
$nCR = nRD$	nRD	0	0
$nCR < nRD$	nCR	$nRD - nCR$	0

6.2 Primary Metrics

The following performance metrics have been identified as primary metrics:

6.2.1 Probability of Detection

Probability of Detection (PD) will be calculated as a curve or surface if the experiments span a sufficient variation in environmental conditions. Detection data will be binned by conditions (environmental and controlled). For each set of conditions, the PD will be calculated as the number of True Positive Detections divided by the sum of the number of True Positive Detections and False Negative Detections in the relevant conditions:

$$PD|_x = \frac{n_{TP}}{n_{TP} + n_{FN}}\Big|_x$$

Where x is the combination of conditions at which the PD is evaluated.

PD results will be calculated for the following three cases unless otherwise agreed by the Performer and Test Center:

1) PD vs emission rate
2) PD vs average wind speed
3) PD vs emission rate and average wind speed

The Performer may request PD be calculated against an independent variable other than wind speed, if they believe the performance of their solution is more impacted by another, recorded and available variable. The Performer may also request only (1) to be calculated with (2) and (3) omitted, producing only a PD curve instead of a surface or series of curves. While the Final Report will contain only the requested PD

curve/surface, all data will be released, and other parties may compute other PD curves/surfaces.

6.2.2False Positive Fraction

The False Positive Fraction will be calculated for the set of all experiments as the number of False Positive Detections divided by the total number of reported Detections.

$$FPF = \frac{N_{FP}}{N_{RD}} = \frac{N_{FP}}{N_{FP} + N_{TP}}$$

The False Positive Fraction does not represent the rate at which a Performer reported a Detection when there were no Emissions at the Facility.

6.2.3False Negative Fraction

The False Negative Fraction will be calculated for the set of all experiments as the number of False Negatives divided by the total number of Controlled Releases.

$$FNF = \frac{N_{FN}}{N_{CR}}$$

The False Negative Fraction does not represent the rate at which Controlled Releases were undetected by a Performer.

6.2.4Survey Time

Survey Time will be calculated as the time between the start of the Emission Survey and the end of the Emission Survey. The testing method will be designed to minimize the need to setup and breakdown equipment between consecutive surveys, allowing Performers to complete a larger number of experiments in a single day of testing. For example, the time required to unpack and assemble an unmanned aerial vehicle (UAV) for an Emission Survey, or the time required to setup auxiliary equipment such as a meteorological measurement station or RTK GPS base station would not be included in the Survey Time. Therefore, Survey Time measured in this testing is likely less than or equal to the Survey Time required at a facility in a field deployment.

6.2.5Localization Precision (Emission Point)

For primary metrics, localization uses only the EmissionPoint provided in the detection report to determine the precision of each True Positive. Each True Positive Detection will be classified into one of three levels of precision, from most precise to least precise:

1) Correct unit: The EmissionPoint was the Emission Point on which the Controlled Release occurred.

2) Correct Facility: The EmissionPoint was within the Facility boundary where the Controlled Release occurred.

6.2.6 Localization Accuracy (Emission Point): Localization Accuracy will be calculated for the set of all experiments as the fraction of reported Detections at each level of precision.

3) Correct unit:

$$LA_{Unit} = \frac{N_{TP_{Unit}}}{N_{RD}} = \frac{N_{TP_{Unit}}}{N_{TP} + N_{FP}}$$

4) Correct Facility

$$LA_{Facility} = \frac{N_{TP_{Facility}} + N_{TP_{Group}} + N_{TP_{Unit}}}{N_{RD}} = \frac{N_{TP}}{N_{TP} + N_{FP}}$$

6.3 Secondary Metrics

Secondary metrics will only be evaluated when optional data fields necessary for their calculation are included in detection reports. The following performance metrics have been identified as secondary metrics:

6.3.1 Quantification Accuracy (Absolute)

Quantification Accuracy will be calculated for each True Positive Detection as the absolute difference (in kg/hr) between the EmissionRate reported and the metered emission rate of the matched Controlled Release.

$$Absolute\ Accuracy = |Measured\ Emission\ Rate\ \left(\frac{kg}{hr}\right) - Actual\ Emission\ Rate\ \left(\frac{kg}{hr}\right)|$$

6.3.2 Quantification Accuracy (Relative)

Quantification Accuracy will also be calculated for each True Positive Detection as the relative difference (in 5) between the EmissionRate reported and the metered emission rate of the matched Controlled Release

$$Relative\ Accuracy = Measured\ Emission\ Rate\ \left(\frac{kg}{hr}\right) - Actual\ Emission\ Rate\ \left(\frac{kg}{hr}\right)$$

6.3.3 Quantification Precision (Absolute)

Quantification Precision will be calculated for each True Positive Detection as the absolute difference between EmissionRateLower and EmissionRateUpper.

$$QP_{abs} = |EmissionRateLower\ \left(\frac{kg}{hr}\right) - EmissionRateUpper\ \left(\frac{kg}{hr}\right)|$$

6.3.4Quantification Precision (Relative)

Quantification Precision will also be calculated for each True Positive Detection as the absolute difference between EmissionRateLower and EmissionRateUpper normalized by the metered emission rate of the matched Controlled Release.

$$QP_{rel} = EmissionRateLower\ \left(\frac{kg}{hr}\right) - EmissionRateUpper\ \left(\frac{kg}{hr}\right)$$

6.3.5 Localization Accuracy (Single Coordinate)

Localization Accuracy will be calculated for each True Positive Detection with a single coordinate pair as the absolute difference (in meters) between the reported coordinate and the location where the matched Controlled Release occurred.

6.3.6 Localization Accuracy (Bounding Box)

Localization Accuracy will be calculated for each True Positive Detection with a bounding box coordinate set as the absolute difference (in meters) between the center of the reported bounding box and the location where the Controlled Release occurred. A true/false value will also be calculated for each True Positive Detection with a bounding box coordinate set to indicate if the Controlled Release was within the reported bounding box.

6.3.7 Bounding Box Accuracy

A true/false value will also be calculated for each True Positive Detection with a bounding box coordinate set to indicate if the Controlled Release was within the reported bounding box. The Bounding Box Accuracy will be calculated as the fraction of True Positive Detections with a bounding box reported where the Controlled Release was within the bounding box.

6.3.8 Localization Precision (Bounding Box)

Localization Precision will be calculated for each True Positive Detection with a bounding box coordinate set as the area (in square meters) of the bounding box.

6.3.9 SurveyTime

Survey speeds and annualized costs will be assessed based on actual number of survey reports submitted for a given Experimental Design Point from which a real SurveyTime will be calculated. In the Final Report, these proven speed metrics will be used rather than questionnaire indicators of SurveyTime the purpose of which was to plan the Experimental Release Point timings, and to set an overall schedule.

7.0 Experimental Design

7.1 Background

Current estimates of landfill emissions have relied heavily on modeling predictors. The potential of direct measurement strategies to reduce the uncertainty inherent in variables used in models has proven attractive. However, direct methods deployed thus far have had their share of challenges in the ability to provide whole landfill emission measurements either consistently or accurately without introducing assumptions or having to model certain parameters. A robust evaluation of current methods in a landfill environment that allows for them to be compared has not been performed.

That last time an effort was conducted in this respect was a study facilitated by EREF in 2010 utilizing a tracer correlation strategy that was used on 2 landfills and that brought multiple emission detection technologies to these sites to conduct simultaneous measurements under a controlled release setting. The study proved to be important in directing the next decade of efforts in direct measurement quantitation of landfill emissions. However, recent advances in emission measurement utilizing drones, aircraft and satellites have introduced potentially more accurate, efficient and cost-effective strategies. However, the same issue that existed in 2010 exists today in that none of the methods have been compared side-by-side to allow for a comparative assessment of the technologies, nor have the technologies been compared against a controlled release of methane to evaluate absolute accuracy (as compared to relative accuracy).

7.2 Objectives

Thus, the primary objectives of this effort are to:

- Conduct a comparative assessment of multiple landfill emissions measurement technologies at a single site simultaneously
- Determine the accuracy of these technologies via a controlled, known release of methane
- Assess annualized costs of utilizing these technologies at different frequencies on sites of different size
- Evaluate variability in accuracy under different site conditions (e.g. weather, temperature, season, etc.) *(NOTE: this objective may be considered optional or as a 2nd phase effort depending on additional cost/time needed to complete it).*

In general terms, the following information outlines the general experimental approach:

7.3 Experimental General Conditions

7.3.1 Controlled Release Configuration

The controlled release will be performed by discharging methane at a known rate from 2 dispersed (perforated tube) and 8- point release locations located within an area of 20 acres or less. This design is intended to emulate fugitive emission sources that one would find across the surface of a landfill.

7.3.2 Measurement Trials

Prior to initiating the controlled release, ambient methane should be measured by all measurement technologies, which will serve as a control for the experiment. For the controlled release portion, methane will be released at known rates and repeated measurements will be conducted and as detailed in your schedule. The measurement trials shall be conducted as follows:

- Methane discharge will occur over a duration that allows adequate time for appropriate dispersion/mixing and measurement, which will dictate the volume of methane required for the study. The specific duration for this initialization period will be approximated based on site conditions and estimated dispersion time. Further, the release flow should be high enough to clearly distinguish between Background values, but within a range that is typical for

landfill fugitive emissions.

- For each release trial, replicates should be performed as technology protocols require it. Duplicate measurements are highly encouraged if time allows, to prove out claimed survey duration. These replicate measurement submissions will be considered as an indicator of SurveyTime and will also help bolster performance statistics. For example, aircraft measurement may require multiple passes, drone-based measurements using a flux curtain technique may need multiple passes, while mobile spectroscopy may require 1 pass per trial. However, based on the rate of travel, Aircraft Survey Solutions may report substantially more replicate measurement reports within a single Experimental Design Point than slower drone-based solutions.
- The controlled release will be performed blind, meaning no technology companies or landfill owners shall be aware of the flow rates being used. 3rd party personnel will manage the release and coordinate with participants.
- To ensure transparency, special observers may be designated to verify the experiment is being conducted without bias. Some possibilities include the EPA and/or university personnel who conduct research related to greenhouse gas emissions.

7.3.4 Assessment Under Variable Conditions

Where possible, and as the weather cooperates, the study design can be used to further evaluate accuracy because it will likely entail duplicates executed on different days under different conditions (e.g. windy, no wind, high/low temperature, different season), which would add significant value to the results obtained.

7.3.5 Compilation of Measurement Results

Participating technology companies shall submit uncompiled data collected for each trial to St. Francis Xavier University. If acquired data is modified and such modification is typical in order to compute final values, this is acceptable provided a detailed explanation is given that justifies the need for doing so. It is expected that each company perform quality assurance of the collected data and that the data submitted to the PI is considered final.

7.3.6 Data Compilation

The Test Centre will compile the data received according to this protocol and conduct a comparative analysis relative to the known release rates and prepare appropriate tables, figures and discussion of the results in a summarized format to be shared as preliminary findings to the EREF project stakeholder group and any designated 3rd parties for advance review. An outline for the final report will also be to EREF by the Test Centre including any testing data used to generate the report. Review comments pertaining to the findings and report outline will be compiled and utilized for the preparation of a final report, which will be released by EREF. As appropriate, a paper may be prepared for submission to a peer-reviewed journal. Additionally, excerpted or summarized information from the effort will be disseminated through data summaries, presentations, and articles (e.g. Waste360, MSW Management, etc.).

7.4 Facility to be Monitored

The Test Center will define the Facility to be monitored during each experiment using a bounding box of coordinates not exceeding 20 acres (of the landfill's 60 total acres). The bounding box may correspond to physical infrastructure, such as a fence line, or an implied boundary such as a property line, right of way, or easement. Consecutive experiments may be performed on the same Facility or different Facilities. Within the bounding box there will be 10 Emission Points. Some Survey Solutions will instead measure the total landfill area, that will comprise additional Background Emission Points.

7.5 Selection of Experimental Design Points

Performers with ability to quantify emissions will be tested first, and will be invited to participate in numerous Experimental Design Point repetitions involving zero, small, medium, and large releases. The test centre will achieve the release rates using a combination of release points. Within any Experimental Design Point, the release

combinations and rate will remain static. Performers can expect them to change between experiments. The majority of Performers with the ability to quantify total methane emissions have indicated they are able to perform their work in a relatively short survey time of typically less than one hour. Special arrangements will be made for Performers who have indicated that highly specific weather conditions to be satisfied for measurement, and uniquely they will be able to move continuously and assess conditions and indicate readiness - at which point the Test Centre will endeavor to keep emission rates constant for the required period of time to complete the measurement. This approach maximizes statistical power and provides fairness to all regardless of operating limitations.

Performers with ability to detect and localize emissions will be tested second and will be invited to participate in Experimental Design Point repetitions involving generally small releases of 0-20 kg/hr per release location, but where the locations and number of sources and emission rates of the leak locations vary between Experimental Design Points. Performers with ability to detect and localize have indicated that it might take several hours to survey the 20-acre test domain using normal procedures, so we expect to achieve 2-3 Experimental Design Points each day. Since each release location within an Experimental Design Point can be treated as a separate binary detection experiment, we can achieve good statistical power even with a small number of Experimental Design Points each day.

Overall, enough Experimental Design Points should be performed in each Controlled Release emission rate of interest to evaluate a Probability of Detection curve. The Test Center will keep track of the number of Experimental Design Points at each emission rate in a design matrix similar to the matrix illustrated in Table 9.

Table 9: Example Experimental Design matrix for Emission Detection testing. A comprehensive testing schedule will be available in the weeks prior to the experiment. True to the blind experiment design, Performers will not have an indication of rates being used in any given Experimental Design Point.

	Emission Rate			
	Zero	Low	Med	High
Number of experiments				

7.5.1 Gas Composition

Gas composition may vary between Experimental Design Points, and depending on the Facility being measured (Total Landfill vs Controlled Release Facility). The range of expected gas compositions for the Controlled Release Facility will be provided by the Test Center to the Performer once it is available from the gas supplier

7.5.2 Emission Rate

One of the primary objectives of this protocol is to evaluate the Probability of Detection curve across a range of emission rates. Therefore, emission rates will be selected by the Test Center for each Experimental Design Point to extend outside – above and below – the normal operating range of the Performer(s) participating at the time of testing.

Emission rates will be restricted to the constraints of the Test Center Controlled Release system, plus any Background Emission Points from the landfill itself. The lower limit and upper limit of the Test Center will be provided by the Test Center to the Performer(s), plus an estimate of background emission rates in each Facility, in advance of testing.

The Test Center has the final authority to select the emission rates considering the engineering design of the Controlled Release system and operational safety considerations.

7.5.3 Maximum Survey Time

The Test Center will establish a maximum Survey Time for each experiment. The Survey Time will be set by the Test Center in accordance with the typical measurement time of each technology. During each experiment, Performers will have up to, but no longer than, the established maximum Survey Time to complete measurements. Therefore, each experiment will end in one of two ways:

a) If a Performer completes the experiment before the maximum Survey Time has elapsed, the Performer should cease survey operations and inform the Test

Center that they are complete, or proceed to conduct replicates (as is encouraged). The Test Center will then provide instructions (or may have previously provided instructions) to move on to the next experiment, if it is ready, or the Test Center will provide a location away from the experiment location to wait until the next experiment is ready.

b) The Performers submitted expected survey times, to which the Test Centre will add an extra margin to establish a maximum Survey Time. If a Performer does not complete the experiment before the established maximum Survey Time has elapsed, for reasons including factors beyond their control such as technology or weather, the Performer will be instructed to cease all survey operations when the time expires. The Test Center will then provide instructions to move onto the next experiment, if it is ready, or provide a place away from the experiment location to wait until the next experiment is ready.

In either (a) or (b), the Performer should record the actual Survey Time in the survey summary (see section 5.3.1) for the experiment. Whether the survey ended in either (a) or (b), performance metrics will be calculated the same way, using the detection reports (including start and end times) recorded by the Performer.

7.5.4 Simultaneous Controlled Releases

Experimental Design Points will normally include multiple simultaneous Controlled Releases from a combination of Emission Points.

7.5.5 Environmental Conditions

The environmental conditions during each experiment will be summarized using the maximum, minimum, mean, and standard deviation of each parameter during the full duration of the test. Test Center will locate two weather stations onsite, one at the top of the landfill, and another at the base. Each station will measure wind speed and direction using a research grade sonic anemometer, along with temperature, barometric pressure, and relative humidity. The stations will also record methane concentrations, although at low resolution (+- 0.5 ppm). These records will be available to Performers, subsequent to submission of their first report as described earlier in the Protocol. Performers may request to update their reports in light of the provided data, and such requests will not reasonably be denied so long as updates are made in a

timely fashion. Discrepancies in submitted values between original and revised submissions will be noted by the Test Centre and may be used in synthesis reporting to address the question of dependence on outside weather data.

One test period may include a limited range of environmental conditions. Results from multiple test periods may be combined to cover a variety of environmental conditions, provided the Survey Solution as documented in section 5.1 remains the same between testing periods. Combining results from multiple test periods may be required to produce a Probability of Detection curve where one axis is an environmental condition such as wind speed.

8.0 Final Report

The Test Center will perform the classification of Detections and calculation of metrics after all experiments are completed and either (a) detection reports have been provided by the Performer for all experiments or (b) two months have elapsed since the last experiment. The calculation of metrics will be performed across the full duration of the testing program.

The Test Center will provide a results report to the Performer. A copy of the original results report will be available to other parties from the Test Center, by request, with the Performers consent for release. R&D Participants involved in this experimental protocol will receive data generated during testing to support the improvement and refinement of their technologies. However, R&D Participants' contributions and outcomes will not automatically be included in any public reporting. Inclusion in public reports will only occur if the Test Centre deems the data appropriate for broader dissemination, and only with the express consent of the R&D Participant (the Performer). This approach ensures that preliminary findings remain confidential unless mutually agreed upon for public release. The results report will include, at minimum, the information described in this section.

In addition to the Final Report Test Centre will also prepare a high level synthesis report, touching on the performance metrics measured and contrasting the strengths and weaknesses of each method, recognizing that all are known to measure methane

but are often intended for different design purposes and roles in landfill methane management. As appropriate, the synthesis report may be prepared for submission to a peer-reviewed journal in the months following the experiments, in which participants will be identified via principle of measurement and not by commercial name.

All final reports plus drafts and final synthesis reports will be to EREF by the Test Centre including any testing data used to generate the reports. Review comments pertaining to the findings and report outline will be compiled and utilized for the preparation of a final synthesis report, which will be released by EREF. Additionally, excerpted or summarized information from the effort will be disseminated through data summaries, presentations, and articles (e.g. Waste360, MSW Management, etc.)

8.1 Experiment Summary

The experiment summary will include the date range in which experiments were performed, the total number of experiments and the total number of Controlled Releases. Experimental conditions will be summarized including the Controlled Release rates, Controlled Release durations, and environmental conditions included during the experiments.

8.2 Performance Metrics

Performance metrics will include all primary metrics as described in section 6.2. Secondary metrics will be reported if the Performer detection reports included the required data for their calculation. Metrics which are calculated individually for each True Positive Detection. For example, Quantification Accuracy (section 6.3.1), will be included as histograms.

8.3 Documentation of Test Protocol

A copy of the test protocol utilized in the experiments will be included.

8.4 Documentation of System Under Test

Documentation of the system under test as reported by the Performer to the Test Center in section 5.1.1 will be included.

8.5 Controlled Release and Detection Data

All Controlled Release and Detection data will be included. Each True Positive, False Positive, and False Negative Detection will be included. Each Detection will include:

1) The Detection classification (True Positive, False Positive, False Negative)
2) Performer reported Detection data, as received by the Test Center, including all data fields listed in Table 5 (applicable to True Positive and False Positive Detections only).
3) The Controlled Release data including timing, metered emission rate with upper and lower 95% confidence limits, Emission Point ID, latitude, longitude, and height (applicable to True Positive and False Negative Detections only).
4) Meteorological conditions as measured by the Test Center for each Controlled Release (applicable to True Positive and False Negative Detections only).
5) Time to detect, Localization Accuracy, Localization Precision, Quantification Accuracy and Quantification Precision metrics calculated for the individual Detection (applicable to True Positive Detections only).

8.6 Flow Meter Calibrations

The Test Center will include calibration records for the flowmeters used in the experiments.

9. Testing at the St. Francis Xavier University Landfill Test Facility

This section will contain information specific to our site including the geolocation of Emission Points, and maps, etc.

9.1 Test Facility Location

The Controlled Release testing will take place at a closed landfill in Petrolia, in Southern Ontario, Canada (Project Longitude: -82.121258° Project Latitude: 42.871952°), 4052 Oil Heritage Road, Petrolia, ON, N0N 1R0.

Figure 3: Petrolia Landfill Location

The Petrolia Landfill site consists of a closed landfill and is operated by Waste Management with an LFG collection system and LFG utilization.

Figure 4: Petrolia Landfill Map Pre-Closure

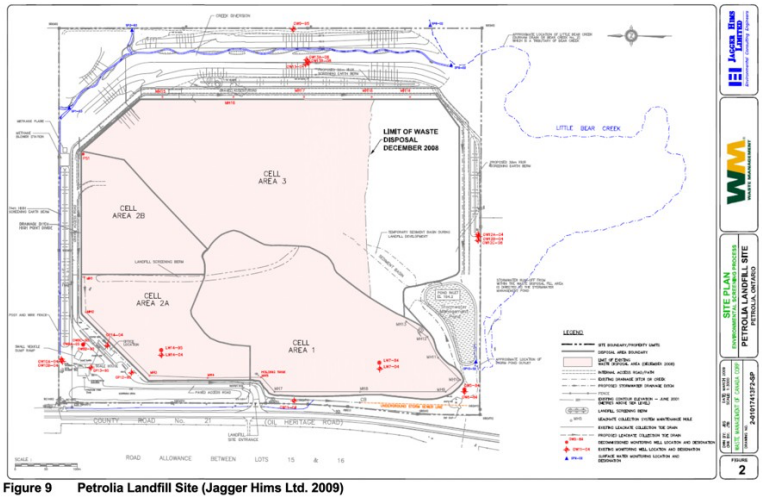


Figure 9 Petrolia Landfill Site (Jagger Hims Ltd. 2009)

9.2 Baseline Emission Rate

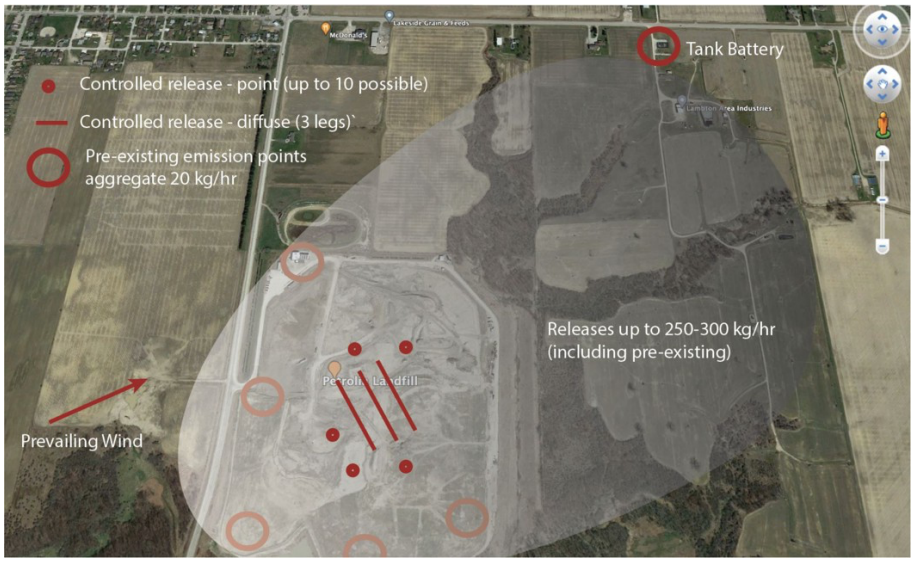
Both ECCC (Environment and Climate Change Canada) and the FluxLab have conducted measurement studies at this site in the past. Measurements coordinated by ECCC in 2021 found site emissions rate estimates via Mobile Gaussian Inversion to be 18.75 kg/hr. Measurements conducted by FluxLab in 2022 found site emission rate estimates via Mobile Gaussian Inversion to be 20 kg/hr. In 2023 background methane

emission rate was estimated to be 24.44 kg/hr using the tracer correlation method.

Figure 5: Petrolia Landfill Emission Points

9.3 Emission Points Geolocation:

Figure 6: Original Release Configuration Concept



Appendix A – Example Survey Summary Document (to be accompanied by quantification or detection reports)

Survey Summary Document

Experiment ID	
Facility ID	
Start Date/Time (yyyy/mm/dd hh:mm)	
End Date/Time (yyyy/mm/dd hh:mm)	
Survey Time (hh:mm)	

Comments:

Preliminary Information:

Describe Emission Detection System Configuration	
Description of Methodology Used During Emission Detection	
Confidence Level at which Emission Detection Data are Reported	
Number of Personnel Required On-Site	
Number of Offsite Personnel	

Detection System Information:

Primary Components	Model Number	Revision Number of Software (Including components, revisions, or customization)

Location of Auxiliary Components:

Auxiliary Components	Latitude	Longitude	Height	Model Number	Revision Number of Software

Personnel:

Name	Role	Onsite/Offsite

Appendix B – Changes from Previous Version 1.4

Added bulk upload format and data examples in 5.3.2 and 5.3.3
Changed EmissionSourceID to DetectionID
Changed reporting to kg/hr from g/hr
Renumbered Tables

Appendix B-1 – Changes from Previous Version 1.5

Basic formatting
Changed instances where emission rate units are listed as g/hr to kg/hr
5.2- Added 5)Performers operating drones will be allowed to perform ground verification measurements in most cases.
5.3-Added Performers must commit to submit data for all measurements that they make during the study.
6.3 - Updated secondary metrics equations to reflect unit consistency
7.3.1-Updated point release source number to 8

7.4 -Updated number of emission points to 10

9.0 - Removed proposed emission source location figure (Figure 7) in section

Appendix B-2 – Changes from Previous Version 1.6

Updated cover page

8.0-Updated wording on r&d technology participation

Appendix B-3 – Changes from Previous Version 1.7

5.3- Added requirement for participants with satellite based solutions to include imagery with their submissions

6.1- Removed facility level detection assessment since search area is provided and all detections reported are usually within the search area (i.e. facility)

7.5.1- Changed wording

9.2 - Added 2023 background methane emissions rate.