FINAL OUTCOMES REPORT

Proof-of-Concept Testing: Software to Quantify Methane Emission Rates in Real-Time

PREPARED FOR
Emissions Reduction Alberta
Edmonton, Alberta

SUBMITTED TO
Dallas Johnson, Ph.D., Project Advisor
Alberta Innovates
Edmonton, Alberta

July 17, 2019

SUBMITTED BY
Minnich and Scotto, Inc.
Freehold, New Jersey, USA

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IN PARTIAL FULFILLMENT OF THE ERA PROJECT

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ERA PROJECT ID O160052

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DISCLAIMER

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SELECTED ACRONYMS AND ABBREVIATIONS

Item	**Meaning**
A	actual (or controlled) methane emission rate
ACCO	Alberta Climate Change Office
AER	Alberta Energy Regulator
AERMET	AERMOD meteorological preprocessor
AERMOD	***A***merican Meteorological Society / ***E***PA ***R***egulatory ***Mod***el
AP-42	Compilation of Air Pollutant Emissions Factors
ASCII	American Standard Code for Information Interchange
A&WMA	Air & Waste Management Association
bLS	backward Lagrangian stochastic
BS	booster station
C	Centigrade
C_M	measured path-integrated concentration (attribution) (mg/m^2);
C_U	predicted unity-based, path-integrated concentration along the measurement path (mg/m^2)
C_{UE}	predicted unity-based, path-integrated concentration along an extended measurement path (mg/m^2)
CAFO	concentrated animal feeding operations
CALPUFF	***Cal***ifornia ***Puff*** Model
CFR	U.S. Code of Federal Regulations
CH_4	methane
CNRL	Canadian Natural Resources Limited
CO_2	carbon dioxide
COSIA	Canada's Oil Sands Innovation Alliance
CRDS	cavity ring-down spectroscopy
CSV	comma-separated value
DAS	data acquisition system
DQO	Data Quality Objective
e-Calc 1	Minnich and Scotto's ***e***missions ***calc***ulation software (first-generation)
e-Calc 2	Minnich and Scotto's e-Calc software (second-generation)
EPA	U.S. Environmental Protection Agency
ER	emission rate
ERA	Emissions Reduction Alberta
FTIR	Fourier-transform infrared
GB	gigabyte
GGP	gas-gathering pipeline
GHG	greenhouse gas
GHz	gigahertz
GPS	global positioning system
H	sensible heat flux
H&S	health and safety

SELECTED ACRONYMS AND ABBREVIATIONS (Cont'd)

Item	Meaning
HAP	Hazardous Air Pollutants
Hz	hertz
IB	interpolated background
IDM	inverse dispersion modeling
IP	intellectual property
L	Monin-Obukhov length
m	meter
MACT	Maximum Achievable Control Technology
MAP	measurement and analysis plan
mb	millibar
MD	Major Deliverable
MDT	Mountain Daylight Time
mg	milligram
MGP	manufactured gas plant
modified e-Calc 2	Minnich and Scotto's modified e-Calc software (second-generation)
MQO	Measurement Quality Objective
MS	Microsoft
MSW	municipal solid waste
mT	metric ton
NOAA	U.S. National Oceanic and Atmospheric Administration
O&G	oil and gas
ORS	optical remote sensing
P	predicted methane emission rate; atmospheric pressure
PC	plume capture; personal computer
"pfl"	AERMOD profile file
PIC	path-integrated concentration
PICMET	***P***ath-***I***ntegrated ***C***oncentration – ***Met***eorology
PP	production pad
ppb	parts per billion
ppbv	parts-per-billion by volume
ppm	parts per million
ppm-m	parts-per-million times meter
ppmv	parts-per-million by volume
PQL	Practical Quantitation Limit
Q_A	actual emission rate
Q_U	unity-based emission rate
QAPP	Quality Assurance Project Plan
QC	quality control
r^2	correlation coefficient
R&D	research and development

SELECTED ACRONYMS AND ABBREVIATIONS (Cont'd)

Item	Meaning
RAM	random access memory
RH	relative humidity
RSD	relative standard deviation
s	second
SA	source attribution
SCAQMD	South Coast Air Quality Management District (California)
"sfc"	AERMOD surface file
sigma theta (σ_θ)	standard deviation of the horizontal wind direction
sigma w (σ_W)	standard deviation of the vertical wind speed (also called sigma phi, σ_ϕ)
SOP	Standard Operating System
T (or T_A)	actual temperature
TDL	tunable diode laser
TRL	Technology Readiness Level
u	east-west wind component
u*	friction velocity
ug	microgram
U.S. EPA	U.S. Environmental Protection Agency
USB	Universal Serial Bus
UTM	Universal Transverse Mercator
v	north-south wind component
w	up-down wind component
WD	wind direction
WS	wind speed
z_0	surface roughness length

EXECUTIVE SUMMARY

BACKGROUND

This Final Outcomes Report for ERA describes an 18-month, methods-development program to modify and field-test Minnich and Scotto's software package for calculating methane emission rates from a variety of upstream, ground-based oil-and-gas industry sources (primary project goal). The end-product was a fully integrated, methane emission-rate measurement system (i.e., the "System") for use with these source-types, in real-time. The project included development of a Set of Specifications for System commercialization.

The secondary project goal, a benefit to the Alberta Climate Change Office, was to apply this software to calculate fugitive methane and carbon dioxide emission rates from the mine-face and tailings pond operations at CNRL's oil-sands facility in Fort McMurray, based on existing data collected in 2015 and 2016. ACCO identified the following objectives:

- To provide best estimates of methane and carbon dioxide emissions, including discernment of any diurnal trends;
- To develop methane/carbon dioxide emission-ratio profiles;
- To assess whether upwind sources had a significant effect upon the reported methane and carbon dioxide attribution from the mine face and tailings pond; and
- To provide recommendations on the type and quality of data needed to optimize the future software performance.

The software tested is known as e-Calc 2. Field testing to support the primary project goal involved the continual, outdoor release of carefully controlled amounts of methane from simulated, leaking upstream sources. The metric for evaluating the software's performance was how well the predicted methane emission rate (P) compared to the controlled (or actual) release rate (A). This P/A comparison was expressed as a percent ratio, and assessed largely as functions of meteorology.

Field tests were conducted over nine days between August 14 and 23, 2018. A total of 211 daytime and 16 nighttime, 15-minute-averaged events were completed for the four simulated sources. Only a single source was monitored on any given measurement day. Supporting team members and responsibilities were:

Innotech Alberta – Controlled methane releases at their R&D facility in Vegreville.

Boreal Laser – Methane measurements using their tunable diode laser (TDL) spectrometer.

Met One Instruments – Design and assembly of a specialized meteorological measurement system.

Loover Partnership – Necessary e-Calc software modification and statistical consulting.

E-Calc (versions 1 and 2) calculates 15-minute-averaged, mass-per-time emission rates (referred to as monitoring events) for most ground-level sources, based on source-attribution (downwind concentration minus the upwind, or background, concentration). Both versions employ inverse dispersion modeling using AERMOD (the U.S. EPA's air dispersion model for regulatory application). Instead of predicting a downwind concentration at a point in space from a known source emission rate, e-Calc predicts that emission rate from a measured downwind (crosswind), path-integrated concentration and contemporaneous onsite meteorology. We sought to modify the software to accommodate a more sophisticated and robust treatment of meteorology for simulating the vertical wind-speed profile and atmospheric turbulence – critical model input parameters. The intent was to eliminate the need for the arduous pre-field tasks and make possible the software's use during the nighttime.

The four simulated sources were:

- a booster station, comprised of a compressor engine and a condensate tank;
- a gas-gathering pipeline assembly;
- a gas transmission line; and
- a production pad.

Primary Project Goal

Treatment of background methane required special attention, as the concentrations were shown to be variable over each measurement day. The inability to assign an accurate background concentration to each individual monitoring event adversely affected the P/A ratios, precluding use of the full complement of emissions data generated for System specification development. We were able to evidence that the accuracy of certain background measurements was compromised by having to initiate them before the methane had completely cleared the downwind TDL beam-path. A strategy was employed to critically examine all of the background data collected and develop new background criteria for monitoring event acceptance in order to minimize this P/A inconsistency.

When the affected monitoring events were removed from further consideration, confidence in the remaining P/A results was deemed sufficient for (initial) specification development, but the situations where System applicability still could not be demonstrated were: (a) during nighttime conditions; and (b) when assessing emissions from the booster-station simulation. Nighttime data were collected during only one evening for one source (Day 9, the gas-gathering pipeline), while data for the booster station were collected during only two measurement days (Days 1 and 2). None of these monitoring events for the two sources met the new methane background criterion.

We finally developed and applied an approach to reassess System applicability for the booster station, which allowed us to extend the System specification to include this source. Unfortunately, we were unable to salvage any of the nighttime data collected during Day 9 for the gas-gathering pipeline.

Secondary Project Goal

The e-Calc software was shown to be a potentially viable, attractive alternative to the techniques currently employed during CNRL mine-face and tailings pond operations. It should be noted that the ACCO data was collected to satisfy the input requirements of CALPUFF – a model applied by CNRL, also in its inverse form. As it turned out, while the ACCO data was voluminous (more than 2,600 combined methane and carbon dioxide 15-minute-averaged TDL measurements for both sources over the 2 years), we were able to use only a small subset of it. Still, we were able to reasonably address ACCO's objectives.

FINAL SYSTEM SPECIFICATIONS, RECOMMENDATIONS, AND LIMITATIONS

Table E-1 present the final System component specifications.

TABLE E-1. FINAL SYSTEM COMPONENT SPECIFICATIONS

Component	Manufacturer/ Provider	Model No.
Tunable diode laser	Boreal Laser	GasFinder3-OP
3D ultrasonic anemometer	R.M. Young	8100
Ambient temperature sensor	Met One	064
Relative humidity sensor	Met One	083
Barometric pressure sensor	Met One	092
Portable 3m tripod	Met One	905
Crossarm assembly	Met One	191-1
Meteorological DAS	Met One (Climatronics)	IMP-865
LoggerNet software	Met One (Climatronics)	Version 4.5
Tablet computer	Dell Inspiron (or equiv.)	P24T
Global positioning system	Trimble (or equivalent)	GEO 5T
Emission-calculation software	Minnich and Scotto	e-Calc 2

Table E-2 presents the final System recommendations and limitations.

TABLE E-2. FINAL SYSTEM RECOMMENDATIONS AND LIMITATIONS

Issue	Methane Emissions Source	Recommendation	Limitation
Monitoring events	(all)	Four successive 15-minute events to form an hourly-average emission rate	Plume meander and other short-term effects may adversely impact 15-minute averages
Wind speed	- Booster stations	Use e-Calc 2 or modified version for WS between 2.0 and 3.0 m/s	- Avoid WS less than 2.0 m/s - Use caution with WS greater than 5.0 m/s
		Use modified version for WS greater than 3.0 m/s	
	- Gas-gathering pipelines - Gas transmission lines - Production pads	Use e-Calc 2 for WS between 2.0 and 5.0 m/s	
Background	(all)	Minimum of six consecutive measurements	If measurements are not consistent, use dual TDL units (simultaneous upwind / downwind measurements)
Nighttime application	(all)	(none)	Nighttime application is not supported

TECHNICAL ACCOMPLISHMENTS

Development of e-Calc 2

E-Calc 2 was developed and demonstrated as a means of accurately calculating emission rates of methane from a variety of ground-based O&G industry sources, in real-time, with only minor pre-field preparation required.

A modified version of e-Calc 2 was developed and demonstrated as a means of accurately calculating methane emission rates from somewhat elevated O&G sources. Although the need exists for further research concerning the software's performance, this technique has the same basic attributes and capabilities as e-Calc 2.

E-Calc 2 Applicability to the Oil-Sands Industry

E-Calc 2 and its attendant GHG measurement technology offers at least three powerful advantages over typically employed approaches: (a) superior accuracy afforded by its capability to adequately address the inherent spatial data-representativeness deficiencies; (b) nominal deployment costs afforded by the fact that the software is already developed and fully functional; and (c) real-time results afforded by minimal labor and CPU-time requirements.

PATENTING

We are unsure whether we will seek a patent for e-Calc 2, as most of the software is simply reverse-engineered from AERMOD (the coding for which resides in the public domain). Patents for the TDL components and the meteorological system components are owned by Boreal Laser and Met One, respectively.

POTENTIAL PARTNERSHIPS

We intend to begin immediately the process of securing an exclusive partnering agreement with a well-established air quality consulting/engineering firm which has a strong Alberta presence. This arrangement will allow us to maximize technology transfer to Alberta, such that all aspects of e-Calc are available to ERA (and other Alberta entities) though a single, high-profile Alberta-based company. We reasonably anticipate that Minnich and Scotto will grant this company exclusive license to e-Calc, and all of its derivatives, for use in Alberta (and possibly the remainder of Canada).

We are confident that the short-term actions and long-term plans identified below will keep this technology relevant and on the forefront in Alberta.

Short-Term Actions

- Secure an exclusive partnering agreement to maximize technology transfer to Alberta
- Propose an ERA project for System demonstration at an MSW landfill
- Propose an ERA project for demonstrating a modified System at a tailings pond

Long-Term Plans

- Propose a program to develop methane emission factors
- Develop and implement an aggressive marketing plan

SECTION 1 – PROJECT DESCRIPTION

Section 1.1 presents an introduction and project background information. **Section 1.2** describes the technology. **Section 1.3** identifies the goals of this project. **Section 1.4** presents a work scope overview.

1.1 Introduction and Background

This Final Outcomes Report describes an 18-month methods-development program, sponsored by the Province of Alberta and administered by Emissions Reduction Alberta (ERA) as part of their "Methane Challenge Initiative." The title of our project was, "Proof-of-Concept Testing: Software to Quantify Methane Emission Rates in Real-Time." The end-product was a fully integrated, methane emission-rate measurement system (i.e., the "System"), which calculates, in real-time, methane emission rates from certain oil-and-gas (O&G) industry sources. The project included development of a Set of Specifications for System commercialization.

The software tested is known as e-Calc 2 (***e***missions ***calc***ulation, second-generation). Nine days of successful field testing, carried out during August 2018, involved the continual, outdoor release of carefully controlled amounts of methane by our project team member, InnoTech Alberta, at their research facility in Vegreville. Other members of the project team were: Boreal Laser, Inc. (Edmonton), responsible for all methane measurements using their tunable diode laser (TDL) system; Met One Instruments, Inc. (Happaugue, New York), responsible for the design and assembly of the specialized meteorological measurement system used in the field; and Loover Partnership (Morristown, New Jersey), responsible for necessary e-Calc software modification and statistical consulting.

The first-generation version of this software (e-Calc 1) calculates mass-per-time emission rates during daytime hours from ground-level sources. E-Calc 1 employs "inverse dispersion modeling (IDM)," based on AERMOD (***A***merican Meteorological Society / ***E***PA ***R***egulatory ***Mod***el) – a U.S. Environmental Protection Agency (U.S. EPA) "Guideline" air dispersion model for regulatory application. Instead of predicting a downwind concentration at a point in space from a known source emission rate (as AERMOD typically does), e-Calc 1 predicts that emission rate from a measured downwind (crosswind), path-integrated concentration and contemporaneous onsite meteorology.

E-Calc 1 can derive emission rates of methane (or any other measured compound) from most ground-based sources. Importantly, this software offers the capability of generating such emission rates in real-time. However, a significant up-front effort is required, prior to field deployment, to enable AERMOD (and thus e-Calc 1) to simulate the vertical wind-speed profile and atmospheric turbulence – critical model input parameters. AERMOD employs what is known as the *flux-gradient approach* for simulating these input parameters.

For this project, we sought to modify the software to accommodate a more sophisticated and robust treatment of meteorology (i.e., to create e-Calc 2 based on a new version of AERMOD – modified to employ the *eddy-correlation approach* for simulating the above model input parameters) and, second, to field-test this second-generation version of the e-Calc software, based on carefully controlled methane releases from simulated, leaking upstream sources. The intent was to eliminate the need for the arduous pre-field tasks and make possible the software's use during the nighttime.

The four simulated sources were:

- a booster station, comprised of a compressor engine and a condensate tank;
- a gas-gathering pipeline assembly;
- a gas transmission line; and
- a production pad.

Only one simulated source was tested on any given measurement day. As mentioned, all controlled methane releases were conducted by InnoTech Alberta, with all field work performed at InnoTech Alberta's Vegreville R&D facility. Path-integrated methane measurements were performed by Boreal Laser using one of their GasFinder TDL spectrometers; all TDL measurements were made at a height of 1.0 meters above the ground. All meteorological measurements were made using a sonic anemometry system designed and assembled by Met One Instruments. The methane source was compressed natural gas, with a methane concentration of 76.6 percent (760,000 ppmv).

It should be noted that there has never been a performance evaluation of AERMOD based on this more sophisticated treatment of meteorology, and the U.S. EPA has yet to provide the software coding for this model option. In theory, the AERMOD results should be improved (and, accordingly, the corresponding e-Calc predictions); however, such results could not be guaranteed.

We know of no other measurement system which can, in real-time, generate accurate estimates of methane emissions from ground-level sources. It is difficult for the Province of Alberta to enforce existing methane reduction mandates without an accurate baseline against which to compare. The rapid and inexpensive means of measuring methane emission rates afforded by the success of this Project is clearly a disruptive technology.

When used in combination with the TDL system, e-Calc offers a common-sense approach for prioritizing repairs in the O&G industry, which can reduce product loss while adding bottom-line profit. By quantifying methane emissions from principal source types within a given industrial sector, the quality of emissions inventories should be vastly improved, thereby facilitating an accurate methane baseline against which future reductions can be reliably assessed.

A second objective of this project, a benefit to the Alberta Climate Change Office (ACCO), was to apply e-Calc (both versions) to calculate the fugitive methane and carbon dioxide emission rates from the Canadian Natural Resources Limited (CNRL) mine-face and tailings pond operations in Fort McMurray.

Finally, as alluded to above, in addition to leaking upstream process components, target markets in Alberta for this System include: (a) municipal solid waste (MSW) landfills; (c) concentrated animal feeding operations (CAFO) facilities; and (c) major oil-sands sources, consisting of mine faces and tailings ponds. In fact, the feasibility of employing e-Calc 2 to assess methane emissions from these oil-sands sources was demonstrated during the work for ACCO, thereby laying the groundwork for a proposed field demonstration at a tailings pond.

1.2 Technology Description

Section 1.2.1 presents a brief history of e-Calc 2's development. **Section 1.2.2** presents relevant technical considerations.

1.2.1 Developmental History

Minnich and Scotto is the architect of e-Calc – an emissions-calculation software package developed for generating air pollutant emission rates from a wide range of fugitive-type, ground-level sources (as well as elevated area sources). This Windows-based, client-server software calculates contaminant emission rates – precise 15-minute-averaged "snapshots" – from these source types. E-Calc is suitable for use with a TDL spectrometer, or any other optical remote sensing (ORS) instrument which generates a path-integrated concentration (PIC). The software can also be used with a rapid-sampling, mobile point-monitoring device, such as a cavity ring-down spectrometer, from which a PIC output can be approximated.

E-Calc is a logical extension of our 2004 PICMET (***P***ath-***I***ntegrated ***C***oncentration – ***Met***eorology) software, created to rapidly assess compliance with pre-established action levels at off-site receptors (e.g., residences), primarily during hazardous waste site cleanups. The PICMET software displays maximum concentrations at user-specified distances downwind of the emissions source, based on path-integrated measurements and atmospheric stability and transport considerations.

PICMET was employed during active cleanups at former manufactured gas plant (MGP) sites in November 2004, and again during December 2006 and May 2007 as part of a 2½-year applied R&D study for the Gas Technology Institute (Des Plaines, Illinois). Results from this latter study demonstrated superior residential protection when compared to traditional monitoring approaches.

Development work on e-Calc began in 2008. E-Calc was originally created for use with open-path Fourier-transform infrared (FTIR) spectroscopy to help MSW landfill owners comply with mandated emissions reporting and permitting requirements for methane and other greenhouse gases. Based on AERMOD, the software incorporates the output from the PIC-generating instrument with coincident onsite meteorological data and other information.

In June 2011, we employed e-Calc to support a legal proceeding by measuring emission rates from several process sources at an Alabama pulp-and-paper mill, including a 1-square-kilometer polishing pond. In August 2014, we used it to measure emission rates from the preliminary settling tanks at a large New York City municipal wastewater treatment plant. In September 2015, we participated in an extensive field project for the South Coast Air Quality Management District (SCAQMD), a California governmental agency, in which we used e-Calc to measure emission rates from 16 oil production wells and tanks, 17 gas stations, and two cattle farms, all in the Los Angeles basin.

We have participated in two third-party e-Calc validation studies, results of which were presented at the March 2016 "Air Quality Measurement Methods and Technology Conference," sponsored jointly by the Air & Waste Management Association (A&WMA) and the U.S. EPA. First, as part of our project for the SCAQMD (described above), our e-Calc software was validated during a 2-day, controlled-release experiment (October 12-13, 2015). Over the study, propane was released at varying emission rates from a scissors-type lift at a pre-designated height of 3 meters (even though e-Calc was designed for ground-level releases only). Thirteen monitoring events (15-minute-averaged) were performed on Day 1, with an additional seven on Day 2.

Next, under contract to Texas A&M University (San Antonio, Texas), we performed a 2-day, e-Calc validation study (November 4-5, 2015), which involved the controlled release of sulfur hexafluoride (SF_6) from ground-level locations simulating a compressor/condensate tank complex (Day 1) and an assembly of gas-gathering pipelines (Day 2).

As mentioned, e-Calc 1 employs the U.S. EPA regulatory version of AERMOD in order to preserve the model's legal Guideline status. For each monitoring event, the generation of input files requires meteorological data together with emissions-characterization and monitoring configuration data. Dispersion coefficients under this approach (i.e., flux-gradient) are assigned based on wind speed, land-use, solar insolation, and statistical data treatments such as the standard deviations of the horizontal wind direction and vertical wind speed. From this information the friction velocity is determined, which is used to develop the vertical wind-speed profile. The vertical wind-speed profile primarily governs the predicted (back-calculated) emission rate in e-Calc 1 (and e-Calc 2).

The flux-gradient approach currently employed in AERMOD has been extensively evaluated in model-validation studies performed by the U.S. EPA over the years. Similarly, the performance of e-Calc 1 was successfully demonstrated during the two validation studies described above.

The upgraded (second-generation) version of e-Calc (e-Calc 2) was created specifically for this ERA project, primarily to eliminate the need for relatively labor-intensive pre-field tasks. As mentioned, e-Calc 2 employs a more sophisticated means of assigning dispersion coefficients – the eddy-correlation (or covariance) approach. This approach typically requires wind measurements (using sonic anemometry) at two heights above the ground. Covariance statistics, calculated from the lower of these two sensors, are then used to determine the friction velocity. The U.S. EPA is planning to update AERMOD to enable application of the eddy-correlation approach, but has yet to release the software coding for this version.

1.2.2 Technical Considerations

Discussed below is: the difference between a concentration and an emission rate; the drawbacks with conventional approaches for deriving emission rates; the benefits of open-path monitoring; and the area-source technique for measuring emission rates, upon which e-Calc is based (both versions).

Concentration vs. Emission Rate

The difference between a source emission rate (mass per time) and an ambient air concentration (mass per volume) is often poorly understood. Further, few investigators truly appreciate the utility of the path-integrated concentration when coupled with onsite meteorology and air dispersion modeling. When properly applied, open-path spectroscopy eliminates the spatial data-representativeness problem inherent in approaches which rely solely on point-sampling techniques. This "whole-plume" sampling approach offers, perhaps, the only means of complying with the U.S. EPA's Data Quality Objective (DQO) process while measuring emission rates, thereby ensuring that end-user needs are met.

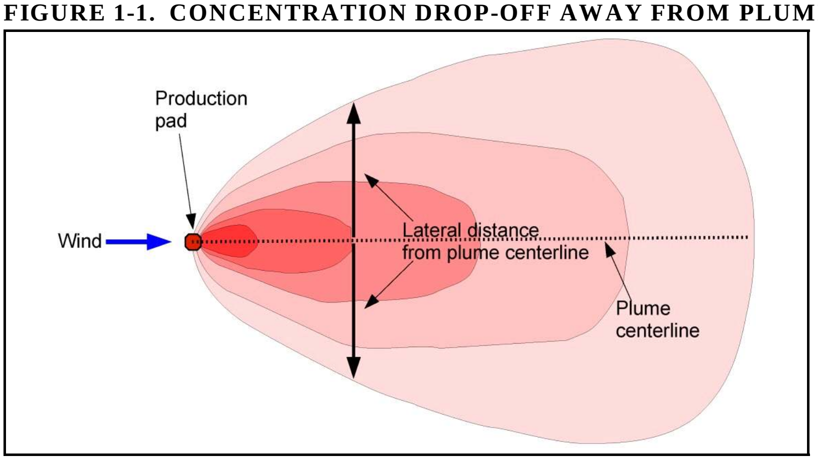
For point-type monitors, gaseous concentrations are typically reported as the mass of contaminant per volume of gas, such as micrograms per cubic meter (ug/m^3), or the volume of contaminant per volume of gas, such as parts per billion (ppbv) or parts per million (ppmv). Path-integrated concentrations, however, are usually reported as parts-per-million times meter (ppm-m). It is often desirable to convert path-integrated concentrations from ppm-m to milligrams-per-cubic-meter times meter (mg/m^3 x m, or mg/m^2) in order to avoid having to consider the compound's molecular weight.

Drawbacks with Conventional Approaches for Deriving Emission Rates

Emission rates derived from point-monitoring data are frequently underestimated, as there is no way of knowing how far from the plume centerline a hand-held monitor (or Summa canister) might be, especially given the fact that wind direction is never constant; in fact, it is generally not possible to ensure the sample isn't inadvertently collected outside of the downwind plume altogether. This fundamental sampling design flaw explains, at least in part, the extreme variability in emission rates reported for most O&G industry process components.

Figure 1-1 illustrates how concentration at any point downwind of a source drops off rapidly as one moves away from the plume centerline.

FIGURE 1-1. CONCENTRATION DROP-OFF AWAY FROM PLUME CENTERLINE

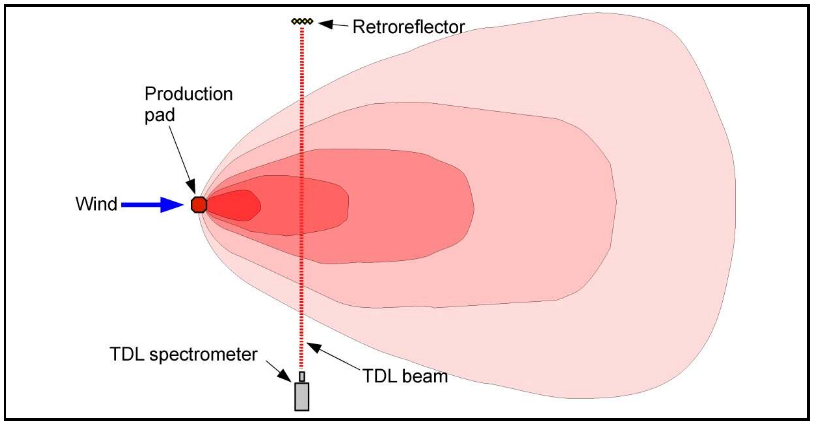


Benefits of Open-Path Monitoring

An open-path spectrometer collects path-integrated data – meaning that contaminants downwind of the source are measured along the entire crosswind dimension of the plume. The spectrometer essentially counts the molecules of the analyte, thus ensuring that concentrations are not “missed” anywhere along the beam-path.

Figure 1-2 illustrates how the entire crosswind plume is sampled with open-path TDL spectroscopy.

FIGURE 1-2. CROSSWIND TDL PLUME SAMPLING



A principal reason that open-path spectroscopy is still not generally recognized as the powerful tool that it is for deriving emission rates is that the resultant path-integrated data is not of a form which can be compared directly to ambient air standards (i.e., point concentrations). But as alluded to earlier, when appropriately coupled with air dispersion modeling, a path-integrated concentration measurement made downwind of an emitting source contains far more information than any point measurement (or collection of point measurements) ever could for purposes of assigning a source emission rate and assessing the resultant downwind impact.

Using dispersion modeling relationships, a source emission rate is “back-calculated,” based on the downwind (cross-plume) path-integrated concentration and onsite meteorology. This source emission rate can best be viewed as a mass-per-time “snapshot” over the 15-minute interval necessary to yield the measured downwind, path-integrated concentration under the particular atmospheric dispersion and transport conditions during that precise block of time.

The *area-source technique* arguably provides the most accurate means of back-calculating this emission rate (discussed next). E-Calc 2 uses AERMOD in its inverse form, together with the area-source technique, for this back-calculation, in real-time.

Area-Source Technique

The area-source technique for emission-rate generation is appropriate for fugitive ground-level and elevated area sources – both homogeneous (uniformly emitting) and heterogeneous (non-uniformly emitting). Employing the principle of mass balance, it identifies a time-averaged source attribution based on a series of downwind path-integrated measurements (1- to 2-meter height), enabling the subsequent generation of emission rates using AERMOD. AERMOD requires measurement of coincident onsite meteorological data, from which atmospheric dispersion and transport are simulated between the source and the beam-path.

The following three-step approach is employed using a TDL spectrometer.

1. Identify Source Attribution

A series of 15-minute-averaged, path-integrated TDL measurements (i.e., monitoring events) are made immediately downwind of the source, such that the cross-plume mass contained within the beam-path is maximized. When significant, the upwind path-integrated concentration can be subtracted from the downwind measurement, thus reducing the conservatism of the source-attribution calculation.

2. Predict the Unity-Based, Path-Integrated Concentration Along the Measurement Path

AERMOD is used to predict the *unity-based*, path-integrated concentration (as opposed to the actual path-integrated concentration) along the downwind TDL measurement path defined in Step 1. This is accomplished by: (a) predicting the point concentration (mg/m^3) at every meter along this path based on a "unity" emission rate (e.g., 1 mg/s) across the source, and the actual meteorology and source configuration; (b) determining, via summing each predicted point concentration, the *path-averaged*, unity-based concentration along the measurement path; and (c) multiplying this path-averaged concentration (mg/m^3) by the TDL measurement path length (m).

In cases where the source is unlikely to emit homogeneously, individual rectangular emission "subareas" must be defined for maximum accuracy to be achieved. The *relative source strength* of each subarea is expressed in the area-source technique (and, thus, e-Calc) in terms of multiples of unity, in which the lowest-emitting subarea is assigned a unity emission rate (i.e., 1 mg/s over the entire rectangle), with higher-emitting ("hot-spot") subareas expressed as multiples of unity.

For the primary project goal, the unity-based emission rate assumed that emissions were uniform across the entire source surface (i.e., there were no hot spots), and that only a single source existed. However, for the secondary project goal, hot spots were represented in the unity modeling by assigning a relative emission factor to each source subarea.

In this latter case, assignment of relative source strengths was based on results of flux-chamber sampling performed by CNRL across the surfaces of the mine face and tailings pond.

3. Scale Unity-Based Modeling Results to Calculate Emission Rate

The actual emission rate, Q_A, is calculated in accordance with the following ratio:

$$\mathbf{C_M / Q_A = C_U / Q_U} \qquad \textbf{(Equation 1-1)}$$

where:

C_M	=	measured path-integrated concentration (attribution) (mg/m^2);
Q_A	=	actual emission rate (mg/s);
C_U	=	predicted unity-based, path-integrated concentration along the measurement path (mg/m^2);* and
Q_U	=	unity-based emission rate (mg/s).

This equation describes the inherent relationship between: (a) the unity-based dispersion modeling; and (b) the actual emission rate and downwind measurements. The cornerstone of the area-source technique, this ratio states that the measured path-integrated concentration (C_M) is to the actual emission rate (Q_A) as the unity-based, path-integrated (modeled) concentration (C_U) is to *its* unity-based emission rate (Q_U); the only unknown term in this equation is the actual emission rate (Q_A).

Plume Capture

An important feature of the area-source technique (included in the e-Calc software) is the capability of generating accurate emission rates without capturing the entire downwind cross-plume mass. Despite measuring only a portion of this mass, employment of the area-source technique allows a "whole-source" emission rate to be determined. The crosswind plume capture, expressed as a percentage of the plume mass, is derived in accordance with the following equation:

$$\mathbf{PC = (C_U / C_{UE}) \times 100} \qquad \textbf{(Equation 1-2)}$$

where, for any given pollutant:

PC	=	plume capture (crosswind) (%);
C_U	=	predicted unity-based, path-integrated concentration along the measurement path (mg/m^2); and
C_{UE}	=	predicted unity-based, path-integrated concentration along an extended measurement path (mg/m^2).

The "extended" measurement path includes the actual TDL beam-path but, for dispersion modeling purposes, this path is extended laterally (each direction from the actual beam-path endpoints) to distances beyond which the predicted impacts are essentially zero.

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* The predicted unity-based, path-integrated concentration along the measurement path can be thought of as the concentration the TDL would "see" if the source were emitting at its assigned, unity-based emission rate.

Meteorological Data

As discussed earlier, coincident onsite meteorological monitoring data is required for simulating atmospheric dispersion and transport, as required in AERMOD. Dispersion and transport parameters are calculated and assigned by e-Calc 2, based on measured and calculated meteorological data.

Required Input Data and Associated Usage

Table 1-1 identifies all input data required to support e-Calc 2. Also depicted is whether each parameter is measured or calculated.

TABLE 1-1. REQUIRED INPUT DATA TO SUPPORT E-CALC 2

Parameter (Monitoring Event-Specific)	Data Type (15-Minute)	
	Measured	Calculated
Global Positioning System		
TDL beam-path endpoints	✔	
Source location (including source height above grade)	✔	
Tunable Diode Laser System		
Methane attribution (path-integrated concentration)	✔	
Attribution correction (for temperature and pressure)		✔
Archived data	✔	✔
Meteorological Instrumentation		
Vector component (u,v,w) wind speed (2m)	✔	
Vector component (u, v) wind speed (5m)	✔	
Horizontal wind speed		✔
Wind direction		✔
Standard deviation of the horizontal wind direction		✔
Standard deviation of the vertical wind speed		✔
Ambient temperature (2 and 5m)	✔	
Virtual temperature		✔
Dew-point temperature (2m)		✔
Relative humidity (2m)	✔	
Barometric pressure (0 to 1m)	✔	
Friction velocity		✔
Monin-Obukhov length		✔
Sensible heat flux		✔
Archived data	✔	✔
E-Calc 2 Software		
Methane emission rate (mass-per-time)		✔
Methane plume capture		✔
Archived data (via MS Access Database Software)	✔	✔

Set-up functions for e-Calc 2 included the siting of the meteorological tower and TDL system, based on forecasted conditions, to determine the appropriate upwind-downwind orientation. A GPS unit was employed to obtain location coordinates for the TDL beam-path endpoints, meteorological instrumentation, and the suspected emissions-source location.

All monitoring events began precisely on the hour or 15 minutes thereafter (e.g., 8:00, 8:15, etc.). Raw, path-integrated TDL methane concentrations (units of ppm-m) were processed with coincident temperature and pressure measurements (15-minute-averaged) to convert these concentrations to units suitable for input into e-Calc 2 (i.e., mg/m^2). All TDL data (both measured and calculated), together with associated diagnostic data, were archived to facilitate independent validation.

The meteorological instrumentation provided direct measurements of 1-second (1 Hz) values, including vector wind components (u,v,w), temperature, relative humidity, and barometric pressure. These data were processed to calculate event-averaged meteorological values, including horizontal wind direction and speed, and standard deviations of the horizontal wind direction and vertical wind speed. Additionally, representative values of friction velocity, sensible heat flux, and Monin-Obukhov length were calculated from the appropriate covariance statistics between the vector wind components, and between the temperature and w vector wind component. Event-averaged relative humidity and atmospheric pressure measurements were also required.

The meteorological data acquisition system was programmed to archive all meteorological parameter data (measured and calculated), together with the back-up values to facilitate QC (quality control) checks, independent validation, and potential R&D studies.

For each measurement configuration, e-Calc 2 employed the source and measurement-path location information (assembled during the set-up function), and generated the meteorological control pathway for retrieval of the surface and profile meteorological data. Upon monitoring event completion, e-Calc 2 automatically assembled the event-specific “sfc” and “pfl” data files, and ran AERMOD to predict the unity-based attribution (incorporating a user-specified unity emission rate). The software then automatically calculated the actual emission rate by scaling the predicted unity modeling emission rate based on the measured path-integrated TDL methane concentration (see Equation 1-1) and associated plume capture (see Equation 1-2).

Results were generated (on-screen and hard copy) within 1 minute of monitoring event completion. For each event, a data-base file was generated to retain all input data and output information, together with the AERMOD input and output files supporting the unity-based attribution predictions.

1.3 Project Goals

Two distinct goals comprised our ERA project. The primary goal was, first, to upgrade the software to accommodate a more sophisticated and robust treatment of meteorology (i.e., to create e-Calc 2 based on a new version of AERMOD – modified to employ the *eddy-correlation approach* for simulating the above model input parameters) and, second, to field-test this second-generation version of the e-Calc software, based on carefully controlled methane releases from the four simulated, leaking upstream sources identified earlier. The intent was to eliminate the need for the arduous pre-field tasks and make possible the software use during the nighttime.

The secondary goal, a benefit to ACCO, was to apply e-Calc (both versions) to essentially re-create the fugitive methane and carbon dioxide emission rates from the CNRL mine-face and tailings pond operations in Fort McMurray, as reported in CNRL's two latest (at the time) annual submissions on facility greenhouse gas (GHG) emissions. Our analysis used onsite, 15-minute-averaged path-integrated methane and carbon dioxide data, collected across portions of these sources in 2015 and 2016 by CNRL using a Boreal Laser TDL spectrometer, together with onsite, coincident meteorological data and contemporaneous flux-chamber sampling data. The hope was that e-Calc would be demonstrated a viable and attractive alternative to the techniques currently employed for measuring GHG's from the oil-sands sources, and that the time and cost for GHG reporting would be greatly reduced. These current techniques include backward Lagrangian stochastic (bLS) modeling, inverse dispersion modeling using CALPUFF, and isolation flux-chamber sampling.

1.4 Work Scope Overview

Tasks, milestones, deliverables, and timelines are presented below.

Task Descriptions

The following six tasks comprised our Scope of Work:

- Task 1 – Work Plan Preparation
- Task 2 – E-Calc Modification
- Task 3 – Construction and Mobilization
- Task 4 – Data Collection
- Task 5 – Data Analysis
- Task 6 – Specification and Report Preparation

Task 1 – Work Plan Preparation

A project work plan was prepared in accordance with the U.S. EPA Data Quality Objective (DQO) process. Application of this process represents the first step in the successful planning of any project involving the collection of environmental data. As such, the work plan applied only to the controlled release portion of the project (the primary project goal).

The work plan consisted of a measurement and analysis plan (MAP) and a quality assurance project plan (QAPP). The MAP addressed all aspects of data collection and analysis. The QAPP described the specific procedures employed to ensure the overall quality of all data collected in the field. These documents consisted the following sections:

MAP

1. Introduction
2. DQO Process and Statement of Problem
3. Objective
4. Management and Responsibilities
5. Scheduling and Coordination
6. Emission-Source Simulation
7. Data Acquisition
8. Data Reduction and Analysis
9. Documentation and Records
10. Reporting and Specification Preparation

QAPP

A. Introduction
B. QC Organization
C. Measurement Quality Objectives

D. Equipment Inventory, Calibration, and Maintenance
E. Method and Equipment Standard Operating Procedures
F. Analytical Standard Operating Procedures
G. Data Control and Validation
H. Statistical Assessment of Measured Emission Rates

Task 2 – E-Calc Modification

Design Overview

E-Calc is designed for use with any monitoring instrument which generates a path-integrated concentration, in this case an open-path TDL spectrometer. E-Calc employs the U.S. EPA regulatory version of AERMOD in order to maintain the model's legal Guideline status. The AERMOD source code resides in the public domain.

For each 15-minute monitoring event, the generation of input files requires coincident site-specific meteorological data, obtained via standard cup-and-vane sensors, together with source-attribution and monitoring configuration data. The TDL spectrometer measures the path-integrated concentration downwind of the source, along the entire crosswind dimension of the plume. In essence, the TDL counts the molecules of the pollutant, thus ensuring that concentrations are not "missed" anywhere along the beam path. Emission rates are calculated in accordance with the area-source technique (see Equation 1-1).

For the controlled-release component, the TDL spectrometer generated the measured path-integrated methane concentration (C_M). AERMOD was configured to yield a predicted concentration at each meter along the beam path; these predictions were then be summed to derive the predicted unity-based path-integrated concentration (C_U). In general, assignment of the unity-based emission rate (Q_U) is accomplished by simply setting Q_U to unity (e.g., 1 mg/s).

Because the mine face and tailings pond (secondary project goal) were shown not to emit homogeneously, individual rectangular emission "subareas" comprising them had to be identified to the best level possible for e-Calc to achieve maximum accuracy. The relative source strengths of these subareas were expressed in e-Calc (and in AERMOD) in terms of multiples of unity, in which the lowest-emitting subarea was simply assigned a unity emission rate (i.e., 1 mg/s over the entire rectangle), with higher-emitting ("hot-spot") subareas expressed as multiples of unity. E-Calc can accommodate a total of 30 individual subareas and 12 emission regimes (i.e., unique emission rates or relative source strengths).

Assignment of relative source strengths was based, in part, on historical flux-chamber data collected across the surfaces of the mine face and tailings pond (to the degree this data was available).

Current Requirements

The program simulates the wind profile in the vertical dimension and the atmospheric turbulence by calculating dispersion coefficients based on wind speed, land-use, solar insolation, and statistical data treatments such as the standard deviations of the horizontal wind direction and vertical wind speed. Boundary layer parameters (e.g., friction velocity, sensible heat flux, and Monin-Obukhov length) are required in the surface meteorological file input to AERMOD. E-Calc currently derives these parameters in the AERMET preprocessor based on the flux-gradient approach.

As mentioned earlier, the onsite wind data used in the current version of e-Calc is collected via standard cup-and-vane sensors. Wind direction, wind speed, sigma theta or σ_θ (standard deviation of the horizontal wind direction), and sigma W or σ_W (standard deviation of the vertical wind speed) are collected (or calculated) from an appropriately configured 3-meter meteorological tower. Air temperature is measured using a portable hand-held instrument, and cloud cover (in tenths) is observed and recorded; the solar elevation angle is calculated in accordance with the National Oceanic and Atmospheric Administration (NOAA) Solar Calculator, https://www.esrl.noaa.gov/gmd/grad/solcalc/.

The current version of e-Calc cannot be applied at night, as turbulence must be simulated based on the temperature difference between 2 and 10 meters. This "delta T" method requires a 10-meter meteorological tower, and such equipment is impractical for rapid deployment.

Upgrade Modifications

The use of dual 3D and 2D ultrasonic anemometers (plus a temperature sensor) was required to run the upgraded version of e-Calc. The controlled methane releases allowed comparison of the P/A emission rates under a full range of atmospheric dispersion and transport conditions for the four simulated sources.

This method of profiling vertical wind speed and atmospheric turbulence is referred to as the eddy-correlation (or covariance) approach; it allows for the direct measurement of boundary layer parameters, resulting in a more accurate assessment of emission rates – at least in theory. The eddy-correlation approach also obviates the need for the AERMET preprocessor, thereby simplifying the e-Calc logic considerably (discussed below). Importantly, this approach enables the rapid deployment of e-Calc, as well as its use during the night.

In this approach, the 3D ultrasonic anemometer measures 1-second orthogonal wind vector components. Together with 1-second temperature measurements obtained from a separate sensor, these components are used to calculate:

- Friction velocity and Monin-Obukhov length, using the covariance statistic between the u (east-west) and w (up-down) wind components and the v (north-south) and w wind components; and

- Sensible heat flux, using the covariance between the w wind component and temperature measurements.

Sigma theta is calculated from 1-second wind direction data generated by the 2D ultrasonic anemometer.

Functional Logic

Figure 1-3 presents the functional logic for e-Calc 1. The more sophisticated treatment of onsite meteorology in e-Calc 2 eliminates the need for the labor-intensive simulation of the boundary layer and surface characterization, as well as the requisite pre-processing software, all of which is depicted inside the heavy dashed lines.

FIGURE 1-3. FUNCTIONAL LOGIC: E-CALC 1

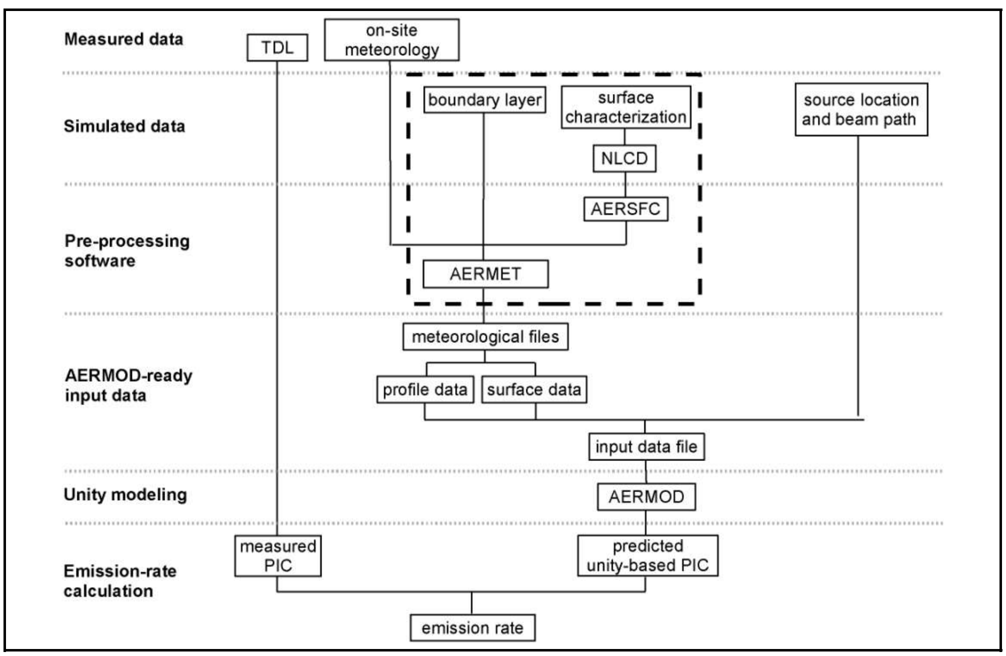
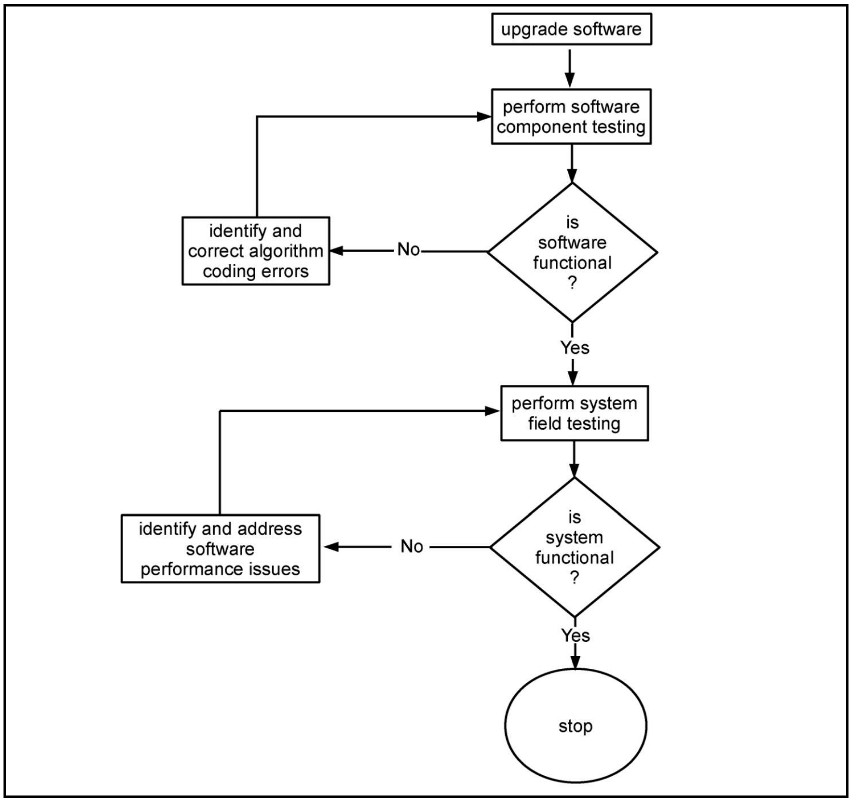


Figure 1-4 depicts the software component and system field testing for e-Calc 2. Software to incorporate the eddy-correlation approach was coded and input by Loover, with subsequent component functionality testing performed by Minnich and Scotto.

FIGURE 1-4. SOFTWARE COMPONENT AND SYSTEM FIELD TESTING: E-CALC 2



Software Component Testing. Procedures governing software component testing involved computer simulation to assess, over a range of source types and sizes, measurement paths, and meteorological conditions, whether each software component, by itself, was functional, performing properly, and generating expected results.

The primary focus was the testing of the algorithms employed to ensure that boundary layer variables, including friction velocity, sensible heat flux, and Monin-Obukhov length, were being correctly calculated from the ultrasonic anemometers and ambient temperature sensor.

System Field Testing. System field testing, the heart of this proof-of-concept project, involved the controlled release of methane, at known emission rates from each simulated source, over a range of atmospheric dispersion and transport conditions in order to assess the accuracy of predicted e-Calc emission rates. Where test results indicate statistically valid emission-rate biases, empirical correction factors were to be developed and incorporated into e-Calc, and the supporting technical justification provided.

Task 3 – Construction and Mobilization

InnoTech Alberta constructed reasonable facsimiles of a production pad, gas-gathering pipeline assembly, gas transmission line, and boosting station (combination compressor engine and condensate tank). Each simulated source was realistic with respect to: (a) the methane leak location(s); and (b) the generation of atmospheric turbulence, caused by the simulated source structure itself.

Typical locations of methane leaks are:

- production pads – leaks from well head;
- gas-gathering pipeline assemblies – leaks from valves or flanges;
- gas transmission lines – leaks from flanges or pipe ruptures; and
- compressor engines and condensate tanks (boosting stations) – leaks from ruptured seals (engine), and leaks from thief hatches or pressure relief valves (tanks).

Source construction also included assembly of two controlled methane-release systems. The first system – single-point release – was moved from source to source, to simulate: (a) ground-level methane leaks from the production pad (where the pipe emerges from the ground); and (b) near-ground (elevated) releases from the gas transmission line (1.5 meter above ground) and the two sources comprising a boosting station (compressor engine and condensate tank). The second system, multipoint release, simulated ground-level methane leaks from the gas-gathering pipeline assembly.

The methane was supplied by a trailer-mounted tank of compressed natural gas, which was connected, via a pressure regulator, to an electronic mass-flow controller. A sample of the outflow gas was analyzed onsite, via gas chromatography, to determine its precise methane content.

The electronic mass flow controller was an Omega system (FMA-1600A Series). All appropriate calibration certificates remain on file with InnoTech Alberta.

Field mobilization included: procurement, set-up, and testing of the TDL and meteorological monitoring systems; testing of the controlled methane-release systems; arranging for supply of ancillary equipment (e.g., generator) and consumables when arriving in the field; onsite health and safety (H&S) training; equipment shipping arrangements; and field personnel transportation (e.g., air, vehicle rental) and lodging arrangements.

Task 4 – Data Collection

Minnich and Scotto was responsible for: (a) all data-collection activities; (b) all field decision-making; and (c) e-Calc and meteorological system operation. All controlled-release measurements was performed by InnoTech Alberta at their Vegreville facility, and all TDL methane measurements was performed by Boreal Laser.

Each day's TDL measurement path was about 100 to 200 meters in length, positioned between approximately 20 and 50 meters downwind of the simulated source, depending on atmospheric stability considerations. The location of each simulated source (or source group) was fixed for all measurements, and was such that the TDL system could be configured to accommodate any mean wind direction, i.e., without encountering objects which might affect line-of-sight or the atmospheric turbulence in the microscale region between the methane source and the TDL beam. The Met One meteorological system was appropriately positioned in accordance with applicable U.S. EPA siting criteria.

A total of eight days of controlled-release measurements was planned. Two full days were allotted for each of the four sources or (source groups). Additionally, 2-hour nighttime measurement "add-ons" were to be included in two of the measurement days.

An average of twenty-four, 15-minute-averaged emission rate "snapshots" (i.e., monitoring events) was expected to be completed during each measurement day, for an anticipated project total of 192 daytime snapshots, i.e., 48 per each source (or source group). Each nighttime "add-on" was expected to yield an additional eight snapshots for two of the sources (or source groups). Selection of sources for the nighttime "add-ons" was a field decision.

Two additional days in the field were budgeted: one day for onsite orientation and health and safety (H&S) instruction, and one more to allow for field coordination and instrument check-out and field set-up upon delivery onsite.

Minnich and Scotto provided daily meteorological forecasts to facilitate field decision-making concerning the next day's activities (source designation, TDL positioning, and whether nighttime measurements will be made).

An e-Calc test report was generated, together with all requisite meteorological data, for each monitoring event. Every effort was made to demonstrate e-Calc's application over the widest variety of meteorological conditions. In order to assess nighttime performance, the work period was to be shifted to include hours after sunset or before sunrise, for two measurement days.

Task 5 – Data Analysis

Primary Project Goal

E-Calc's performance in predicting the controlled methane release rate was assessed, based on source type and category of meteorological conditions (e.g., day vs. night, strong vs. light winds).

For each source type and set of meteorological conditions, a simple statistical analysis was performed to determine the degree to which the predicted methane emission rates conform to the actual or "true" emissions (i.e., the controlled emission rates). Statistical analyses were also intended to determine the type of probability distribution (e.g., normal, skewed, or random) which best characterized the predicted data set.

Appropriate correlation tests between actual and predicted source-specific emission rates were performed to quantify the e-Calc prediction errors as functions of turbulence and the downwind distance between the source and the TDL beam path. The correlation test results were intended to facilitate improvements to the e-Calc software, as well as an understanding of associated limitations.

The intent was to develop source-specific, empirical correction factors, should test results yield statistically valid, systematic biases in the e-Calc results. These correction factors would then be incorporated into e-Calc for subsequent re-analysis of all emission-rate snapshots.

Secondary Project Goal

Table 1-2 presents the minimum number of acceptable measurement-event pairs, based upon initial review of the 2015 and 2016 CNRL data.

TABLE 1-2. MINIMUM NUMBER OF ACCEPTABLE MEASUREMENT-EVENT PAIRS

	Mine Face		Tailings Pond	
Year	Methane	CO_2	Methane	CO_2
2015	30	20	20	4
2016	30	20	0	0

Individual hard-copy, e-Calc reports were generated for each acceptable monitoring-event pair. As part of this task, separate letter reports were prepared and submitted for the existing and upgraded e-Calc versions (e-Calc 1 and e-Calc 2, respectively). Each report identified the data utilized and provided a detailed description of the assumptions and limitations associated with both the calculated methane and CO_2 emission rates and the specific objectives of the ACCO. The latter report included a tabular comparison of the e-Calc results (i.e., e-Calc 1 vs. e-Calc 2).

Task 6 – Specification and Report Preparation

A set of specifications for a fully integrated methane emission-rate measurement system was developed and assembled. These specs were of a quality sufficient to facilitate commercialization.

A comprehensive final project report (separate from this Final Outcomes Report) was prepared, which summarized all field work results, including depictions of all experimental designs, statistical analysis results, all re-analysis results, and an e-Calc report for each monitoring event.

Project Milestones and Interim Deliverables

The following Project Milestones were identified:

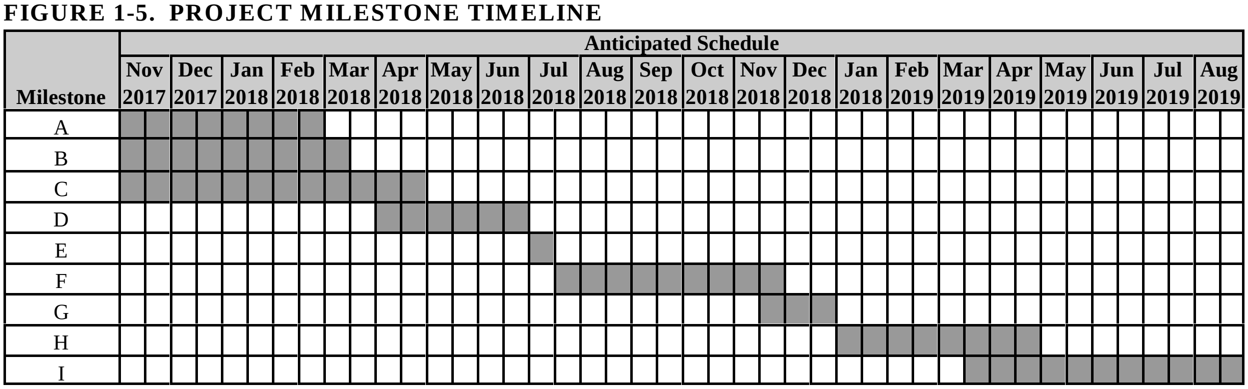
- A – ACCO Mine-Face and Tailings Pond Data Analysis and Reporting (e-Calc 1)
- B – Work Plan Preparation
- C – E-Calc Modification
- D – Construction and Mobilization
- E – Controlled-Release Data Collection
- F – Controlled Release Data Analysis (e-Calc 2)
- G – ACCO Mine-Face and Tailings Pond Data Analysis and Reporting (e-Calc 2)
- H– Specification Preparation
- I – Final Report Preparation (separate and distinct from this Final Outcomes Report)

Stand-alone, Interim Project Deliverables were submitted upon completion of Milestones A, B, F, G, H, and I.

Project Timeline

Figure 1-5 depicts the timeline for each milestone identified above.

FIGURE 1-5. PROJECT MILESTONE TIMELINE



SECTION 2 – OUTCOMES AND LEARNINGS

Section 2.1 addresses the literature review performed to support both the creation and field-testing of the e-Calc software design (primary project goal) and the application of e-Calc to the ACCO mine-face and tailings pond data (secondary project goal). **Section 2.2** describes the technology development, installation, and commissioning. **Section 2.3** presents the experimental procedures and methods. **Section 2.4** provides the modeling details. **Section 2.5** presents the experimental and model simulation results. **Section 2.6** discusses the project outcomes. **Section 2.7** presents an analysis and discussion of results. **Section 2.8** identifies the important lessons learned.

All of the above sections apply to the primary project goal. However, it is noted that only Sections 2.1 and 2.6 through 2.8 apply to the secondary project goal.

2.1 Literature Review

During the planning phases of both the primary and secondary project goals, we reviewed all available U.S. EPA guidance on AERMOD in order to make sure that e-Calc 2 was fully consistent with the latest model updates.

For the primary project goal, we also consulted with Dr. Akula Venkatram, one of AERMOD's developers and among the world's premier atmospheric science and microclimate researchers, concerning the optimum wind sensor measurement heights for e-Calc 2's wind-profile simulation. Dr. Venkatram is a Professor at the University of California, Center for Environmental Research & Technology, Riverside, California 92507 (951-827-2195).

Following are the sources reviewed for each project goal.

Both Primary and Secondary Project Goals

AERMOD Implementation Guide. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Air Quality Assessment Division, AERMOD Implementation Workgroup, Research Triangle Park, NC; EPA-454/B-16-013; December 2016.

AERMOD Model Formulation and Evaluation. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Air Quality Assessment Division, Research Triangle Park, NC; EPA-454/ R-17-001; May, 2017.

AERSURFACE User's Guide. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Air Quality Assessment Division, Air Quality Modeling Group, Research Triangle Park, NC; EPA-454/B-08-001; January 2008 (Revised 01/16/2013).

A Method for Estimating VOC Emission Rates from Area Sources Using Remote Optical Sensing. R.L. Scotto, T.R. Minnich; A&WMA/USEPA International Symposium on the Measurement of Toxic and Related Air Pollutants; Durham, NC; May 1991.

User's Guide for the AMS/EPA Regulatory Model – AERMOD. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Air Quality Assessment Division, Air Quality Modeling Group, Research Triangle Park, NC; EPA-454/B-16-011; December 2016.

Primary Project Goal Only

AERMOD Training, Understanding the Key Surface Characteristics Used by AERMET, a PowerPoint Presentation (undated). Texas Commission on Environmental Quality; http://www.cabq.gov/airquality/documents/pdf/tceqsfcroughnessguidance.pdf.

A Brief Practical Guide to Eddy Covariance Flux Measurements: Principles and Workflow Examples for Scientific and Industrial Applications (Version 1.0.1). G. Burba, D. Anderson; LI-COR Biosciences, Lincoln, NE.

Optimal Sensor Locations for the Backward Lagrangian Stochastic Technique in Measuring Lagoon Gas Emission. K.S. Ro, K.C. Stone, M.H. Johnson, P.G. Hunt, T.K. Flesch; Journal of Environmental Quality; July 14, 2014.

Uncertainty in Deriving Dispersion Parameters From Meteorological Data. A Report Prepared for Atmospheric Dispersion Modelling Liaison Committee; V. Auld, R. Hill, T. J. Taylor; Westlakes Scientific Consulting, LTD; Cumbria, UK; June 2003.

User's Guide for the AERMOD Meteorological Preprocessor (AERMET). U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Air Quality Assessment Division, Air Quality Modeling Group, Research Triangle Park, NC; EPA-454/B-16-010; December 2016.

User's Guide to the Building Profile Input Program. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Technical Support Division, Research Triangle Park, NC; EPA-454/R-93-038; October 1993 (Revised April 21, 2004).

Validation Testing of the Area-Source Technique Using EPA Method TO-16. Final Extended Abstract # 31; R.L. Scotto, T.R. Minnich, S.H. Perry, O. Pikelnaya, A. Polidori, L. Tisopulos, S. Stuver, J. Alonzo; Presented at the Conference: Air Quality Measurement Methods and Technology; Chapel Hill, NC; March 15-17, 2016.

Secondary Project Goal Only

Inverse Dispersion Modelling Data from an Area Fugitive Emission Survey at a Large Oil Sands Mine: 2015 and 2016 Data Descriptions. Y. Liu; Climate Change Engineer, Compliance and Regulation, Alberta Climate Change Office, Edmonton, Alberta T5J 1G4; 2015 and 2016 (separate compilations).

Meteorological Monitoring Guidance for Regulatory Modeling Applications. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards; Research Triangle Park, NC; EPA-454/R-99-005; February 2000.

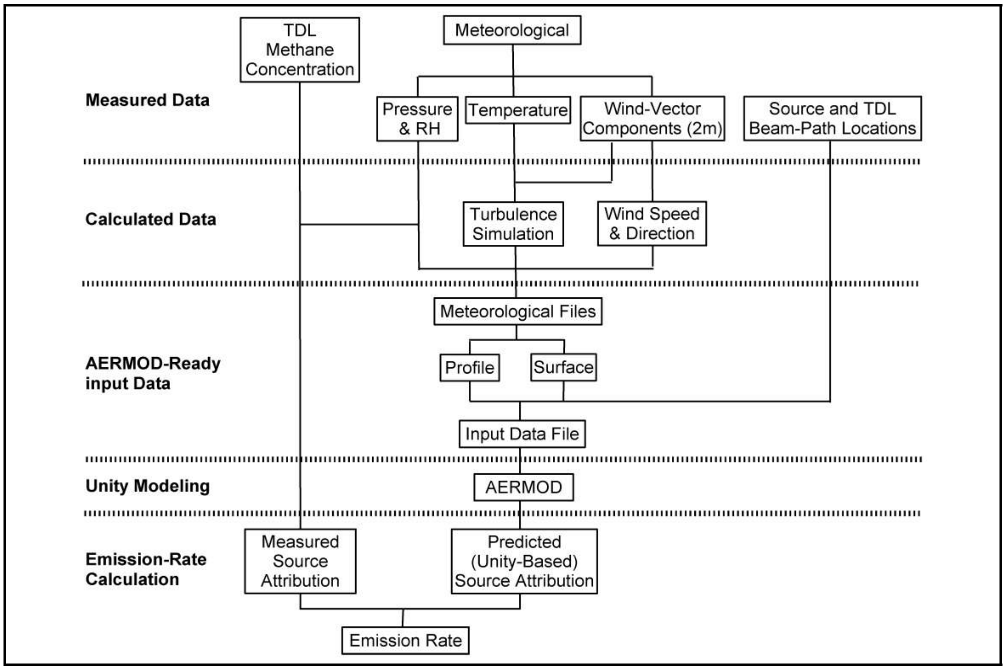
Quantification of Area Fugitive GHG Emissions at Oil Sands Mines by a Novel Inverse Dispersion Modelling (IDM) Approach. F.R. Robe, C. Reuten, A.M. Seguin, D. Chadder, N. Veriotes, T.K. Flesch; CPANS, Edmonton, AB; May 9, 2017.

A User's Guide for the CALMET Meteorological Model (Version 5). J.S. Scire, F.R. Robe, M.E. Fernau, R.J. Yamartino; Earth Tech, Concord, MA; January 2000.

2.2 Technology Development, Installation, and Commissioning

Figure 2-1 presents the functional logic for e-Calc 2.

FIGURE 2-1. FUNCTIONAL LOGIC: E-CALC 2



Measured Data

Measured data consists of the TDL methane concentration(s), meteorological parameters, and source and TDL beam-path locations.

TDL Methane Concentration(s)

These are the measurements for determining source attribution. In general, this requires subtracting the downwind, path-integrated concentration from the upwind PIC. However, when it can be shown that the upwind PIC is negligible by comparison, source attribution can be reasonably approximated simply from the downwind PIC.

Meteorological Parameters

Measured meteorological parameters consist of vector component wind speed (u,v,w), ambient temperature, relative humidity, and barometric pressure, all from a height of 2 meters (except pressure, 0 to 1 meter).

Source and TDL Beam-Path Locations

A GPS is used to determine the precise locations of the source, as well as the downwind TDL beam-path endpoints.

Calculated Data

The calculated data simulates the atmospheric turbulence in order for acceptance by AERMOD (i.e., "AERMOD-ready"). As discussed more thoroughly in Section 2.5.5 (subheading "Covariance Algorithm Confirmation"), e-Calc 2 employs the eddy-correlation (or covariance) approach, which requires the measurement of wind using sonic anemometry. Covariance statistics are used to determine the friction velocity. The power-law equation is then used to generate the vertical wind-speed profile in the lower few meters of the atmosphere, based on the calculated friction velocity and the sonic anemometer wind measurements.

AERMOD-Ready Input Data

All meteorological data must be in precise formats for AERMOD acceptance. Two types of AERMOD-ready files are generated: a "profile" file and a "surface" file.

<u>Profile File</u>

The profile file ("pfl") contains the meteorological data necessary to create a vertical wind-speed profile. This data consists of wind speed and direction, as well as the information to simulate turbulence. This latter information includes temperature and wind-based statistics to estimate the fluctuating components of the wind.

<u>Surface File</u>

The surface file ("sfc") contains standard meteorological surface observations (wind speed, wind direction, and temperature, all from measurements at 2 meters), together with turbulence estimates. This includes other calculated parameters as discussed in Section 1.2.2.

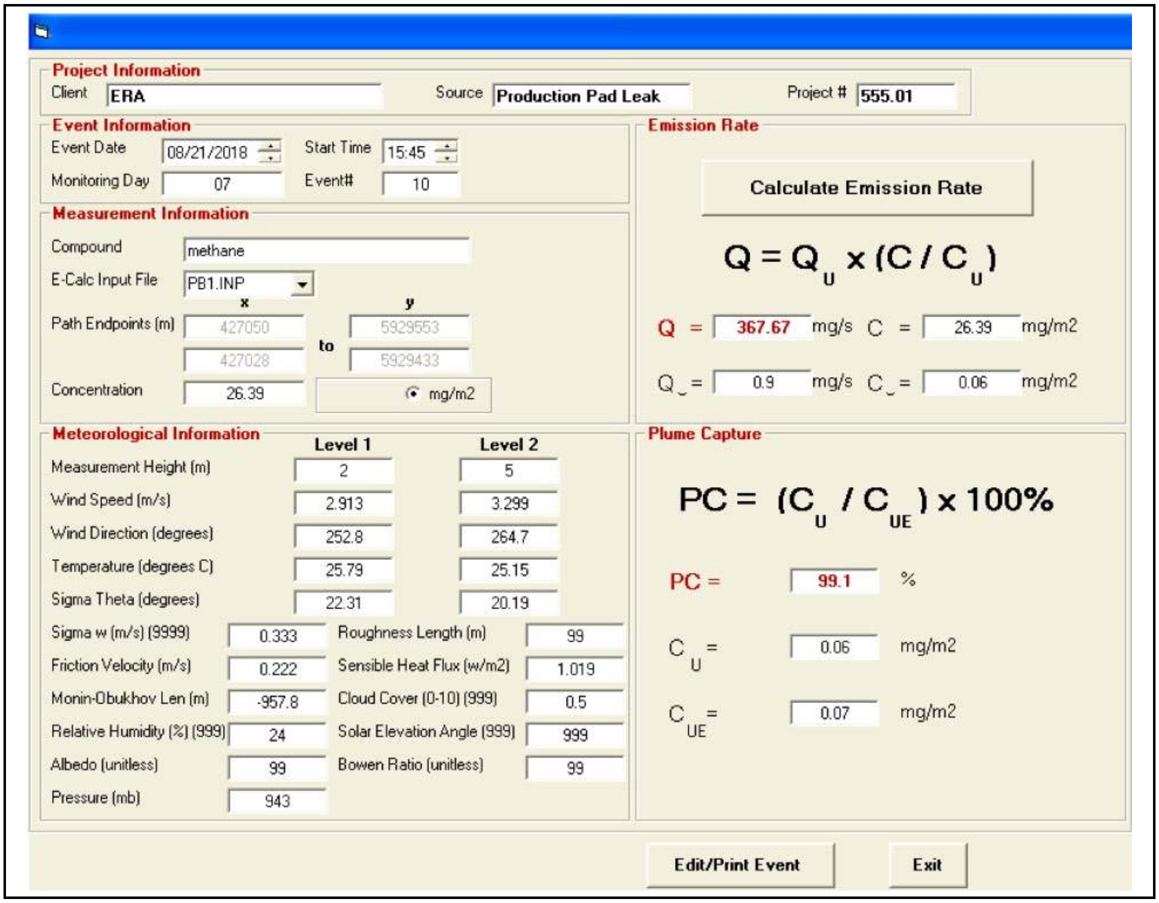
Unity Modeling

The purpose and procedure for performing the unity modeling in AERMOD is described in Step 2 of the area-source technique approach (see Section 1.2.2).

Emission-Rate Calculation

Figure 2-2 presents an example Monitoring Event Analysis Screen (actual screen from the field-testing). The methane emission rate is calculated in accordance with Equation 1-1, presented in Step 3 of the area-source technique approach (Section 1.2.2). Review, editing, validation, and printing of e-Calc results are performed by pressing the "Edit/Print Event" button at the bottom of this screen.

FIGURE 2-2. EXAMPLE MONITORING EVENT ANALYSIS SCREEN



2.3 Experimental Procedures and Methods

Section 2.3.1 discusses the experimental design. **Section 2.3.2** identifies the data-collection needs. **Section 2.3.3** describes the field logistics and sequence of activities employed. **Section 2.3.4** discusses documentation and record-keeping.

2.3.1 Design

Figures 2-3 through **2-6** presented the simulated process sources. These were: a production pad (well-head leak, where the pipes emerge from the ground); a gas-gathering pipeline assembly (valve or flange leak); a gas transmission line (flange or rupture leak); and a booster station (ruptured compressor-engine seal leak or condensate tank thief-hatch or pressure-relief valve leak).

FIGURE 2-3. SIMULATED METHANE SOURCE: PRODUCTION PAD

FIGURE 2-4. SIMULATED METHANE SOURCE: GAS-GATHERING PIPELINE

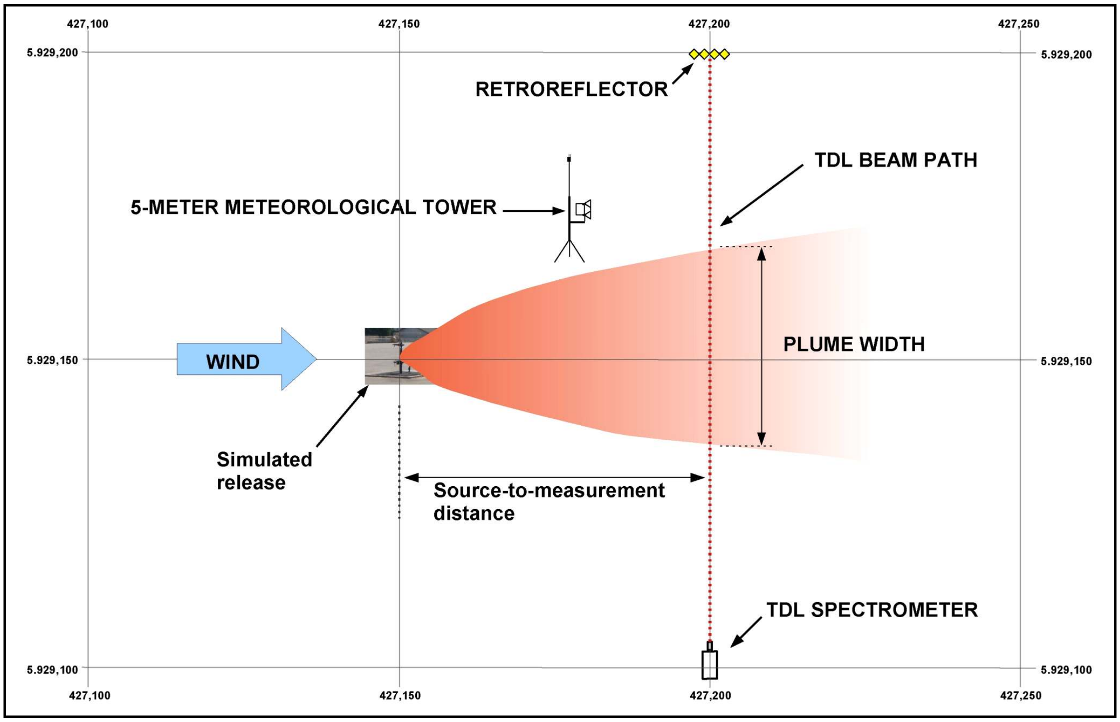
FIGURE 2-5. SIMULATED METHANE SOURCE: GAS TRANSMISSION LINE

FIGURE 2-6. SIMULATED METHANE SOURCE: BOOSTER STATION

Potential Measurement Configurations

Figure 2-7 presents a schematic illustration of the experimental design. The TDL and retroreflector were moved, as needed, based on the mean wind direction. The meteorological tower was sited at a position representative of the plume dispersion and transport conditions between the controlled-release location and the TDL measurement path, in accordance with applicable U.S. EPA siting criteria. The distance between the simulated source and the measurement path ranged from 20 meters (Day 1) to 75 meters (Day 2).

FIGURE 2-7. EXPERIMENTAL DESIGN: SCHEMATIC ILLUSTRATION



Source-Receptor Input Data

Information required for implementing the unity-based modeling included the emission source (location coordinates, orientation, booster-station dimensions, grade elevation, and release height above grade) and the measurement path (grade elevation of the TDL beam-path and coordinates of the beam endpoints).

Overview of the Data-Collection Component

A total of eight days of controlled-release measurements were budgeted. Two full days were allocated for each of the four sources (or source groups). Additionally, 2-hour nighttime measurement "add-ons" (before sunrise or after sunset) were included in two of the measurement days. The intent was to collect, for each source, a sufficient number of measurement events within both unstable (daytime) and stable (nighttime) atmospheric regimes.

An average of twenty-four, 15-minute-averaged emission rate "snapshots" (i.e., monitoring events) was expected to be completed during each measurement day, for an anticipated project total of 192 daytime snapshots; i.e., 48 per each source (or source group). Each nighttime add-on was expected to yield a additional eight snapshots.

2.3.2 Data-Collection Needs

Measured Data

Table 2-1 identifies all data which were measured directly. The path-integrated TDL measurements were collected and generated as 1-second averages. A uniform methane mass flow rate was set for each measurement day (unknown to the e-Calc operator), and was checked for drift (and recorded) approximately every hour. The meteorological measurements were generated both as 1-second values and 15-minute block averages.

TABLE 2-1. DATA MEASURED DIRECTLY

Measurement
Path-Integrated Measurements
methane
Mass-Flow Measurements
methane
Direct Meteorological Measurements
wind speed vectors u, v, and w at 2 meters
wind speed vectors v and w at 5 meters
ambient temperature at 2 and 5 meters
atmospheric pressure at 2 meters

Reduced Data

Table 2-2 identifies the meteorological parameters needed to support e-Calc. These input parameters were derived from measurements made directly in the field.

TABLE 2-2. DERIVED METEOROLOGICAL PARAMETERS AND ASSOCIATED RAW MEASUREMENTS

Derived 15-Minute Parameter for E-Calc Input									Raw 1-Second Measurement
Horiz. Wind (Speed & Dir.)	Sigma Theta	Sigma Phi	Friction Velocity	Rough-ness Length	Sensible Heat Flux	Monin-Obukhov Length	Temperature Amb.	Temperature 2-5m Profile	
x			x	x		x			2m u-comp. 3D wind vector
x			x	x		x			2m v-comp. 3D wind vector
		x	x		x	x			2m w-comp. 3D wind vector
x	x			x					5m v-comp. 2D wind vector
x	x			x					5m w-comp. 2D wind vector
					x	x	x	x	2m ambient temperature
								x	5m ambient temperature

2.3.3 Field Logistics and Sequence of Activities

The start-time for each monitoring event was synchronized with the clock governing collection of the meteorological data. All monitoring events began precisely at the quarter hour; i.e., at the top of the hour or 15, 30, or 45 minutes past. All meteorological data was recorded onto a data logger which was periodically downloaded onto a flash drive (memory stick) in order to minimize the chances of data loss.

The sequence of each day's field activities was:

1. Select Measurement Configuration and Perform Equipment Set-Up and Start-Up
    - Finalize the go/no-go decision; if a go, continue
    - Determine the source location and measurement configuration
    - Provide the monitoring event identification sequencing numbers for the day
    - Perform meteorological system check-out and start-up
    - Set up the controlled release apparatus, and site and power-up the TDL system

2. Conduct Data Collection
    - Commence data collection, once the TDL and controlled release systems have stabilized (uniform controlled release rate for each field day)
    - Perform documentation of all data-collection activities, including anything which may affect data quality

3. Perform Post-Data-Collection Tasks
    - Electronically back up all TDL and meteorological data, using high-capacity memory sticks
    - Prior to equipment shut-down and/or breakdown, identify and document any issue or concern potentially adverse to the quality of the data collected
    - Review all documentation

4. Conduct Planning Meeting for Next Day's Activities
    - Review meteorological forecast to support a go/no-go decision
    - Select the source type to be monitored
    - Identify any technical and logistical problems, either having occurred or anticipated, and a plan of action for their resolution
    - Decide whether to perform nighttime testing

Figure 2-8 presents the field data-collection form filled out by the Field Manager after each monitoring event.

FIGURE 2-8. FIELD DATA-COLLECTION FORM

PROOF-OF-CONCEPT E-CALC TESTING
VEGREVILLE, ALBERTA

FIELD-DATA COLLECTION FORM

Event No. ________

Date __ / __ / 18 (MO DAY YR)

Start Time (MDT) ________

Simulated Source ☐ Production Pad ☐ Gas-Gathering Pipeline Assembly ☐ Gas Transmission Line ☐ Compressor Engine

Beam Orientation ______ to ______ degrees

TDL Path Length ______ m

Downwind Distance ______ m

MEASURED VALUES

Methane Conc. (mg/m²)	2m Height			5m Height		Temperature			Pressure (mm Hg)
	u WS (m/s)	v WS (m/s)	w WS (m/s)	v WS (m/s)	w WS (m/s)	Ambient 2m (°K)	Ambient 5m (°K)	Dew Pt. 2m (°K)	

CALCULATED VALUES

Wind Speed		Wind Direction 5m (degrees)	Sigma		RH (%)	Rough. Length (m)	Friction Velocity (m/s)	Sensible Heat Flux (W/m²)	Monin-Obukhov Length (m)
2m (m/s)	5m (m/s)		Theta (5m) (degrees)	Phi (2m) (m/s)					

Comments ________________________________

Sign-Off ________________ **Date** ____________

Minnich and Scotto
ERA Project

2.3.4 Documentation and Record-Keeping

The documentation and records generated in the field were sufficiently comprehensive to ensure the technical validity of the data collected, and to support independent validation of the project findings.

Meteorological Measurement System

Meteorological data was collected, processed, and stored using a Met One IMP-865 programmable data logger. The data logger had the capability of storing the directly measured, 1-second (1 Hz) raw values, together with internally tabulated, 15-minute-averaged measured and derived values. All data was stored in a ASCII CSV text file format.

Tunable Diode Laser System

Path-integrated methane data was collected each second. The data was processed on an internal data logger (4 GB capacity), designed to allow for data transfer and downloading as needed. Stored as 1-second raw values in ASCII CSV format, all data was copied daily onto a flash drive for transfer to a separate field PC, from which 15-minute values were tabulated for each monitoring event.

Controlled-Release System

A spreadsheet detailing all controlled-release rate data was prepared. This included the mean release rate for each monitoring event, together with all supporting QC information, including tabulation of the total precision and accuracy (i.e., the mass flow controller plus the natural gas composition analysis) for each release rate.

2.4 Modeling Details

The essence of this project was to test the e-Calc 2 software for application to leaking upstream process sources in the O&G industry. Both e-Calc versions (e-Calc 1 and e-Calc 2) are based on AERMOD, the U.S. EPA's Guideline air dispersion model.

The reader is referred to Section 1 of this Final Outcomes Report (especially Sections 1.1 and 1.2) for a comprehensive, detailed description of all aspects of the modeling performed.

2.5 Results of Experiments and Model Simulations

The metric for evaluating the performance of e-Calc 2 in addressing the primary project goal was how well the predicted methane emission rate compared to the controlled (or actual) release rate. This P/A comparison is expressed throughout as a percent ratio, and assessed largely as functions of meteorology.

Table 2-3 presents a summary of the field testing each measurement day. Tests were conducted between August 14 and 23, 2018. A total of 211 daytime and 16 nighttime, 15-minute-averaged monitoring events were completed for the four simulated sources.

The controlled emissions were constant over each measurement day (one exception), but at differing rates as selected by InnoTech Alberta.

TABLE 2-3. SUMMARY OF DAILY FIELD TESTING

Day	Date (2018)	Day of the Week	Simulated Source	Release Ht. Above Grade (m)	# of Valid Events		# of Background Readings
					Daytime	Nighttime	
1	Aug. 14	Tuesday	booster station (BS)	3	29	0	2
2	Aug. 15	Wednesday	booster station	3	26	0	4
3	Aug. 16	Thursday	gas-gathering pipeline (GGP)	1	26	0	6
4	Aug. 17	Friday	gas-gathering pipeline	1	24	0	6
5	Aug. 18	Saturday	gas transmission line (GTL)	0.4	24	0	4
6	Aug. 20	Monday	gas transmission line	0.4	25	0	6
7	Aug. 21	Tuesday	production pad (PP)	0.4	23	0	8
8	Aug. 22	Wednesday	production pad	0.4	20	0	8
9	Aug. 23	Thursday	gas-gathering pipeline	1	14	16	10
				Total	**211**	**16**	**54**

Section 2.5.1 addresses assignment of the methane background values. **Section 2.5.2** presents composite results for the entire nine-day measurement program. **Section 2.5.3** presents the results by simulated source. **Section 2.5.4** presents preliminary conclusions from this data analysis. **Section 2.5.5** describes an initial set of supplemental analyses performed to address a significant source of P/A error; none of these analyses was envisioned in the original Work Scope (see Section 1.4). **Section 2.5.6** provides an assessment of whether a single wind sensor could be considered satisfactory. **Section 2.5.7** describes the final analysis performed – a refined assessment to address the booster station (a source previously dismissed from further consideration).

2.5.1 Assignment of Methane Background Values

E-Calc (versions 1 and 2) predicts an emission rate based on the attribution from a fugitive ground-level source. In general, source attribution is determined by subtracting the background (or upwind) concentration from the downwind concentration for each monitoring event – 15 minutes, in this case. When the background concentration is negligible, the source attribution can be ascribed solely to the downwind value (i.e., background measurements are not required).

For this project, however, treatment of the background methane concentration required special attention, as the background was shown to be: (a) variable over the measurement day; and (b) quite significant, relative to the source attribution. Several-minute background measurements were made immediately before and after each data "block," in which a block was defined as a continuous (uninterrupted) series of monitoring events. The background value assigned to each monitoring event was then linearly interpolated between the two actual measurements.

Table 2-4 presents the background methane concentrations assigned to each monitoring event over the entire nine days of measurements. Also depicted are the measurement day and date, the simulated source, and the local end-time of each event. The bolded numbers represent background values, measured during times when the controlled methane-release system was turned off. All other numbers (i.e, not bolded) represent the interpolated background values, as discussed above.

The greatest source of analysis uncertainty (and, therefore, potential error) was the inability to "ground-truth" these interpolated background methane concentrations. In general, the confidence in the background value assigned to any particular monitoring event was roughly proportional both to the rate of change of the interpolated value from one event to the next, and to the closeness between the event and the nearest background measurement (i.e., forward or backward in time).

TABLE 2-4. BACKGROUND METHANE CONCENTRATIONS FOR EACH BLOCK OF DATA (ppm)

End-Time (Local)	Day 1 Aug. 14 BS	Day 2 Aug. 15 BS	Day 3 Aug. 16 GGP	Day 4 Aug. 17 GGP	Day 5 Aug. 18 GTL	Day 6 Aug. 20 GTL	Day 7 Aug. 21 PP	Day 8 Aug. 22 PP	Day 9 Aug. 23 GGP
9:00		**2.136**							
9:15		2.149							
9:30		2.161							
9:45		2.174							
10:00	**1.976**	2.186							
10:15	1.972	**2.199**		**2.201**					
10:30	1.968			2.181					
10:45	1.965			2.161					
11:00	1.961			2.141					
11:15	1.957			2.121		**1.834**			
11:30	1.953			2.101		1.832			
11:45	1.949		**2.090**	2.081		1.830			
12:00	1.945		2.087	2.061		1.827		**2.049**	
12:15	1.942	**2.077**	**2.084 / 2.056**	2.041		1.825		2.042	
12:30	1.938	2.071	2.040	2.021		1.823		2.035	
12:45	1.934	2.066	2.024	2.001	**1.888**	1.821	**1.947**	2.027	
13:00	1.930	2.060	2.008	1.981	1.887	1.818	1.941	2.020	
13:15	1.926	2.055	**1.992**	1.961	1.886	**1.816 / 1.808**	1.934	2.013	
13:30	1.922	2.049	**1.960**	**1.941 / 1.909**	1.885	1.810	1.928	2.006	
13:45	1.919	2.043	1.960	1.912	1.883	1.811	1.921	1.998	
14:00	1.915	2.038	1.959	1.916	1.882	1.813	**1.915**	**1.991/1.993**	
14:15	1.911	2.032	1.959	1.919	1.881	1.814		1.998	
14:30	1.907	2.027	1.958	1.923	1.880	1.816	**1.726**	2.003	**2.728**
14:45	1.903	2.021	1.958	1.926	1.879	1.817	1.723	**2.008/1.928**	2.557
15:00	1.899	2.015	1.957	1.930	1.878	1.819	1.720	1.926	**2.386**
15:15	1.896	2.010	1.957	**1.933**	1.877	1.820	1.717	1.923	
15:30	1.892	2.004	1.956	**1.915**	1.876	**1.822 / 1.819**	1.715	1.921	
15:45	1.888	1.998	1.956	1.934	1.874	1.820	1.712	1.918	
16:00	1.884	1.993	1.955	1.953	1.873	1.820	1.709	1.916	**2.446**
16:15	1.880	1.987	1.955	1.972	1.872	1.821	1.706	1.913	2.361
16:30	1.876	1.982	1.954	1.992	**1.871 / 1.873**	1.822	**1.706/1.706**	1.911	2.276
16:45	1.873	1.976	1.954	2.011	1.874	1.822	1.705	**1.908/1.906**	2.191
17:00	1.869	1.970	1.953	2.030	1.875	1.823	1.704	1.915	**2.106/2096**
17:15	1.865	1.965	1.953	**2.049**	1.875	1.823	1.702	1.923	2.107
17:30	**1.861**	1.959	1.952		1.876	1.824	1.701	1.932	2.108
17:45		1.954	1.952		1.877	1.825	1.700	1.940	2.110
18:00		**1.948**	1.951		1.878	1.825	1.699	**1.949**	2.111
18:15			1.951		1.879	**1.826**	1.697		2.112
18:30			1.950		1.880		**1.696/1.694**		2.113
18:45			1.950		1.880		1.701		2.115
19:00			1.949		1.881		1.708		2.116
19:15			**1.949**		**1.882**		1.715		**2.117/2.109**
19:30							1.721		2.110
19:45							1.728		2.111
20:00							**1.735**		2.112
20:15									2.113
20:30									2.115
20:45									2.116
21:00									2.117
21:15									2.118
21:30									**2.119/2.114**
21:45									2.113
22:00									2.112
22:15									2.111
22:30									2.110
22:45									2.109
23:00									2.109
23:15									2.108
23:30									2.107
23:45									2.106
0:00									2.105
0:15									**2.104**

2.5.2 Composite Results

In this section, the predicted-to-actual emission rates are shown for the nine days of measurements, as a whole. The statistics presented are: P/A relative standard deviation (RSD) vs. block number, wind speed, and standard deviation of the horizontal wind direction (sigma theta or σ_θ); and P/A bias vs. block number. The P/A statistics are analyzed in greater detail, on a source-by-source basis, in Section 2.5.3.

Table 2-5 presents an overall statistical analysis summary. For each measurement day, presented are the simulated source, the data blocks and associated monitoring events (data blocks are numbered sequentially), and, for each block, the closest separation between the controlled release and the downwind TDL beam. Also presented for each data block are the predicted and actual emission rates (mg/s), as well as the statistics identified above. In general, the P/A bias and relative standard deviation were determined to be the best measures of assessing the block-to-block e-Calc 2 performance.

TABLE 2-5. OVERALL STATISTICAL ANALYSIS SUMMARY

Day	Source	Data Block	Events	Separation Distance (m)	Predicted (P) (mg/s)	Actual (A) (mg/s)	Bias (%)	RSD (%)	2m Wind Speed (m/s)	2m Sigma Theta (degrees)
1	Booster Station	1	1-29	20.4	666.5	403.4	65.2	25.0	3.45	13.08
2	Booster Station	2	1-4	20.4	1658.9	322.7	414.1	364.0	1.16	19.72
		3	5-26	23.1	480.3	322.7	48.8	65.4	2.70	11.41
3	Gas-Gathering Pipeline	4	1	42.5	506.6	443.7	14.2	n/a	2.50	12.23
		5	2-4	42.5	347.0	443.7	-21.8	14.4	1.73	22.49
		6	5-26	42.5	475.1	443.7	7.1	29.0	3.22	13.49
4	Gas-Gathering Pipeline	7	1-12	29.6	560.4	403.4	38.9	11.8	3.21	14.59
		8	13-18	29.6	539.9	403.4	33.8	9.2	3.21	15.22
		9	19-24	29.6	490.8	403.4	21.7	12.5	2.98	18.04
5	Gas Transmission Line	10	1-14	75.0	754.5	645.4	16.9	24.4	6.79	12.46
		11	15-24	75.0	834.6	645.4	29.3	20.4	4.91	12.12
6	Gas Transmission Line	12	1-7	54.5	534.8	726.0	-26.3	21.6	2.62	30.52
		13	8-15	54.5	650.6	726.0	-10.4	23.6	3.33	23.58
		14	16-25	54.5	709.3	726.0	-2.3	24.9	2.67	22.93
7	Production Pad	15	1-4	43.9	263.2	363.0	-27.5	29.0	2.57	25.71
		16	5-11	43.2	362.1	363.0	-0.3	17.7	2.80	26.89
		17	12-18	43.2	386.4	363.0	6.5	17.4	2.33	21.30
		18	19-23	43.2	402.8	363.0	11.0	29.3	1.25	10.23
8	Production Pad	19	1-7	57.6	391.1	484.0	-19.2	19.1	2.02	17.01
		20	8-9	57.6	456.8	484.0	-5.6	39.0	3.26	15.60
		21	10-16	31.0	505.3	484.0	4.4	11.1	3.23	11.65
		22	17-20	31.0	631.6	484.0	-30.5	10.4	1.30	12.88
9	Gas-Gathering Pipeline	23	1	52.0	2256.8	1613.4	39.9	n/a	2.98	13.91
		24	2-4	31.1	1324.5	726.0	82.4	9.0	5.25	12.08
		25	5-12	31.1	1193.5	726.0	64.4	13.2	5.49	9.90
		26	13-20	31.1	1359.1	726.0	87.2	12.2	4.34	12.91
		27	21-30	31.1	1154.7	726.0	59.0	27.2	3.82	9.16

Figure 2-9 presents the P/A relative standard deviation vs. block number over all nine measurement days. Excluded from this graph are Block 2 (booster station, Day 2), Block 4 (gas-gathering pipeline, Day 3), and Block 23 (gas-gathering pipeline, Day 9). Block 2 was designated a statistical outliner in this and the three subsequent figures (discussed in Section 2.5.3). Blocks 4 and 23 each consisted of a single monitoring event, thereby precluding calculation of the relative standard deviation.

In general, the P/A relative standard deviation decreased with increasing block number, as indicated by the best-fit line. This improvement over time was likely due to the increased number of background measurements with latter measurement days, as can be seen from Table 2-3.

FIGURE 2-9. P/A RELATIVE STANDARD DEVIATION VS. BLOCK NUMBER

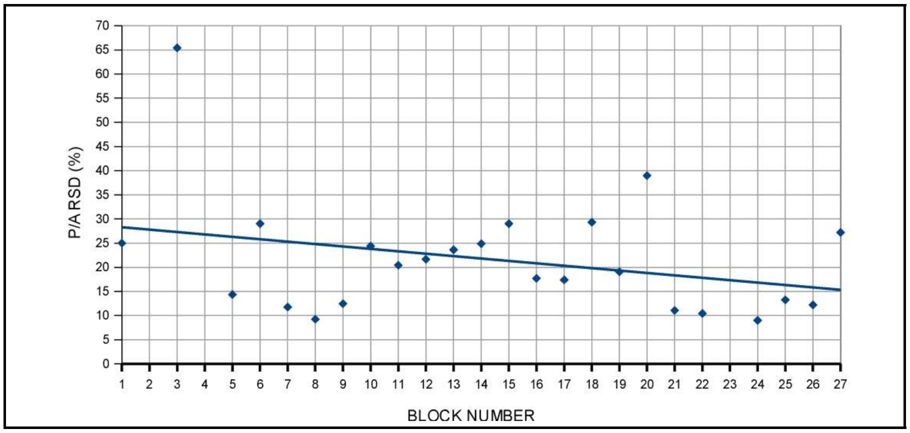


Figure 2-10 presents the P/A bias vs. block number over the nine measurement days. Except for Block 1 (booster station, Day 1), Block 3 (booster station, Day 2), and Blocks 24 through 27 (gas-gathering pipeline, Day 9), the bias was within about 40 percent (+/−) for all of these 20 remaining blocks, and within about 20 percent for 13 of those.

FIGURE 2-10. P/A BIAS VS. BLOCK NUMBER

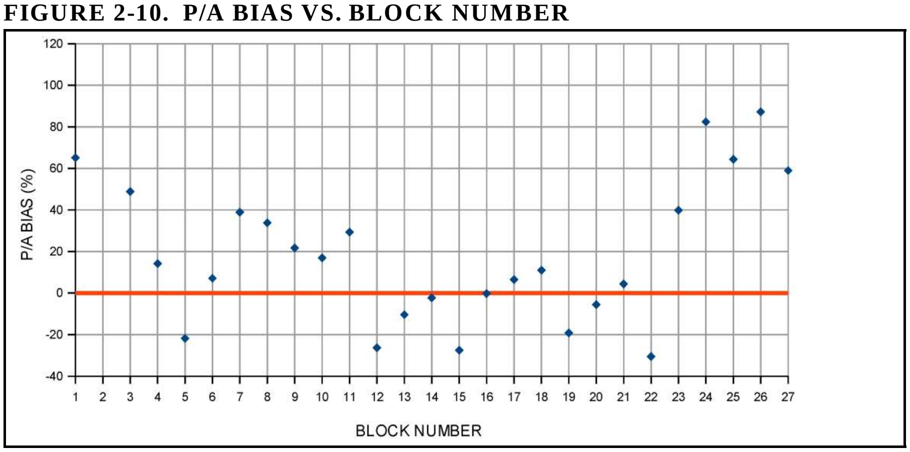


Figure 2-11 presents the P/A relative standard deviation vs. wind speed at 2 meters. There appeared to be little correlation between the P/A relative standard deviation and mean 2-meter wind speed, as indicated by the best-fit line and a correlation coefficient (r^2) of 0.013 (not shown).

FIGURE 2-11. P/A RELATIVE STANDARD DEVIATION VS. WIND SPEED (2m)

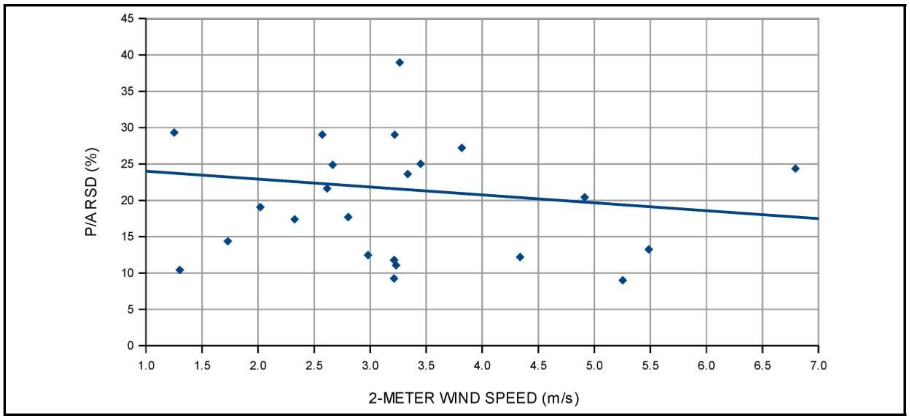
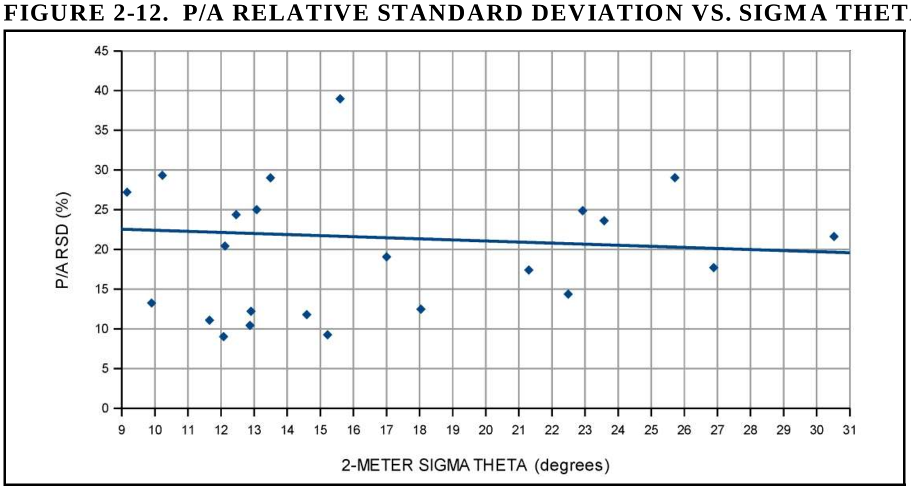


Figure 2-12 presents the P/A relative standard deviation vs. sigma theta at 2 meters. The standard deviation of the horizontal wind direction is generally a measure of atmospheric stability, whereas the lower the value, the less horizontal dispersion and the greater stability. While one might expect a direct correlation between sigma theta and the P/A relative standard deviation, such was not the case ($r^2 = 0.005$). The likely reason for this lack of correlation was the fact that the plume capture was generally at (or close to) 100 percent for most monitoring events, indicating that the horizontal dispersion was properly accounted for in the e-Calc software.

FIGURE 2-12. P/A RELATIVE STANDARD DEVIATION VS. SIGMA THETA (2m)



2.5.3 Results by Simulated Source

Analysis results for the four simulated sources are summarized in this section.

- Booster Station
  The simulated booster station, a wooden box (length 16.5 meters, width 3.1 meters, and height 3.0 meters), was constructed to represent a typical enclosure which might house a compressor engine within a condensate-tank complex. The controlled methane was released via Tygon tubing which extended the height of the enclosure, centered on the rooftop.

- Gas-Gathering Pipelines
  The gas-gathering pipeline leaks were simulated using a small, rectangular lattice-type array of 2.5-centimeter-diameter copper piping. The pipes were pierced with about 70 or 80 small holes in order to distribute the methane flow to the ambient air. The piping array was about 1.8 meters by 0.9 meters in size, and was positioned 1.0 meters above the ground.

- Gas Transmission Line
  An underground gas transmission line leak was simulated by placing a bucket (0.4 meters tall and 0.4 meters in diameter) placed on the ground, and introducing the methane into the center of the bucket bottom. The overlying soil through which the methane had to flow to escape through the top of the bucket was simulated by adding some 200 small, cylindrical stainless steel pall rings (height and diameter approximately 2.5 centimeters), filling the entire bucket.

- Production Pad
  A production pad will typically leak at the well head. This type of leak was simulated using an empty bucket (0.4 meters tall and 0.4 meters in diameter) placed on the ground, and introducing the methane into the center of the bucket bottom. This approach was similar to the underground gas transmission pipeline simulation (Days 5 and 6), except that the bucket remained empty.

For each measurement day, a table was prepared which detailed, for each monitoring event: the TDL attribution; the predicted e-Calc 2 methane emission rate and the associated plume capture; the actual (or controlled) methane release rate; the 2- and 5-meter meteorological sensor height information (wind speed, wind direction, actual temperature, and sigma theta); the turbulence parameters consisting of the standard deviation of the vertical wind speed, friction velocity, Monin-Obukhov length, and sensible heat flux; the relative humidity; and the atmospheric pressure. These tables are not reproduced herein.

Booster Station – Days 1 and 2

Figure 2-13 presents, for Day 1, the P/A bias vs. event end-time for the booster station simulation. From Table 2-5, the Day 1 actual emission rate was 403.4 mg/s, and the mean P/A bias for the Block 1 (Events 1 through 29) was +65.2 percent.

FIGURE 2-13. DAY 1 – BOOSTER STATION: P/A BIAS VS. EVENT END-TIME

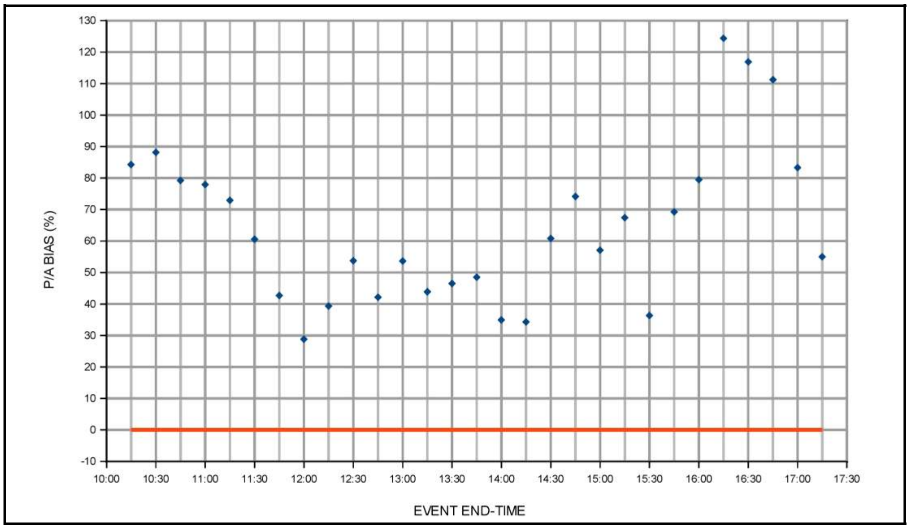
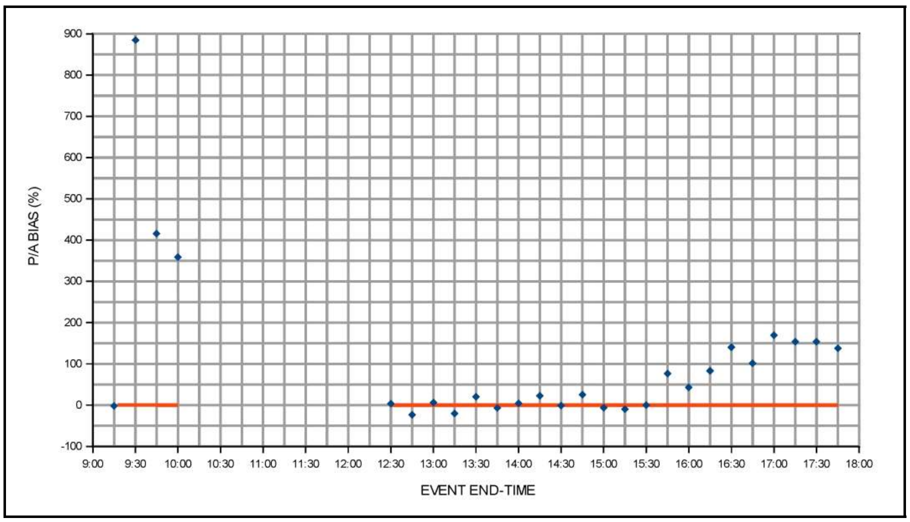


Figure 2-14 presents, for Day 2, the P/A bias vs. event end-time for the booster station simulation. From Table 2-5, the Day 2 actual emission rate was 322.7 mg/s, and the mean P/A biases were: Block 2 (Events 1 through 4), +414.1 percent; and Block 3 (Events 5 through 26), +48.8 percent.

FIGURE 2-14. DAY 2 – BOOSTER STATION: P/A BIAS VS. EVENT END-TIME



Gas-Gathering Pipeline – Days 3, 4, and 9

Figure 2-15 presents, for Day 3, the P/A bias vs. event end-time for the gas-gathering pipeline simulation. From Table 2-5, the Day 3 actual emission rate was 443.7 mg/s, and the mean P/A biases were: Block 4 (Event 1), +14.2 percent, Block 5 (Events 2 through 4), −21.8 percent, and Block 6 (Events 5 through 26), +7.1 percent.

FIGURE 2-15. DAY 3 – GAS-GATHERING PIPELINE: P/A BIAS VS. EVENT END-TIME

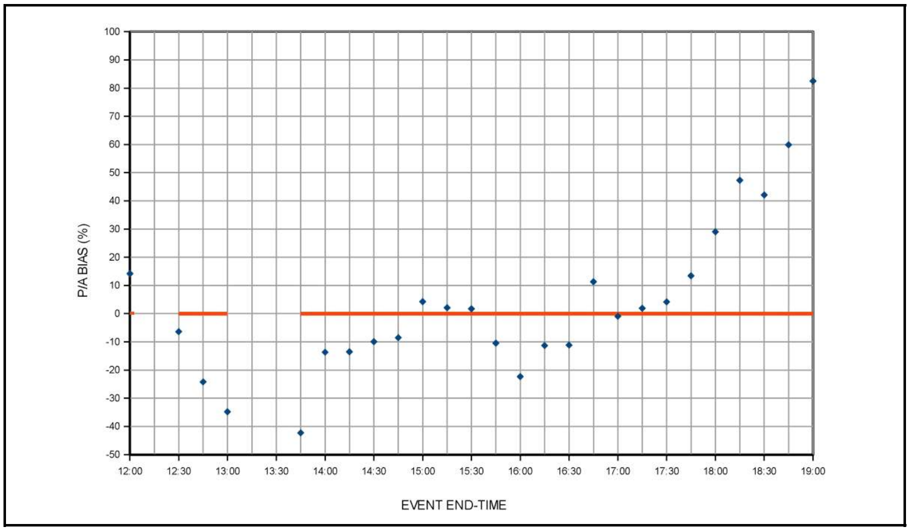


Figure 2-16 presents, for Day 4, the P/A bias vs. event end-time for the gas-gathering pipeline simulation. From Table 2-5, the Day 4 actual emission rate was 403.4 mg/s, and the mean P/A biases were: Block 7 (Events 1 through 12), +38.9 percent; Block 8 (Events 13 through 18), +33.8 percent; and Block 9 (Events 19 through 24), +21.7 percent.

FIGURE 2-16. DAY 4 – GAS-GATHERING PIPELINE: P/A BIAS VS. EVENT END-TIME

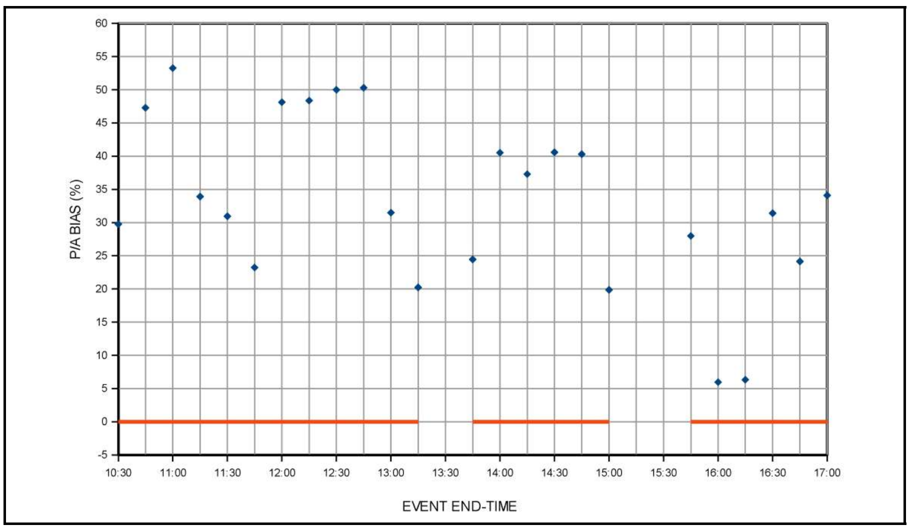
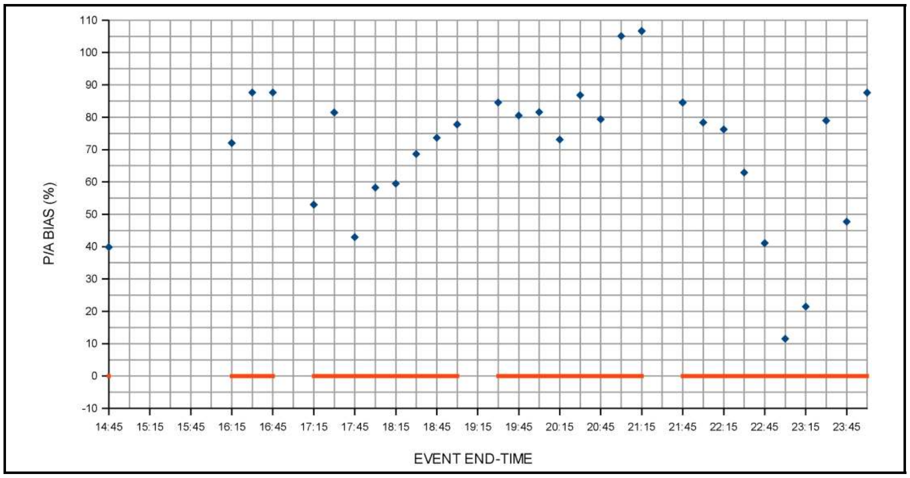


Figure 2-17 presents, for Day 9, the P/A bias vs. event end-time for the gas-gathering pipeline simulation. From Table 2-5, the Day 9 actual emission rate was 1,613.4 mg/s for Block 23, and 726.0 mg/s for Blocks 24 thorough 27. The mean P/A biases were: Block 23 (Event 1), +39.9 percent; Block 24 (Events 2 through 4), +82.4 percent; Block 25 (Events 5 through 12), +64.4 percent; Block 26 (Events 13 through 20), +87.2 percent; and Block 27 (Events 21 through 30), +59.0 percent. The final 16 events (beginning with the end-time of 20:00) were the only events able to be performed during nighttime conditions for the entire study.

FIGURE 2-17. DAY 9 – GAS-GATHERING PIPELINE: P/A BIAS VS. EVENT END-TIME



Gas Transmission Line – Days 5 and 6

Figure 2-18 presents, for Day 5, the P/A bias vs. event end-time for the gas transmission line simulation. From Table 2-5, the Day 5 actual emission rate was 645.4 mg/s, and the mean P/A biases were: Block 10 (Events 1 through 14, end-times 13:00 – 16:15), +16.9 percent; and Block 11 (Events 15 through 24, end-times 16:45 – 19:00), +29.3 percent.

FIGURE 2-18. DAY 5 – GAS TRANSMISSION LINE: P/A BIAS VS. EVENT END-TIME

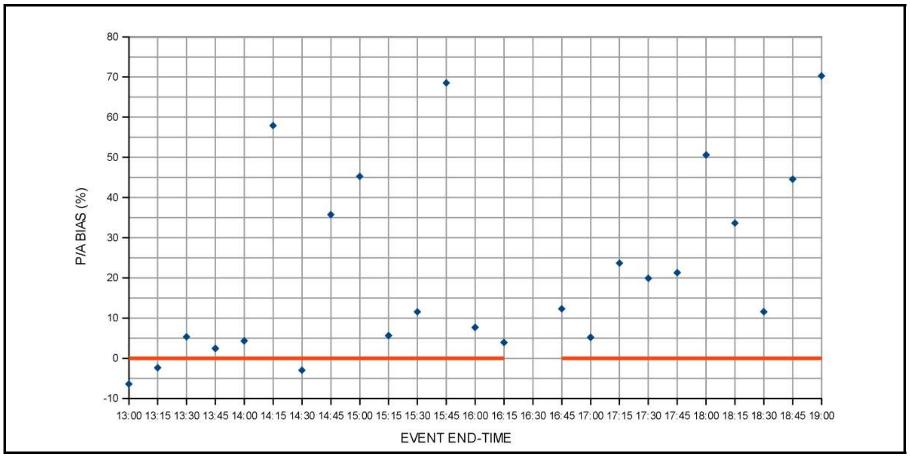
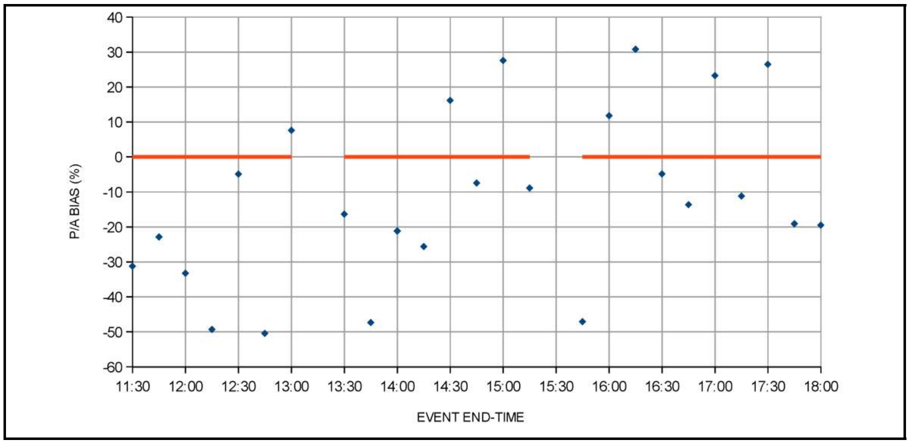


Figure 2-19 presents, for Day 6, the P/A bias vs. event end-time for the gas transmission line simulation. From Table 2-5, the Day 6 actual emission rate was 726.0 mg/s, and the mean P/A biases were: Block 12 (Events 1 through 7, end-times 11:30 through 13:00), −26.3 percent; Block 13 (Events 8 through 15 end-times 13:30 – 15:15), −10.4 percent; and Block 14 (Events 16 through 25, end-times 15:45 – 18:00), −2.3 percent.

FIGURE 2-19. DAY 6 – GAS TRANSMISSION LINE: P/A BIAS VS. EVENT END-TIME



Production Pad – Days 7 and 8

Figure 2-20 presents, for Day 7, the P/A bias vs. event end-time for the production pad simulation. From Table 2-5, the Day 7 actual emission rate was 363.0 mg/s, and the mean P/A biases were: Block 15 (Events 1 through 4, end-times 13:00 – 13:45), −27.5 percent; Block 16 (Events 5 through 11, end-times 14:45 – 16:15), −0.3 percent; Block 17 (Events 12 through 18, end-times 16:45 – 18:15), +6.5 percent; and Block 18 (Events 19 through 23, end-times 18:45 – 19:45), +11.0 percent.

FIGURE 2-20. DAY 7 – PRODUCTION PAD: P/A BIAS VS. EVENT END-TIME

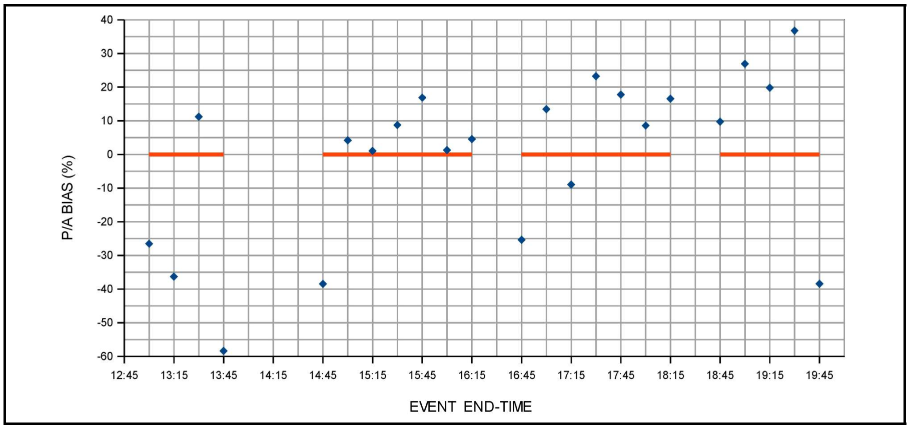
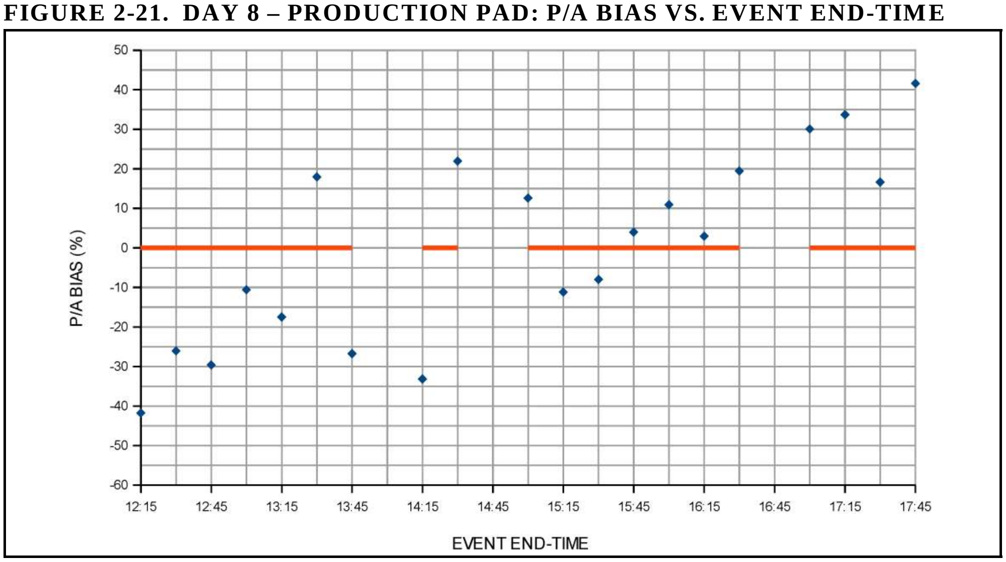


Figure 2-21 presents, for Day 8, the P/A bias vs. event end-time for the production pad simulation. From Table 2-5, the Day 8 actual emission rate was 484.0 mg/s, and the mean P/A biases were: Block 19 (Events 1 through 7, end-times 12:15 – 13:45), −19.2 percent; Block 20 (Events 8 and 9, end-times 14:15 – 14:30), −5.6 percent; Block 21 (Events 10 through 16, end-times 15:00 – 16:30), +4.4 percent; and Block 22 (Events 17 through 20, end-times 17:00 – 17:45), −30.5 percent.

FIGURE 2-21. DAY 8 – PRODUCTION PAD: P/A BIAS VS. EVENT END-TIME



2.5.4 Preliminary Conclusions

The primary project goal was generally achieved, based on the original Work Scope (see Section 1.4). An exception, however, was that we were unable to develop source-specific empirical correction factors despite the fact a general systematic bias was observed in the P/A results. The large scatter of the P/A data and the confounding issue concerning assignment of monitoring event background values precluded our ability to develop these empirical adjustments to e-Calc 2.

Background issues notwithstanding, the statistical performance of e-Calc 2 in addressing the project goal was still somewhat disappointing overall. Although a major reason for the less-than satisfactory P/A results was the inability to assign an accurate methane background concentration to each monitoring event, it was evident there were other factors at play as well. Presented next are considerations with respect both to the model (i.e., AERMOD), and to the interpolated background methane concentrations.

AERMOD Considerations

For the booster-station simulation, e-Calc 2 clearly over-predicted during Day 1, likely owing to the establishment of a "rotor" downwind of this somewhat elevated source. On the other hand, once the TDL beam was moved further downwind on Day 2 (Block 3), the software performed quite well. The exception to this, however, was when the wind was very light (less than about 1.4 m/s at 2 meters), resulting in methane pooling which, in turn, led to a breakdown of the model and anomalously high emission-rate predictions. It should be noted that the AERMOD Implementation Guide cautions model users about prediction inaccuracies under very light wind conditions (less than 1 m/s at a height of 10 meters), due to plume meander.

Another problem primarily affecting the booster station was the fact that, for small, slightly elevated non-buoyant sources such as this, under most conditions, the model holds constant the elevation of the plume centerline within about 50 meters downwind of the source (beyond which it tends to mix uniformly in the vertical dimension). In this case, therefore, the model positioned the plume centerline at the booster station's methane release height (3 meters above the ground). However, we were able to demonstrate that for these days (Days 1 and 2), the plume centerline, in actuality, was brought closer to the ground (to within about 1 or 1.5 meters, depending on the data block) before reaching the TDL beam-path. In summary, the model "thought" that the plume centerline was higher than it actually was and, accordingly, the concentration measured at the beam-path height (1 meter) was less than the predicted concentration. The result, therefore, was that the model erroneously corrected (i.e., over-predicted) the subsequent emission rate.

For the other simulated sources, (the gas-gathering pipeline, gas transmission line, and production pad), the biggest problem appeared to be associated with emission-rate over-predictions as the atmosphere became more stable during the late afternoon. This was especially evident during Day 3 (gas-gathering pipeline), and to a lesser degree to Day 5 (gas transmission line). It appeared that the eddy-correlation (or covariance) approach employed in the new AERMOD version (and, therefore, e-Calc 2), under these conditions, was unable to properly simulate the vertical wind-speed profile below the height of the lowest wind-speed measurement, i.e., 2 meters.

Background Methane Considerations

As discussed in Section 2.5.1, background methane was shown to be variable over each measurement day, and quite significant relative to the source attribution. The value assigned to each monitoring event was derived by linear interpolation based on the two actual background measurements made just prior to and after each block of data.

Table 2-6 presents, for each data block, the mean interpolated background methane concentration (IB), the mean methane source attribution (SA), and the ratio of these values (IB/SA). Source attribution was derived by subtracting the mean background concentration from the mean downwind concentration for each data block (in much the way it was derived for the individual monitoring events). These ratios illustrate the necessity of having an accurate background concentration to assign to each monitoring event.

TABLE 3-6. RATIO OF INTERPOLATED BACKGROUND METHANE SOURCE ATTRIBUTION

Day	Source	Data Block	Events	Mean Methane Concentration (ppm)		Ratio (IB / SA)
				Interpolated Background (IB)	Source Attribution (SA)	
1	Booster Station	1	1-29	1.919	0.333	5.8
2	Booster Station	2	1-4	2.168	1.193	1.8
		3	5-26	2.013	0.287	7.0
3	Gas-Gathering Pipeline	4	1	2.087	0.338	6.2
		5	2-4	2.024	0.285	7.1
		6	5-26	1.955	0.284	6.9
4	Gas-Gathering Pipeline	7	1-12	2.071	0.371	5.6
		8	13-18	1.921	0.377	5.1
		9	19-24	1.982	0.355	5.6
5	Gas Transmission Line	10	1-14	1.880	0.154	12.2
		11	15-24	1.878	0.208	9.0
6	Gas Transmission Line	12	1-7	1.825	0.195	9.4
		13	8-15	1.815	0.206	8.8
		14	16-25	1.823	0.282	6.5
7	Production Pad	15	1-4	1.931	0.148	13.1
		16	5-11	1.715	0.360	4.8
		17	12-18	1.701	0.463	3.7
		18	19-23	1.715	1.286	1.3
8	Production Pad	19	1-7	2.020	0.471	4.3
		20	8-9	2.001	0.201	9.9
		21	10-16	1.918	0.670	2.9
		22	17-20	1.928	2.051	0.9
9	Gas-Gathering Pipeline	23	1	2.557	1.152	2.2
		24	2-4	2.276	0.783	2.9
		25	5-12	2.112	0.697	3.0
		26	13-20	2.114	0.917	2.3
		27	21-30	2.109	0.901	2.3

Although not of use directly in this project, we chose to plot the entire set of measured background readings (all days) as a function of the time of day, in order to explore the premise that background concentrations are higher in the morning due to nighttime temperature inversions.

Figure 2-23 depicts the measured background (methane) concentration vs. the time of day for all measurement days (total of 54 readings per Table 2-3).

Figure 2-24 depicts the same information except for elimination of the Day 9 results (due to anomalous atmospheric conditions). The best-fit curve illustrates how the background concentration was generally highest in the early part of the day, then leveled off or slowly declined as the day wore on ($r^2 = 0.418$). We believe, in general, that the higher concentrations earlier in the day were indeed the result of temperature inversions (normally occurring during many nights), acting to inhibit vertical dispersion and hence served as a methane "lid." These inversions then dissipated during the daytime under the destabilizing influence of the sun.

FIGURE 2-23. MEASURED BACKGROUND CONCENTRATION VS. TIME (ALL DAYS)

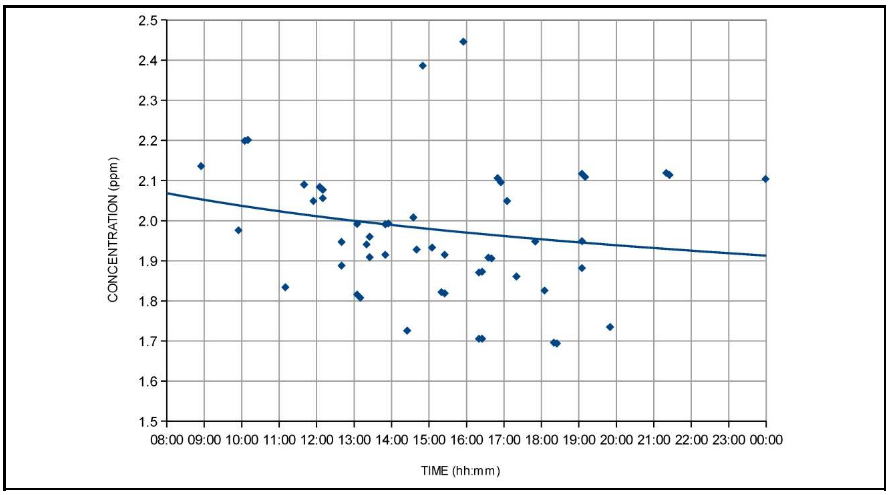
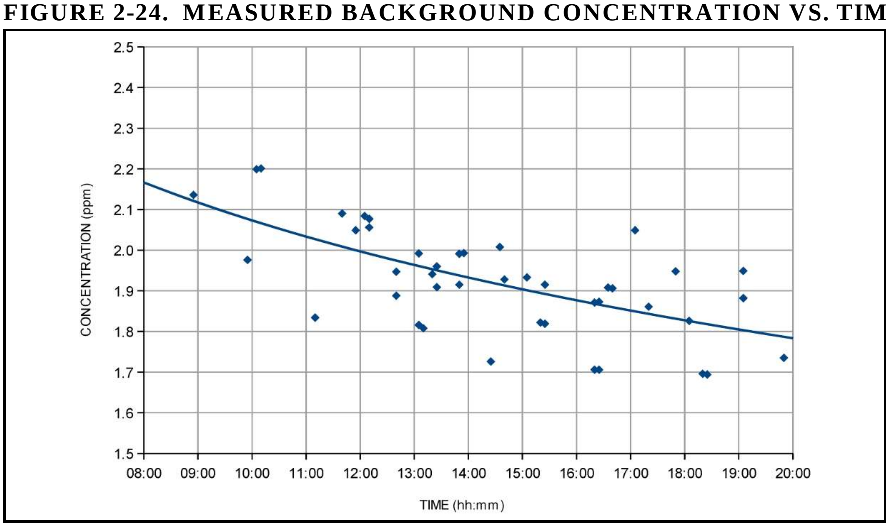


FIGURE 2-24. MEASURED BACKGROUND CONCENTRATION VS. TIME (DAYS 1-8 ONLY)



The periodic background methane measurements evidenced that the background was generally changing over the course of each measurement day. Although a linear interpolation was judged the best means of assigning a background value to each monitoring event, there was no assurance that this assumption reflected reality. In fact, there was no way of knowing whether some of these high P/A biases weren't caused by a background spike at some point during a particular data block.

Similarly, from Table 2-6, since the mean background concentration was generally quite large compared to the mean source attribution there was a practical limit in our ability to discern, for any given monitoring event, how much of the P/A bias could be attributed to the performance of e-Calc 2 (as opposed to the error in the assigned background value).

2.5.5 Initial Set of Supplemental Analyses

The practical implications of the background methane issue notwithstanding, further examination of the program results led us to believe that we had isolated a significant source of P/A error, related to employment of the eddy-correlation (or covariance) approach. As mentioned above, we suspected that the model, as configured, was unable to properly simulate the vertical wind-speed profile in the lowest few meters of the atmosphere. The eddy-correlation approach constructs this profile based solely on wind-sensor measurements at two heights. For this project, these heights (2.0 and 5.0 meters) were selected based on an exhaustive literature survey and on recommendations from one of the leading researchers in the field (see Section 2.1). Initial examination confirmed that the lower height (2 meters) was not ideal, and that model performance would likely be improved if the wind sensor were lowered.

The following subsequent analyses were performed prior to finalizing the System specification:

- Confirmation of the covariance algorithm employed; and
- A more refined treatment of background methane data to assess the acceptability of the original positioning of the bottom sensor.

The analysis approach developed and implemented to address these issues was both focused and technically sound, and was successful in removing much of the P/A emission-rate inconsistency. Extensive additional dispersion modeling employing both e-Calc 1 and e-Calc 2 was performed.

An overview of each subsequent analysis is presented next, followed by a detailed description of the methods employed and the resultant conclusions.

- Analysis #1: Covariance Algorithm Confirmation
  The purpose of this analysis was to confirm that the covariance algorithms employed to support the eddy-correlation approach were correctly implemented in the field. Before beginning additional background variability work (which would reduce even

further the amount of data upon which to base the specifications), an approach was designed to verify that these algorithms were implemented correctly. The logic was that if there had been a problem, the P/A results would have been compromised, irrespective of the background issues.

- Analysis #2: Further Treatment of Background Data
  Through further examination of the background data, the purpose of this analysis was to improve the P/A emission-rate ratios until there was sufficient confidence in these results to: (a) justify moving forward with the specification development; and (b) confirm the original positioning of the bottom wind sensor (2-meter height).

Covariance Algorithm Confirmation

E-Calc 2 employs the eddy-correlation (or covariance) approach, which typically requires the measurement of wind at two heights above the ground – in this case, 2 and 5 meters. Covariance statistics, calculated from the lower of these two sensors, are then used to determine the friction velocity. Friction velocity (units of meters-per-second) is a stability parameter used in AERMOD to characterize atmospheric turbulence. It is a measure of mechanical effects alone, i.e., wind sheer at ground-level.

In the flux-gradient approach (e-Calc 1), friction velocity is calculated from the surface roughness length, which characterizes the roughness of the terrain. The roughness length is obtained from published tables as part of the pre-field activities. AERMOD uses the friction velocity, together with surface characterization pre-processing software and a wind measurement from a single height, to generate the vertical wind-speed profile, which primarily governs the predicted (back-calculated) emission rate in e-Calc 1 (and e-Calc 2).

In the eddy-correlation approach (e-Calc 2), the friction velocity is instead derived using the time-averaged fluctuations of the horizontal and lateral vectors from the lower of the two wind sensors. The power-law equation is used to generate the vertical wind-speed profile based on the calculated friction velocity and the wind measurements from both sensor heights.

The current version of AERMOD employs the flux-gradient approach to calculate friction velocity. This approach has been extensively evaluated in model-validation studies performed by the U.S. EPA over the years. As mentioned in Section 1.2, the U.S. EPA is planning to update AERMOD based on the eddy-correlation approach, but has yet to release the software coding for this version.

We ultimately concluded that the most viable means of determining whether the eddy-correlation approach had been correctly implemented in the field was to repeat the e-Calc 2 modeling using e-Calc 1, and then compare the friction-velocity values calculated as part of the two software versions. The close tracking of these two friction-velocity depictions (graphs not reproduced herein) provided ample evidence that the covariance algorithms employed to support the eddy-correlation approach were correctly implemented, and we were able to move forward with the next analysis.

Further Treatment of Background Data

The background methane concentrations assigned to each monitoring event were presented in Table 2-4. In each case, this value was derived by linear interpolation of the actual background measurements made just prior to and after each block of data. While this approach for assigning background concentrations to individual monitoring events appeared sound, the results were only marginally satisfactory. Therefore, we had to acknowledge the likelihood that there were other factors governing the quality of the interpolated background data, which needed to be explored.

In order to identify an additional criterion for background "acceptance," we focused on those situations where two consecutive background measurements were made. The logic was that the quality of the background depiction would be in question if these readings varied too much, as it was unlikely that the actual background concentration would change significantly over such a short duration. From Table 2-4, it can be seen that consecutive background readings were taken a total of 15 times over the nine days of measurements. In 13 of these instances, the measurements comprising these background "pairs" were taken at the beginning and end of a single 15-minute period; in the remaining two instances, they were taken over consecutive 15-minute periods.

The additional criterion was that any set of consecutive background readings had to be within 3 parts per billion (ppb) of each other, or the adjacent blocks of data were rejected. Only five such sets of background data met this 3-ppb threshold: one each on Days 3, 5, and Day 6, and two on Day 7. We accepted interpolated concentrations from a maximum of four events either side of each acceptable background pair, as long as the per-event rate of change of the interpolated value was less than 2 ppb. For example, on Day 7, both consecutive background readings met the 3-ppb threshold, but the per-event rate of change for the final block of data was more than 6 ppb (due to the high final background measurement for the day), thereby causing elimination of the entire block.

Table 2-7 presents the initial universe of acceptable monitoring events based on the above refined background criteria. The mean 2-meter wind speed, the actual and predicted emission rate, and the P/A bias are shown for each of the 31 events identified. The mean P/A biases for the seven groups of continuous events ranged between 2.4 and 22.9 percent. By comparison, the U.S. EPA considers any emission-rate measurement system to be excellent if it can consistently be within 30 percent of the actual emissions.

Because of random phenomena affecting short-term application of AERMOD, the initial System specification included the recommendation that an average of four successive measurements (monitoring events) be used to create an hourly emission rate.

As to the suggestion that the P/A results might have been improved had the bottom sensor been repositioned lower, we believe that the Table 2-7 results based on the 2-meter sensor height were sufficiently acceptable. This issue, however, is one of several which might merit consideration in any future field-testing studies.

TABLE 2-7. INITIAL UNIVERSE OF ACCEPTABLE MONITORING EVENTS

Monitoring Event		Mean 2m	Emission Rate (mg/s)		
No.	End-Time (MDT)	Wind Speed (m/s)	Actual (A)	Predicted (P)	P/A Bias (%)
Day 3 (August 16, 2918) – Gas-Gathering Pipeline					
5	13:45	2.74	443.7	256.2	-42.3
6	14:00	2.77	443.7	383.0	-13.7
7	14:15	2.82	443.7	383.7	-13.5
8	14:30	2.57	443.7	399.7	-9.9
	Mean	**2.73**	**443.7**	**355.7**	**-19.9**
Day 5 (August 18, 2018) – Gas Transmission Line					
11	15:30	7.23	645.4	720.0	11.6
12	15:45	6.36	645.4	1,087.7	68.5
13	16:00	6.33	645.4	695.0	7.7
14	16:15	6.03	645.4	670.9	3.9
	Mean	**6.49**	**645.4**	**793.4**	**22.9**
15	16:45	6.09	645.4	724.8	12.3
16	17:00	5.05	645.4	679.1	5.2
17	17:15	5.51	645.4	798.1	23.7
18	17:30	5.53	645.4	774.0	19.9
	Mean	**5.55**	**645.4**	**744.0**	**15.3**
Day 6 (August 20, 2018) – Gas Transmission Line					
12	14:30	3.75	726.0	843.4	16.2
13	14:45	3.06	726.0	672.1	-7.4
14	15:00	3.36	726.0	926.2	27.6
15	15:15	3.15	726.0	661.6	-8.9
	Mean	**3.33**	**726.0**	**775.8**	**6.9**
16	15:45	2.74	726.0	384.2	-47.1
17	16:00	2.75	726.0	811.6	11.8
18	16:15	3.23	726.0	949.5	30.8
19	16:30	2.97	726.0	690.6	-4.9
	Mean	**2.92**	**726.0**	**709.0**	**-2.4**
Day 7 (August 21, 2018) – Production Pad					
8	15:30	3.17	363.0	394.8	8.8
9	15:45	3.02	363.0	424.3	16.9
10	16:00	2.91	363.0	367.7	1.3
11	16:15	2.85	363.0	379.5	4.6
	Mean	**2.99**	**363.0**	**391.6**	**7.9**
12	16:45	2.18	363.0	270.9	-25.4
13	17:00	2.51	363.0	411.8	13.4
14	17:15	2.61	363.0	330.5	-9.0
15	17:30	2.48	363.0	447.3	23.2
16	17:45	2.38	363.0	427.5	17.8
17	18:00	2.13	363.0	394.1	8.6
18	18:45	2.00	363.0	423.1	16.6
	Mean	**2.33**	**363.0**	**386.5**	**6.5**

2.5.6 Assessment of Whether a Single Wind Sensor is Satisfactory

Upon completion of this initial set of supplemental analyses, there was an additional opportunity to explore whether and to what degree these results would be compromised should the meteorological instrumentation requirements of e-Calc 2 be simplified by eliminating the upper-most wind sensor (5-meter height). Specifically, we explored the possibility of whether satisfactory P/A results could be obtained using a single wind sensor (3D sonic anemometer), positioned at a height of 2 meters. If successful, the System specifications and field logistics would be simplified (i.e., the 5-meter sensor would no longer be required).

E-Calc 2 was re-run using the meteorological data from the single sensor (2-meter height) for the P/A results remaining from Analysis #2 in the prior section, and these results were compared to those for the same data set using both sensors (2- and 5-meter heights).

Table 2-8 presents, for the 31 high-quality monitoring events from Analysis #2 (Section 2.5.5), a comparison of the e-Calc 2 P/A emission rates with both wind sensors vs. the single wind sensor. Shown for each monitoring event are:

- the event number and end-time;
- the mean 2-meter wind speed;
- the actual emission rate;
- the predicted emission rate and the relative difference (both sensor scenarios); and
- the P/A bias and the arithmetic difference (both sensor scenarios).

The thick horizontal lines separating monitoring events (Days 5, 6, and 7) signify the 15-minute period during which the dual background measurements were made (see Table 2-4).

In general, the consistency between the two wind-sensor scenarios was judged excellent, and provided ample justification for preparing the System specifications based on the single-sensor scenario.

These results appeared to be somewhat dependent upon wind speed, in which slightly higher (or more conservative) emissions rates were predicted for Days 5 and 6 under the single-sensor scenario, when the wind speed was generally greater than 3 m/s. On the other hand, on Day 7 when the wind speed was generally less than 3 m/s, the predicted emission rates for single-sensor scenario were slightly lower (or less conservative). Still, for purposes of developing the System specification, these differences are extremely minor and are of largely academic interest only.

TABLE 2-8. E-CALC 2 COMPARISON: TWO WIND SENSORS VS. A SINGLE WIND SENSOR

Monitoring Event		Mean	Emission Rate (ER) (mg/s)			ER Relative	P/A Bias (%)		
No.	End-Time (MDT)	2m WS (m/s)	Actual	Predicted 2 Sensors	Predicted 1 Sensor	Difference (%)	2 Sensors	1 Sensor	Difference (2 - 1)
Day 3 (August 16, 2018) – Gas-Gathering Pipeline									
5	13:45	2.74	443.7	256.2	279.3	(9.0)	(42.3)	(37.1)	(5.2)
6	14:00	2.77	443.7	383.0	415.0	(8.4)	(13.7)	(6.5)	(7.2)
7	14:15	2.82	443.7	383.7	432.0	(12.6)	(13.5)	(2.6)	(10.9)
8	14:30	2.57	443.7	399.7	423.2	(5.9)	(9.9)	(4.6)	(5.3)
Daily Mean		**2.73**	**443.7**	**355.7**	**387.4**	**(9.0)**	**(19.9)**	**(12.7)**	**(7.2)**
Day 5 (August 18, 2018) – Gas Transmission Line									
11	15:30	7.23	645.4	720.0	744.6	(3.4)	11.6	15.4	(3.8)
12	15:45	6.36	645.4	1,087.7	1,107.5	(1.8)	68.5	71.6	(3.1)
13	16:00	6.33	645.4	695.0	708.7	(2.0)	7.7	9.8	(2.1)
14	16:15	6.03	645.4	670.9	684.3	(2.0)	4.0	6.0	(2.0)
15	16:45	6.09	645.4	724.8	759.6	(4.8)	12.3	17.7	(5.4)
16	17:00	5.05	645.4	678.9	699.6	(3.0)	5.2	8.4	(3.2)
17	17:15	5.51	645.4	798.1	815.4	(2.2)	23.7	26.3	(2.6)
18	17:30	5.53	645.4	774.0	798.0	(3.1)	19.9	23.6	(3.7)
Daily Mean		**6.02**	**645.4**	**768.7**	**789.7**	**(2.8)**	**19.1**	**22.4**	**(3.2)**
Day 6 (August 20, 2018) – Gas Transmission Line									
12	14:30	3.75	726.0	843.4	851.1	(0.9)	16.2	17.2	(1.0)
13	14:45	3.06	726.0	672.1	673.6	(0.2)	(7.4)	(2.2)	(5.2)
14	15:00	3.36	726.0	926.2	931.6	(0.6)	27.6	28.3	(0.7)
15	15:15	3.15	726.0	661.6	665.1	(0.5)	(8.9)	(8.4)	(0.5)
16	15:45	2.74	726.0	384.2	386.5	(0.6)	(47.1)	(46.8)	(0.3)
17	16:00	2.75	726.0	811.6	819.5	(1.0)	11.8	12.9	(1.1)
18	16:15	3.23	726.0	949.5	950.8	(0.1)	30.8	31.0	(0.2)
19	16:30	2.97	726.0	690.6	703.1	(1.8)	(4.9)	(3.2)	(1.7)
Daily Mean		**3.13**	**726.0**	**742.4**	**747.7**	**(0.7)**	**2.3**	**3.6**	**(1.3)**
Day 7 (August 21) – Production Pad									
8	15:30	3.17	363.0	394.8	407.4	(3.2)	8.8	12.2	(3.4)
9	15:45	3.02	363.0	424.3	402.6	5.1	16.9	10.9	6.0
10	16:00	2.91	363.0	367.7	366.1	0.4	1.3	0.9	0.4
11	16:15	2.85	363.0	379.5	382.0	(0.7)	4.6	5.2	(0.6)
12	16:45	2.18	363.0	270.9	265.7	1.9	(25.4)	(26.8)	1.4
13	17:00	2.51	363.0	411.8	415.6	(0.9)	13.4	14.5	(1.1)
14	17:15	2.61	363.0	330.5	327.2	1.0	(9.0)	(9.9)	0.9
15	17:30	2.48	363.0	447.3	443.4	0.9	23.2	22.2	1.0
16	17:45	2.38	363.0	427.5	426.9	0.1	17.8	17.6	0.2
17	18:00	2.13	363.0	394.1	392.1	0.5	8.6	8.0	0.6
18	18:15	2.00	363.0	423.1	422.8	0.1	16.6	16.5	0.1
Daily Mean		**2.39**	**363.0**	**385.6**	**384.5**	**0.4**	**6.2**	**5.9**	**0.3**

2.5.7 Booster-Station Analysis

Once we determined that a single wind sensor would be satisfactory for e-Calc 2, it became apparent that valid results could be obtained for the booster station (previously dismissed from further consideration).

Situation Recap

As a recap, significant temporal variability in the measured background methane concentrations led to a lack of consistency in the P/A ratios derived from the controlled-release results (Section 2.5.4). This prevented us from developing the System specifications based on the full complement of measured data. We therefore committed to perform the additional critical examination and analysis of the background data necessary to remove most of this P/A inconsistency, and to move forward with this effort. In the end, we were able to sufficiently evidence that the accuracy of certain background measurements was compromised, largely by initiating these measurements before all of the methane had completely cleared the TDL beam-path.

When the affected monitoring events were removed from further consideration, confidence in the remaining P/A results was deemed sufficient for (initial) specification development, but the situations where System applicability still could not be demonstrated were: (a) during nighttime conditions; and (b) when assessing emissions from the booster-station simulation. Nighttime data were collected only during Day 9 (gas-gathering pipeline), and booster-station data were collected only during Days 1 and 2. None of monitoring events during these three days passed the new methane background criterion.

However, we committed to reassess System applicability for the booster station. As shown below, we were able to distill some meaningful results from this analysis, and extend the System specification to include the booster station. Unfortunately, we were unable to salvage any of the nighttime data collected during Day 9.

Presented next are: the analysis objective and the method employed; the new scheme developed for treatment of background methane; and the results of this final supplemental analysis.

Objective and Method

The objective of this analysis was to reassess P/A emission-rate results for the booster station, based on an alternative source treatment method for simulating the methane release from atop the building enclosure.

The first such option examined involved modeling the source as a point release, using AERMOD's building-downwash pre-processing program. It was hypothesized that this method would more realistically simulate plume dispersion downwind of this somewhat elevated source (3-meter height). However, because the extent of the downwind cavity region is a function of wind speed, the results under the particular conditions observed were actually worse than originally obtained.

The next option examined involved modeling the booster station as a volume source in AERMOD, with the controlled release assumed to be non-buoyant (i.e., the methane temperature the same as, or colder than, the ambient air). Assuming no plume rise, the entire plume mass will descend from the building's downwind roof-top edge into the building-wake or cavity-recirculation region (volume source), immediately adjacent to, and to the lee of, the building. This simulation, judged the most realistic for this elevated source, necessitated the modification of e-Calc 2 (hereafter referred to as the *modified e-Calc 2 version*) for use with the booster station, and other similarly elevated sources.

New Scheme for Background Methane Treatment

Because the refined Milestone H background analysis failed to yield acceptable background data for any of the booster-station monitoring events, we needed to develop and apply a new background scheme to retain some of the results from these days (Days 1 and 2).

<u>Day 1</u>

Upon yet further consideration, we concluded there was no reason to reject the initial measured background concentration of 1.976 ppm during Day 1, despite concerns about the final concentration (1.861 ppm; refer to Table 2-4). Therefore, we chose to accept the first four monitoring events from this day's block of data. However, because of uncertainty in the final measured concentration, we elected to hold the background concentration constant at 1.976 ppm for all four events.

<u>Day 2</u>

While the same logic as above might be applied to the first block of data for this day (Table 2-4), we chose not to accept any of these monitoring events. Because the final measured methane concentration for this block was greater than any interpolated value, the argument that the methane had not cleared the TDL beam-path could not be supported and, therefore, there was evidence that the actual background was changing over this data block.

As for the second block of data for Day 2, we concluded the first group four monitoring events was acceptable, based on the same logic applied to the Day 1 analysis. The background concentration was held constant at 2.077 ppm for these four events.

Results

Table 2-9 presents, for the booster station, a comparison between the results from e-Calc 2 (area source) and the modified e-Calc 2 version (volume source), based on assignment of a constant methane background concentration for each block of data as discussed above. Predicted, event-specific emission rates are shown for both source-type simulations, with the P/A biases calculated for each. The measured wind speeds are also shown. A single volume source is assumed, and plume parameters are estimated using U.S. EPA's suggested procedure as described in the AERMOD

User's Guide.

The lateral dimension was estimated by dividing the structure width (10 feet, or 3.05 meters) by 4.3, which yields 0.71 meters.

The vertical dimension was estimated by dividing the structure height (also 10 feet, or 3.05 meters) by 2.15, which yields 1.42 meters.

The volume source height above grade was assumed equal to one-half the structure height, height of the adjacent building, 1.52 meters.

TABLE 2-9. BOOSTER-STATION ANALYSIS: AREA-SOURCE VS. VOLUME-SOURCE SIMULATIONS

Event No.	Event End-Time (MDT) (hh:mm)	TDL Methane Attribution (ppm-m)	TDL Methane Attribution (mg/m2)	Area-Source Prediction Emission Rate (P) (mg/s)	Area-Source Prediction Plume Capture (%)	Volume-Source Prediction Emission Rate (P) (mg/s)	Volume-Source Prediction Plume Capture (%)	Actual Emission Rate (A) (mg/s)	P/A Bias Area Source (%)	P/A Bias Volume Source (%)	Wind Speed (m/s)
Day 1 (August 14, 2018)											
1	10:15	55.46	34.15	734.3	100.0	438.8	98.8	403.2	82.1	8.8	3.549
2	10:30	51.55	31.72	739.4	100.0	407.8	98.8	403.2	83.4	1.1	3.709
3	10:45	51.08	31.40	695.3	100.0	416.8	99.1	403.2	72.5	3.4	3.909
4	11:00	46.31	28.41	677.8	100.0	386.6	99.1	403.2	68.1	-4.1	4.005
			Mean	**711.7**		**412.5**			**76.5**	**2.3**	**3.793**
Day 2 (August 15, 2018)											
5	12:30	70.60	43.58	329.2	90.8	312.0	86.9	322.7	2.0	-3.3	2.099
6	12:45	50.59	31.19	238.0	87.3	239.0	83.4	322.7	-26.3	-25.9	2.080
7	13:00	69.09	42.57	328.2	97.3	289.6	95.5	322.7	1.7	-10.3	2.337
8	13:15	43.96	27.06	234.6	93.2	213.5	90.8	322.7	-27.3	-33.9	2.458
			Mean	**282.5**		**262.5**			**-12.5**	**-18.3**	**2.244**

The modified e-Calc 2 version (volume-source simulation) shows a marked improvement over the area-source simulation for the first block of data (Day 1, Events 1-4), as determined by the calculated P/A biases. For the second block of data (Day 2, Events 5-8), the area-source simulation yields slightly better results, although the difference is judged not significant.

2.6 Project Outcomes

As discussed in Section 1.3, the primary goal of this project was to create an upgraded emissions-calculation software package (e-Calc 2), appropriate for real-time use with upstream O&G industry sources. The long-term objective remains the commercialization of the System, with all aspects of component design and specification included as part of the project itself.

The secondary goal of this project was to assess the application of e-Calc (both versions) to CNRL mine-face and tailings pond operations.

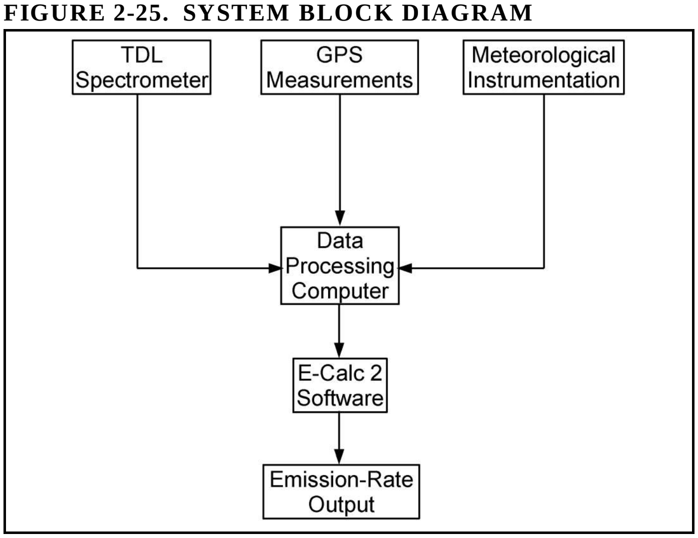
Sections 2.6.1 and **2.6.2** present the outcomes for the primary and the secondary project goals, respectively.

2.6.1 Primary Project Goal

System Overview

Figure 2-25 is a System block diagram. Measured data from the TDL spectrometer, the GPS unit, and the meteorological instrumentation feed into a data-processing computer. The processed data streams then feed into the e-Calc 2 software, and the 15-minute-averaged methane emission rates are generated, in real-time.

FIGURE 2-25. SYSTEM BLOCK DIAGRAM



The System is comprised of the following components:

- e-Calc 2
- Boreal Laser GasFinder3-OP TDL system
- Met One Instruments meteorological system
- global positioning system
- data acquisition and processing

E-Calc 2

The e-Calc 2 software is supported by a PC with a Windows 10, 7, or XP operating system, on which Microsoft Visual Basic, Microsoft Access Database, and Seagate Crystal Report Professional are installed. The PC has a 64-bit operating system (at a minimum), 1.50 GHz processor, and 4.0 GB of RAM.

Boreal Laser GasFinder3-OP TDL System

Components for the TDL system include a spectrometer, a retroreflector, and a PC containing the manufacturer's DAS and reporting software.

Met One Instruments Meteorological System

The Met One meteorological system is a specially designed collection of components, some of which are from other manufacturers. These components include: an RM Young ultrasonic 3D anemometer; Met One's sensors to measure temperature, relative humidity, and barometric pressure; and a Climatronics Corporation data logger. (It should be noted that Climatronics Corporation is wholly owned and operated by Met One Instruments, Inc.)

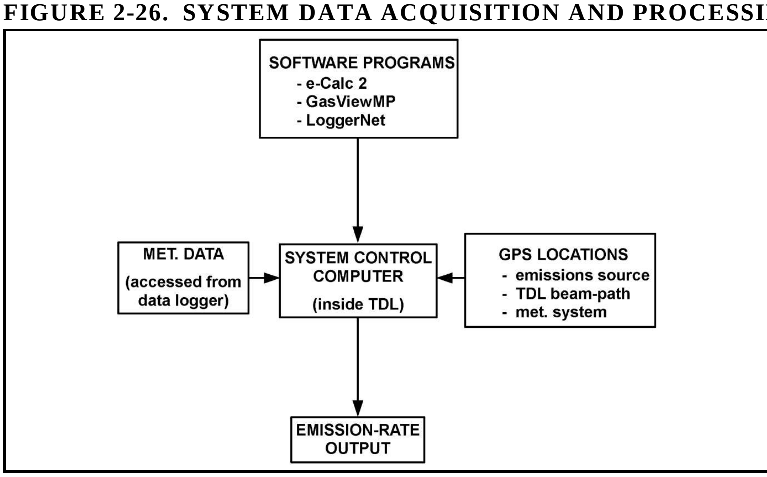
Global Positioning System

A Trimble GPS (or equivalent) is required.

Data Acquisition and Processing

Figure 2-26 depicts a System data-acquisition and processing diagram, as originally envisioned.

FIGURE 2-26. SYSTEM DATA ACQUISITION AND PROCESSING



All data-acquisition activities and e-Calc 2 applications are controlled by the System Control Computer located inside the Boreal TDL. This PC contains the e-Calc 2 software, the LoggerNet 4.5 (or equivalent) software for meteorological system operation, and the existing GasViewMP software for TDL system operation. Manual GPS entry of all location coordinates is required for the emissions source, the TDL beam-path end-points, and the meteorological system.

The GasViewMP program is used to control and operate the TDL, and to generate the methane attribution measurement in a form suitable for input to e-Calc 2. This program also facilitates data storage (including supporting QC information) and data-generation results (in this case, text or CSV), suitable for automated polling by the e-Calc 2 software.

A dedicated data logger for the Met One system (separate from the System Control PC) is employed for assembly of all measured data, and for calculation and assembly of all other data, in forms suitable for input to e-Calc 2 (text or CSV). Automated communication between the data logger and the System Control PC is accomplished via direct cable connection (RS232/USB) or via wireless communication technology. Set-up, control, and management of all data-logger operations is accomplished via specialized LoggerNet software, including uploading of programs, data polling, and data storage.

From the System Control PC, e-Calc 2 generates real-time, event-specific results, once automated access to the TDL and meteorological data is established. Results can be presented on-screen, as well as in hard-copy reports.

System Components

Table 2-10 depicts the final System component specifications. This itemization incorporates results from the Major Deliverables for Milestone B (Field-Work Planning), Milestone F (Controlled-Release Program), Milestone H (Initial System Specification), and Milestone I (Supplemental Booster Station Analysis).

TABLE 2-10. FINAL SYSTEM COMPONENT SPECIFICATIONS

Component	Manufacturer/ Provider	Model No.	Purpose
Tunable diode laser	Boreal Laser	GasFinder3-OP	Methane measurement
3D ultrasonic anemometer	R.M. Young	8100	WS, WD, σ_ϕ, u*, z_0, H, L
Ambient temperature sensor	Met One	064	H, L, wind profile
Relative humidity sensor	Met One	083	L
Barometric pressure sensor	Met One	092	Concentration correction, L
Portable 3m tripod	Met One	905	Sensor mounting
Crossarm assembly	Met One	191-1	Sensor mounting
Meteorological DAS	Met One (Climatronics)	IMP-865	Meteorological data processing
LoggerNet software	Met One (Climatronics)	Version 4.5	Meteorological data processing
Tablet computer	Dell Inspiron (or equiv.)	P24T	QC, internet access for forecasting
Global positioning system	Trimble (or equivalent)	GEO 5T	UTM coordinate measurements
Emission-calculation software	Minnich and Scotto	e-Calc 2	Ground-level emissions

System Recommendations and Limitations

Table 2-11 presents a summary compilation of the final System recommendations and limitations.

TABLE 2-11. FINAL SYSTEM RECOMMENDATIONS AND LIMITATIONS

Issue	Methane Emissions Source	Recommendation	Limitation
Monitoring events	(all)	Four successive 15-minute events to form an hourly-average emission rate	Plume meander and other short-term effects may adversely impact 15-minute averages
Wind speed	- Booster stations	Use e-Calc 2 or modified version for WS between 2.0 and 3.0 m/s	- Avoid WS less than 2.0 m/s - Use caution with WS greater than 5.0 m/s
		Use modified version for WS greater than 3.0 m/s	
	- Gas-gathering pipelines - Gas transmission lines - Production pads	Use e-Calc 2 for WS between 2.0 and 5.0 m/s	
Background	(all)	Minimum of six consecutive measurements	If measurements are not consistent, use dual TDL units (simultaneous upwind / downwind measurements)
Nighttime application	(all)	(none)	Nighttime application is not supported

2.6.2 Secondary Project Goal

E-Calc was applied (both versions) to re-create fugitive methane and carbon dioxide emission rates from the CNRL mine-face and tailings pond operations in Fort McMurray. The intent was to use onsite, 15-minute-averaged path-integrated methane and carbon dioxide data, collected across portions of these sources in 2015 and 2016 by CNRL using a Boreal Laser TDL spectrometer, together with onsite, coincident meteorological and flux-chamber data (also collected by CNRL). All data was provided by ACCO; accordingly this data is hereafter referred to as the ACCO data.

ACCO identified four specific objectives, achievement of which would be of considerable value:

- To provide best estimates of methane and carbon dioxide emissions, including discernment of any diurnal trends;
- To develop methane/carbon dioxide emission-ratio profiles;
- To assess whether upwind sources had a significant effect upon the reported methane and carbon dioxide attribution from the mine face and tailings pond; and
- To provide recommendations on the type and quality of data needed to optimize e-Calc performance in the future.

Results of these analyses are presented in Section 2.7.2. It should be noted that the ACCO data was collected to satisfy the input requirements of CALPUFF – a model applied by CNRL, also in its inverse form. As it turned out, while the ACCO data was voluminous (more than 2,600 combined methane and carbon dioxide 15-minute-averaged TDL measurements for both sources over the two years), we were able to use only a small subset of it. Still, we were able to reasonably address these objectives.

2.7 Analysis and Discussion of Results

As stated in Section 2.6, the primary goal of this project was to create an upgraded emissions-calculation software package (e-Calc 2), appropriate for real-time use with upstream O&G industry sources, with all aspects of System component design and specification for eventual commercialization included as part of the project itself. The secondary goal of this project was to assess the application of e-Calc (both versions) to CNRL mine-face and tailings pond operations in order to support ACCO needs.

Sections 2.7.1 and **2.7.2** present analysis and discussion of the primary and the secondary project goals, respectively.

2.7.1 Primary Project Goal

As detailed in Section 2.5.4, the primary project goal was generally achieved, based on the original Work Scope. However, we were unable to develop source-specific empirical correction factors, despite the fact a general systematic bias was observed in the P/A results. The large scatter of the P/A data and the issue concerning assignment of monitoring event background values precluded our ability to develop these empirical adjustments to e-Calc 2.

These factors necessitated performance of a series of supplemental analyses outside our original Work Scope (described in Sections 2.5.5 through 2.5.7). Results of the original controlled-release study combined with these supplemental analyses demonstrated that the System was appropriate for real-time use with upstream O&G industry sources. The results also led to the development of detailed specifications to support System commercialization.

System component specifications were presented in Table 2-10, while System recommendations and limitations were detailed in Table 2-11. This latter table addresses the minimum number of successive monitoring events recommended to form an hourly methane emission rate, as well as criteria for acceptable wind-speed ranges and collection of background methane concentrations. Unfortunately, results of the original Work Scope and the supplemental analyses were unable to support System application during nighttime hours – one of the project's intended objectives.

2.7.2 Secondary Project Goal

Table 2-12 presents the e-Calc-derived mean methane and carbon dioxide emission rates, in metric tons per year (mT/yr) by source and year, as well as the ratio between carbon dioxide and methane (CO_2/CH_4 ratio). In general, carbon dioxide emissions were much greater than methane for both sources. In each year, e-Calc 1 predicted significantly greater emission rates than e-Calc 2 for the mine face (both compounds), but similar emission rates to e-Calc 2 for the tailings pond.

TABLE 2-12. MEAN E-CALC EMISSION RATES BY SOURCE AND YEAR

Compound	Emission Rate (Metric Tons per Year)							
	Mine Face				Tailings Pond			
	2015		2016		2015		2016	
	e-Calc 1	e-Calc 2	e-Calc 1	e-Calc 2	e-Calc 1	e-Calc 2	e-Calc 1	e-Calc 2
Methane	38,449	26,676	3,745	2,284	3,446	3,357	1,431	7,350
Carbon Dioxide	1,579,038	924,074	3,889,824	2,718,214	145,592	158,738	12,969,006	13,693,825
CO_2/CH_4 Ratio	41	35	1,039	1,190	42	47	9,063	1,863

Observations

The first observation was that the mean 2016 carbon dioxide emissions were much greater than those for methane (both sources), while this difference was more than 3 orders of magnitude for each source (both e-Calc versions). And yet in 2015, the e-Calc 1 and e-Calc 2 carbon dioxide emissions were only 41 and 35 times greater, respectively, for the mine face, and 42 and 47 times greater, respectively, for the tailings pond. Not being privy to any data except the raw results as described herein, we were unable to speculate on any physicochemical reasons as to why this might be so.

The second observation concerned the variability about the mean emission rates, as discussed above. Empirically, we would normally be inclined to assign a higher quality to those emissions data with less variability. This would lend the most credence to the mine-face data. While it might be tempting to conclude, based on this observation, that the mine-face emissions data were of a quality higher than the tailings pond data, we do not believe that such was the case. Instead, on a more fundamental level, we believed this observation (and the overall lack of reproducibility in the individual events) were due primarily to insufficient TDL path-lengths, and that inadequate relative source-strength apportionments and likely problems with the TDL instruments (or their operation) only served to exacerbate the situation.

The third observation was the lack of consistency in the overall emissions behavior between the two years (both sources). For example, the mean mine-face methane emission rate was 10.3 times greater in 2015 than in 2016 for e-Calc 1, and 11.7 times greater for e-Calc 2. Conversely, for the tailings pond, the mean carbon dioxide emission rate was 89.1 times greater in 2016 than in 2015 for e-Calc 1, and 86.3 times greater for e-Calc 2.

For each source (both years), in the context of e-Calc input needs, two basic factors significantly affected the quality of the ACCO data. These factors precluded achievement of the minimum spatial data-representativeness criteria for both: (a) determination of source attribution (the downwind TDL path-lengths); and (b) identification and quantification of the relative source-strength apportionment (the flux-chamber sampling configurations).

Despite these limitations, we concluded that enough usable data still remained to infer some meaningful results with respect to the ACCO objectives (discussed below). It should be noted that little can be said whether employment of e-Calc 2 resulted in a material improvement over e-Calc 1 in achieving the ACCO objectives, as the quality issues associated with the ACCO data (with respect to e-Calc needs) were overriding.

Achievement of ACCO Objectives

Downwind TDL Path Lengths

The first (and primary) quality-affecting issue was that the downwind TDL path-lengths, in all cases, were far too short relative to the downwind source dimensions, thus significantly compromising accuracy in the predicted e-Calc emission rates.

Ideally, the path-integrated concentration should be measured along the entire crosswind dimension of the source plume. In this case, the downwind measurement paths spanned distances of some 3.5 kilometers for the mine face and 7 kilometers for the tailings pond. Even the longest path-lengths (474 meters for the mine face and 267 meters for the tailings pond) were only a small fraction of these distances, resulting in very small plume-capture percentages. Accordingly, our confidence in the overall quality of the e-Calc results was substantially compromised.

Flux-Chamber Sampling Configurations

The second quality-affecting issue was that the flux-chamber data was too sparse to be able to confidently assess the relative source strength across each source subarea. Although especially true for the mine face, this factor was judged overall to be not nearly as important as the downwind TDL path-lengths.

Emission Rates and Ratios

In the Milestone G Interim Project Report, a total of 28 individual graphs compared and contrasted the carbon dioxide and methane emission rates and emission ratios for the mine face and tailings pond (not reproduced herein). All emission rates were plotted from daily means based on the event emission rates. Generally, the mine face emissions rates and emissions ratios (both compounds) tracked fairly well between e-Calc 1 and e-Calc 2. There was little consistency between the emission rates and ratios, however, on a day-to-day or even an event-to-event basis.

Diurnal Emission Trends

No diurnal emission trends could be discerned, as the only valid nighttime ACCO data in terms of e-Calc was limited to four tailings pond events, and then only for e-Calc 2. It is interesting to note that the CO_2/CH_4 ratio was reasonably uniform during these four events, but that was about all which could be said for this extremely limited set of nighttime data.

Impacts of Upwind Sources

Following is a discussion on whether there were upwind sources which could have had an effect upon the reported carbon dioxide and methane attributions.

- *Carbon Dioxide*

  As discussed in Section 2.4, because all upwind carbon dioxide TDL measurements for the tailings pond were anomalously high in 2016, we believed it reasonable to conservatively assign the upwind concentrations (both sources and years) a fixed value of 402.8 ppm as measured by the CRDS instrument, consistent with the regional ambient background for this non-reactive compound.

  We re-examined the upwind carbon dioxide TDL data for all valid MEP's in light of the possibility that these upwind readings were real (i.e., there were no instrument problems), caused by a source further upwind. However, the only source-year combination where the data suggests there could have been an upwind attribution of carbon dioxide was the tailings pond in 2016.

  The upwind TDL for the tailings pond in 2016 was located on the southwest shore (Southwest Pond site in Figure 3-4); the upwind TDL value was greater than the corresponding downwind value for all seven valid measurement event pairs. Assuming the TDL was operating properly, this evidences the possibility of a nearby upwind interfering carbon dioxide source, likely originating along or just inland of the southern-most portion of the tailings pond western shoreline.

- *Methane*

  Upwind TDL concentrations of methane, on the other hand, were reasonably uniform for the duration of each measurement day for both sources (i.e., no anomalously high readings). In our opinion, the event-to-event differences in upwind concentrations were consistent with the spatial and diurnal variability in ambient background levels typically associated with this compound. Therefore, no upwind source of methane was evidenced for either source.

Recommendations for Future Use of E-Calc

Following are specific recommendations concerning data collection for future e-Calc use at very large sources, such mine faces and tailings ponds. If these recommendations were to be followed, we stated confidently that accurate emission rates could be generated in a highly cost-effective manner with minimal difficulty.

- *Source-Attribution*
  The path-length necessary to capture a sufficient portion of the downwind plume is greater than can be achieved by a TDL (or any other optical remote sensing instrument). This does not even consider the insurmountable problems caused by measurement-path obstructions, especially for sources with complex terrain such as a mine face.

  The only practical means of measuring the downwind plume for such sources is a rapid-sampling, point-monitoring system configured to generate path-averaged concentrations. A continually sampling CRDS system, driven along the downwind source perimeter at a uniform speed, is ideal for generating such data, and was strongly recommended.

- *Relative Source-Strength Apportionment*
  One means of determining relative source-strength apportionment across a mine face or a tailings pond is by collecting samples at the center points of uniformly spaced grids, immediately above the source surface. It is feasible to collect such data by directing a drone (close to the surface during calm or light winds), upon which is mounted a real-time sampling device (such as a closed-cell TDL), and to transmit these results, together with sample coordinates, to an onsite command center.

  Perhaps an easier approach is to employ a motor boat for collecting the hot-spot data via a hand-held instrument positioned just above the pond surface during reasonable calm conditions. These readings would be taken at the center-point of each subarea determined by a similar grid to be established atop the source. A total of about 24 square subareas should be sufficient to provide a reasonable level of model accuracy. Ideally, the emissions-characterization study should be performed twice: prior to and upon completion of all monitoring events. However, in this case, for a source this large, once was judged satisfactory.

- *Meteorological Measurements*
  <u>E-Calc 1</u>. E-Calc 1 simulates the wind profile in the vertical dimension and the atmospheric turbulence by calculating dispersion coefficients based on wind speed, land use, solar insolation, and statistical data treatments, such as the standard deviations of the horizontal wind direction and vertical wind speed. Boundary layer parameters (e.g., friction velocity, sensible heat flux, and Monin-Obukhov length) are required in the surface meteorological file input to AERMOD. E-Calc 1 simulates these parameters in the AERMET preprocessor based on the *flux-gradient approach*.

The onsite wind data used e-Calc 1 is collected via standard cup-and-vane sensors. Wind direction, wind speed, sigma theta or σ_θ (standard deviation of the horizontal wind direction), and sigma W or σ_W (standard deviation of the vertical wind speed) are collected (or calculated) from an appropriately configured 3-meter meteorological tower. Air temperature is measured using a portable hand-held instrument, and cloud cover (in tenths) is observed and recorded; the solar elevation angle is derived in accordance with the U.S. National Oceanic and Atmospheric Administration (NOAA) Solar Calculator. E-Calc 1 cannot be applied at night without a 10-meter meteorological tower.

E-Calc 2. E-Calc 2 employs dual 3D and 2D ultrasonic anemometers (plus a temperature sensor) at two heights. This method of profiling wind speed and atmospheric turbulence, referred to as the *eddy-correlation (or covariance) approach*, allows for the direct measurement of boundary layer parameters, resulting in a more accurate assessment of emission rates – at least in theory. This approach also obviates the need for the AERMET preprocessor, thereby simplifying the e-Calc logic, and can be applied at night.

In this approach, both the friction velocity and the Monin-Obukhov length are calculated using the covariance statistic between the u (east-west) and w (up-down) wind components and the v (north-south) and w wind components; sensible heat flux is calculated using the covariance between the w wind component and the temperature. The 3D ultrasonic anemometer and temperature sensor measures 1-second orthogonal wind and temperature, from which the covariance values are generated. Sigma theta is calculated from wind direction data generated by the 2D ultrasonic anemometer. (It should be noted that a simpler meteorological configuration is described in Section 2.5.6.)

2.8 Important Lessons Learned

Sections 2.8.1 and **2.8.2** identify the important lessons learned while addressing the primary and secondary project goals, respectively.

2.8.1 Primary Project Goal

Following are important lessons learned concerning the System proof-of-concept:

- *Success in Demonstrating System Applicability*
  The overarching lesson learned from this proof-of-concept demonstration was that the methane emission-rate measurement system is appropriate for application to upstream O&G sources, and that the meteorological component of the System design could actually be simplified with no attendant loss of accuracy.

- *Treatment of Background Methane*
  In order to accurately calculate the methane attribution from a given source, it is imperative that the background methane behavior be understood and accounted for during System application. Dual TDL units are recommended for simultaneous upwind and downwind methane measurements during each monitoring event if background concentrations cannot be shown in advance to be sufficiently consistent.

- *Modified e-Calc 2*
  For the simulated booster station, a volume-source treatment was shown to be superior to the area-source treatment (upon which e-Calc 2 is based). This led to creation of the *modified e-Calc 2 version*, suitable for use with booster stations and other similarly elevated sources; i.e., sources with methane release heights on the order of 3 meters above grade.

2.8.2 Secondary Project Goal

Following are important lessons learned concerning application of e-Calc to the CNRL mine-face and tailings pond GHG data (methane and carbon dioxide):

- *Technical Viability*
  Based on mine-face and tailings pond GHG data from CNRL (2015 and 2016), both versions of e-Calc (e-Calc 1 and 2) were shown to be potentially viable, attractive alternatives to the techniques currently employed at this oil-sands facility (bLS modeling, inverse dispersion modeling using CALPUFF, and flux-chamber sampling).

- *Cost Advantage*
  The time and cost for GHG reporting at these (and similar) oil-sands sources can be greatly reduced).

SECTION 3 – GREENHOUSE GAS AND NON-GHG IMPACTS

There will be no GHG reduction resulting from the completed project *per se*, as the System is strictly limited to the real-time calculation of methane emission rates from upstream O&G industry sources. By quantifying methane emission rates in real-time, however, it may be expected that a common-sense approach to prioritizing leaking pipelines, valves, and flanges may be implemented, thus reducing methane emissions. Further, there is no reason to believe that such a methane-reduction strategy will be limited to this particular industry, as this project has shown that GHG emissions from sources in Alberta as large as mine faces and tailings ponds can enjoy a similar benefit. Finally, MSW landfills and CAFO facilities are two more industry sectors for which the System will be applicable.

SECTION 4 – OVERALL CONCLUSIONS

Primary Project Goal

The successful testing of the e-Calc 2 software for quantifying methane emission rates from upstream O&G industry sources was achieved. This success led to development of a Set of Specifications for a fully integrated system for commercialization. The System – consisting of a Boreal Laser TDL unit, requisite Met One meteorological monitoring equipment, and the e-Calc 2 software – is capable of generating emission rates under most daytime meteorological conditions from these (and other) methane sources in real-time, every 15 minutes, with only a modicum of up-front (pre-field) preparation.

Secondary Project Goal

The e-Calc software was shown to be a potentially viable, attractive alternative to the techniques currently employed during CNRL mine-face and tailings pond operations. To this end, as discussed in Section 6.2.1, we intend to propose another ERA project to demonstrate the viability of a modified System for measuring methane and CO_2 emission rates from an active tailings pond.

SECTION 5 – SCIENTIFIC ACHIEVEMENTS

Section 5.1 addresses the status of the System patenting. **Section 5.2** addresses publications and conference presentations. **Section 5.3** describes several technical accomplishments arising from completion of our ERA project.

5.1 Patent Status

We are unsure at this time whether we will seek a patent for e-Calc 2 (or for the modified e-Calc 2 version), as most of the software is simply reverse-engineered from AERMOD (the coding for which resides in the public domain). More germane to this issue, however, is the history in the United States concerning the patenting of air measurement software which has the same basic objective and intended applicability as e-Calc. The downside of patenting generally translates into less user-acceptance, which may outweigh the IP protection benefit. We suspect this to be the reason that the WindTrax bLS software is offered free of charge by Thunder Beach Scientific (see http://www.thunderbeachscientific.com/).

While patent protection may be inapplicable to the Software itself, patents for the TDL components and the meteorological system components are owned by Boreal Laser and Met One, respectively, thus providing further IP protection when used in collaboration with e-Calc.

5.2 Publications and Conference Presentations

There have been no publications or conference presentations based on results of our ERA project. However, we are planning to present project results at a U.S. EPA air dispersion modeling specialty conference to be held in early 2020, and possibly at the 2020 A&WMA Annual Conference to be held in San Francisco, California (June 29 - July 2). We may also elect to present at several Canadian conferences over the next year or two (such as any organized by ERA or COSIA), especially should some of the proposed short-term actions be realized (Section 6.2). We shall seek approval from ERA for these (and any other) presentations well in advance of the respective conferences.

5.3 Technical Accomplishments

Following are several technical accomplishments arising from completion of our ERA project.

Development of e-Calc 2 for Ground-Based Methane Sources

E-Calc 2 has been successfully demonstrated as a means of accurately calculating emission rates of methane from a variety of ground-based O&G industry sources, in real-time, with only minor pre-field preparation. There are simply no other techniques with these capabilities on the market today.

Development of the Modified e-Calc 2 Version for Elevated Methane Sources

The modified e-Calc 2 version employs the volume-source algorithms in AERMOD for accurately calculating methane emission rates from somewhat elevated O&G sources. Although the need exists for further research concerning the software's performance, this technique has the same basic attributes, capabilities, and market advantages as e-Calc 2.

E-Calc 2 Applicability to the Oil-Sands Industry

Methane and CO_2 emissions from mine faces and tailings ponds are typically assessed using isolation flux chambers. This method, however, has serious limitations from a data-representativeness perspective, despite the fact that flux chambers are the approved emissions measurement technique for these sources. Recently, inverse dispersion modeling using CALPUFF has been employed in an attempt to address this data-representativeness deficiency. While an accurate approach in theory, input to CALPUFF requires highly sophisticated and expensive pre-processing of complex, onsite meteorological data which, for the oil-sands sources, has historically taken weeks to perform – thus rendering this method infeasible for real-time application.

E-Calc and its attendant GHG measurement technology offers at least three powerful advantages over the flux-chamber and/or other IDM approaches: (a) superior accuracy afforded by its capability to adequately address the spatial data-representativeness deficiency inherent in the use of flux chambers; (b) nominal deployment costs afforded by the fact that the software is already developed and fully functional; and (c) real-time results afforded by minimal labor and CPU-time requirements.

The analyses we performed for ACCO in achieving the secondary project goal led directly to the conceptualization and design of a detailed approach to demonstrate the utility of the e-Calc 2 software for application at a tailings pond. A costed proposal entitled, "*Field Demonstration of a Real-Time, Software-Based System to Quantify Fugitive Methane Emissions From a Typical Oil-Sands Tailings Pond*" was submitted to ACCO on October 10, 2018 for consideration (more on this in Section 6.2).

SECTION 6 – NEXT STEPS

Section 6.1 presents the next steps for the technology and innovation. **Section 6.2** discusses the short-term actions and long-term plan with respect to System commercialization (i.e., TDL, meteorological, and e-Calc 2 components). **Section 6.3** details the potential partnerships currently under development.

The System is fully functional now, in conformance with the hardware specifications set forth in Section 2.6.1 (see Table 2-10).

6.1 Technology and Innovation

The emission-rate measurement System (as demonstrated in our ERA project) has immediate application for determining methane emission rates from a number of Alberta industry types, as discussed in this section. The market initially identified for System commercialization was leaking process components in upstream sources in the O&G industry. This market was expected to be viable as long as: (a) methane continued to be recognized for its role in climate change; and (b) domestic oil and gas production continued to remain in Canada's national interest. The recent repeal of Alberta's "carbon tax" has, in our estimation, reduced the market potential for the System – at least for the O&G industry in the short-term. However, the federal government intends to implement a national levy on carbon emissions in the coming year, which would essentially negate the effect of the provincial carbon tax repeal on the overall market in the O&G industry.

As far as we know, the Province is still committed under the Climate Leadership Plan to achieving a 45 percent reduction in methane emissions from O&G operations by 2025. The improvement of measurement techniques is acknowledged as one component to help achieve this goal, as an accurate methane emissions baseline can be established, against which future reductions can be reliably assessed.

We also believe there is a market for System application to other Alberta industries. Broadly speaking, this market is any entity with a need or desire to quantify methane emissions from ground-level sources – national carbon levy notwithstanding. Two additional industries having sources for which the existing System could be applied are MSW landfills and CAFO facilities.

MSW Landfills

In 2015, there were 35 MSW landfills in Alberta. In addition to providing an emissions baseline, accurate measurement of landfill methane emissions would be integral in assessing the feasibility and/or effectiveness of methane-recovery systems for beneficial reuse or energy generation.

CAFO Facilities

As of January 2018, Alberta had nearly five million head of cattle, with 151 feedlots comprised of 1,000 head or more. Alberta has the most cattle in Canada, accounting for 42% of the national herd in 2016. The ability to accurately measure methane emission rates from cattle feedlots could be useful in developing feeding strategies (higher quality feed with balanced nutrient ratios) to reduce the generation of methane. Methane emissions from other types of CAFO facilities, such as large hen houses, are also a concern and represent another System application.

A potential market also exists for oil-sands sources – specifically mine faces and tailings ponds – to support annual GHG (methane and CO_2) reporting requirements (see Section 5.3). Most of Alberta's oil production comes from its enormous oil-sands deposits (11 currently operating oil-sands mines), placing Canada third in the world for the largest total oil reserves, behind only Venezuela and Saudi Arabia.

Two proposed follow-up ERA projects are described in Section 6.2.1.

6.2 System Commercialization

In the context of our ERA project, a component of System commercialization involved a high degree of automation to be accomplished by having the e-Calc software controlled by Boreal Laser's operating system computer housed inside the TDL unit, thereby enabling the System to operate largely unattended. Although this level of automation was not achieved, the project has clearly demonstrated that the System is market-ready with no barriers to inhibit commercialization.

Despite e-Calc 1 already being fully functional before the project began, the Technology Readiness Level at that time could be viewed as low as TRL 4, as the software which describes the theoretical equations governing simulation of the wind profile and the atmospheric turbulence had to be developed and integrated, and ultimately shown to work. Regardless, upon project completion we would view the readiness level as TRL 9.

6.2.1 Short-Term Actions

The following short-term actions are envisioned:

- Secure an exclusive partnering agreement to maximize technology transfer to Alberta
- Propose an ERA project for System demonstration at an MSW landfill
- Propose an ERA project for demonstrating a modified System at a tailings pond

Secure an Exclusive Partnering Agreement to Maximize Technology Transfer to Alberta

A short-term action that we plan on initiating immediately is to secure an exclusive partnering agreement with a well-established air quality consulting/engineering firm (and possibly with a premier air monitoring firm) having a strong Alberta presence. The purpose is to maximize technology transfer to Alberta, as it is clear that ERA's interests are best served by having all aspects of e-Calc available to them (and other Alberta entities) though this single, high-profile Alberta-based firm.

Propose an ERA Project for System Demonstration at an MSW Landfill

Together with the above partner and the owner of an operating MSW landfill, we intend to propose an ERA project which would demonstrate System viability for measuring methane emission rates from such a source, in real-time. Results of this project would support evaluation of the feasibility and/or effectiveness of methane-recovery systems for beneficial reuse or energy generation. It would also support the long-term plan concerning emission-factor development (see Section 6.2.2).

Propose an ERA Project for Demonstrating a Modified System at a Tailings Pond

As discussed earlier, the System (with some modification) is applicable for measuring emissions from the principal GHG emitters in the oil-sands industry: mine faces and tailings ponds. Together with the above partner and the owner of an operating oil-sands facility, we intend to propose another ERA project (or possibly a combined landfill/tailings pond initiative), which would demonstrate the viability of a modified System for measuring GHG emission rates (methane and CO_2) from an active tailings pond. As discussed in Section 2.7.2, the magnitude of the required downwind measurement path precludes use of a TDL system for making these measurements. A continually sampling CRDS system, driven along the downwind source perimeter at a uniform speed, is currently envisioned as the means to generate this data (also discussed in Section 2.7.2). This proposed ERA project will be similar to the one described to ACCO in our October 2018 proposal (see Section 5.3).

6.2.2 Long-Term Plans

The following long-term plans are envisioned over the next two years:

- Propose a program to develop methane emission factors
- Develop and implement an aggressive marketing plan

Propose a Program to Develop Methane Emission Factors

In the U.S., a major element of the Clean Air Act (Section 112 – National Emissions Standards for Hazardous Air Pollutants) requires that sources of hazardous air pollutants (HAP) must achieve "Maximum Achievable Control Technology," or MACT, which is defined (for existing sources) as "no less stringent than the average emission limitation achieved by the best performing 12 percent of the existing sources . . ." This regulation has proven to be a highly effective means of reducing human exposure to a wide range of HAP. As of this writing, we are unsure whether a similar program exists in Alberta which could be extended to methane; if so, this could be a valuable means of reducing emissions from industries with large methane emissions, carbon tax notwithstanding.

Based on future discussion with Alberta Innovates, we could prepare a costed proposal to expand upon such a MACT-based approach for controlling methane emissions. If implementation of a similar program appears to be viable, the hope would be that funding could be obtained to perform a field-measurement program to derive emission-factor ranges for representative MSW landfills and CAFO facilities (and possibly even individual O&G industry process sources). In this way, companies could choose to default to generic emission factors instead of conducting their own measurements, in much the same way that the U.S. EPA allows use of AP-42 emission factors today.

Depending on how the carbon tax plays out in the coming months and years for the oil-sands industry sources, there would be nothing to prevent extending this MACT-based concept to mine faces and tailings ponds, thus reducing (or possibly eliminating) the need for assembling annual GHG emissions inventories.

Develop and Implement an Aggressive Marketing Plan

Together with our exclusive air quality consulting/engineering partner (Section 6.2.1), we will develop and implement an aggressive plan to market the (modified) System to entities in Alberta and elsewhere in Canada and the U.S. This will include extensive conference participation, including System demonstrations at trade-shows (see Section 7).

6.3 Potential Partnerships Under Development

Integral to our overall business-development plan, we intend to begin immediately the process of securing an exclusive partnering agreement with a well-established air quality consulting/engineering firm which has a strong Alberta presence. As discussed in Section 6.2.1, the purpose of this arrangement will be to maximize technology transfer to Alberta such that all aspects of e-Calc are available to ERA (and other Alberta entities) though a single, high-profile Alberta-based company.

We anticipate that Minnich and Scotto will grant this company exclusive license to e-Calc, and all of its derivatives, for use in Alberta (and possibly the remainder of Canada). For future proposed ERA projects (Section 6.2.1), we envision that all System-related field work will be performed by this company, but that Minnich and Scotto will maintain administrative project responsibility working closely with ERA, similar to this current ERA project.

We will continue to cultivate the partnerships which have been in place since project conception. These include InnoTech Alberta, Boreal Laser, Met One, and Loover Partnership.

SECTION 7 – COMMUNICATIONS PLAN

The overall plan for communicating information about the System to third-parties consists of several components:

- ***Conference and Trade-Show Presentations and Exhibits***
  As discussed in Section 6.2.2, we will develop and implement an aggressive plan with an exclusive partner to market the System to entities in Alberta and elsewhere in Canada and the U.S. This will include extensive conference participation, including System demonstrations at trade-shows and selected conference exhibits over the next few years. At this time, we envision that presentations will be given at those conferences organized by ERA and COSIA in Alberta, and by the U.S. EPA and A&WMA in the United States.

- ***Corporate Promotion from Exclusive Partner***
  Corporate promotion from our exclusive partner will be an effective means of communicating information about the (modified) System. Of the firms we have identified to pursue regarding the partnering agreement, one has been involved in IDM studies at mine-face and tailings pond operations and is widely acknowledged as a major force in this marketplace.

- ***System Marketing via Boreal Laser***
  Boreal will continue discussion about e-Calc with their leak-detection distributers and customers, and will follow up with us should an opportunity arise for System deployment.