PSI-1402/
TR-1979

Extended Performance Handheld and Mobile Sensors for Remote Detection of Natural Gas Leaks

Phase II Final Report

Reporting Period Start Date: 10/01/02
Reporting Period End Date: 12/31/04

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May 2005

Under Cooperative Research Agreement DE-FC26-02NT41603
Between Physical Sciences Inc. and DoE NETL

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ACKNOWLEDGMENT STATEMENT:

This Final Report was prepared with the support of the U.S. Department of Energy, under Award No. DE-FC26-02NT41603. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the author(s) and do not necessarily reflect the views of the DoE.

DISCLAIMER:

Abstract

This report summarizes work performed by Physical Sciences Inc. (PSI) to advance the state-of-the-art of surveying for leaks of natural gas from transmission and distribution pipelines. The principal project goal was to develop means of deploying on an automotive platform an improved version of the handheld laser-based standoff natural gas leak detector previously developed by PSI and known as the Remote Methane Leak Detector or RMLD. A laser beam which interrogates the air for methane is projected from a spinning turret mounted upon a van. As the van travels forward, the laser beam scans an arc to the front and sides of the van so as to survey across streets and to building walls from a moving vehicle. When excess methane is detected within the arc, an alarm is activated. In this project, we built and tested a prototype Mobile RMLD (MRMLD) intended to provide lateral coverage of 10 m and one lateral scan for every meter of forward motion at forward speeds up to 10 m/s. Using advanced detection algorithms developed as part of this project, the early prototype MRMLD, installed on the back of a truck, readily detected simulated gas leaks of 50 liters per hour. As a supplement to the originally planned project, PSI also participated in a DoE demonstration of several gas leak detection systems at the Rocky Mountain Oilfield Testing Center (RMOTC) during September 2004. Using a handheld RMLD upgraded with the advanced detection algorithms developed in this project, from within a moving vehicle we readily detected leaks created along the 7.4 mile route of a virtual gas transmission pipeline.

Table of Contents

List of Figures

List of Figures (Continued)

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Executive Summary

This report describes work performed by Physical Sciences Inc. (PSI) to advance the state-of-the-art of surveying for leaks of natural gas from transmission and distribution pipelines. The principal project goal was to develop means of deploying on an automotive platform an improved version of the handheld laser-based standoff natural gas leak detector previously developed by PSI and known as the Remote Methane Leak Detector or RMLD. Figure 1 illustrates the concept: A laser beam which interrogates the air for methane is projected from a spinning turret mounted upon a van. As the van travels forward, the laser beam scans an arc to the front and sides of the van so as to survey across streets and to building walls from a moving vehicle. When excess methane is detected within the arc, an alarm is activated. As illustrated, the configuration would be most useful for surveying streets and sidewalks in municipal settings.

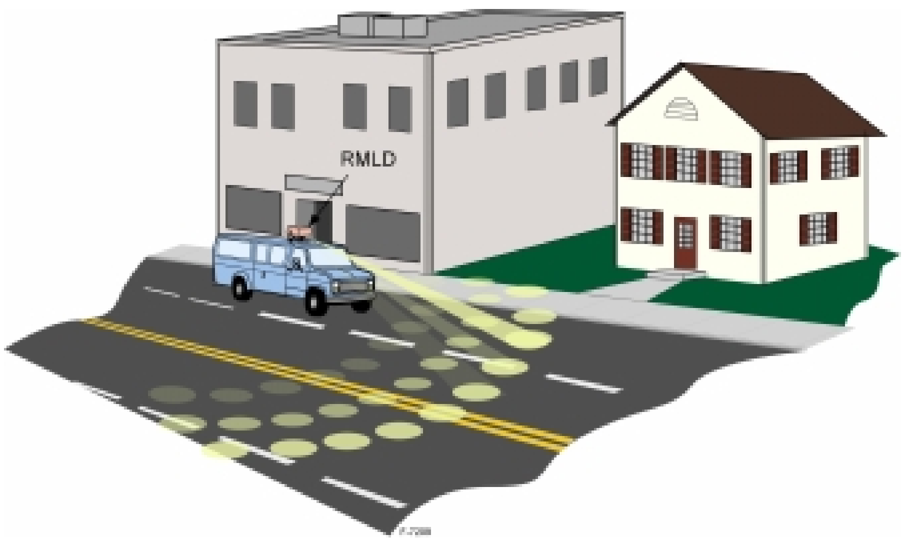

Figure 1. Mobile RMLD concept.

In this project, we built and tested a prototype Mobile RMLD (MRMLD) intended to provide lateral coverage of 10 m and one lateral scan for every meter of forward motion at forward speeds up to 10 m/s. The early prototype MRMLD has readily detected simulated gas leaks of 50 liters per hour (2 scfh).

The basic project comprised four specific and distinct tasks:

- Task 1. Develop and install enhanced detection algorithms providing the speed and sensitivity needed to accommodate the scanned laser beam;
- Task 2. Evaluate the feasibility of concurrently sensing ethane without significant modification of the survey tool; and
- Task 3. Design and demonstrate a means for scanning the laser beam and the associated detection components.
- Task 4. As a supplement to the originally planned project, PSI participated in a DoE demonstration of several gas leak detection systems at the Rocky Mountain Oilfield Testing Center (RMOTC) during September 2004.

In Task 1, we developed and implemented several improvements to the handheld RMLD that were instrumental for achieving success in Tasks 3 and 4. Furthermore, these improvements led to commercial acceptance of the technology by the leak survey community. The most significant improvement was implementation of an audio output enabling a user to distinguish a gas leak plume from ambient methane. Another significant improvement was to enhance the calculation speed, which reduced false alarms when observing rapidly changing topographies. These two improvements enabled successful leak detection from moving platforms.

In Task 3, we implemented technology with a spinning reflective turret as illustrated by Figure 1. With this system mounted on a rolling cart, we demonstrated its ability to sensitively detect methane.

During tests at RMOTC in Task 4, we used a handheld RMLD, upgraded with the algorithms of Task 1, to locate leaks. The surveyor rode in the back of a truck driving along a virtual pipeline route. Methane leaks created along the route by test planners were located with the RMLD. Leaks that the RMLD were expected to find were located with 90% success.

Background

The US natural gas transmission system comprises approximately 250,000 miles of pipeline, 1700 transmission stations and 17,000 compressors. This transmission system serves local distribution companies that operate some 500-1000 gate stations supplying roughly 132,000 surface metering and pressure regulation sites stationed along 1,000,000 miles of distribution pipeline terminating at 61,000,000 end-user customer meters.[1] Maintaining the security and integrity of this system is a continual process of searching for, locating, and repairing leaks.

Leak surveying is very labor intensive, in part because all currently available natural gas detectors must be positioned within a leak plume to detect the leak. Prior to the current project, Physical Sciences Inc. (PSI), in conjunction with Heath Consultants (Houston, TX) and the Northeast Gas Association (New York, NY), and with funding from PSE&G (NJ), SoCal Gas (CA), and the US EPA, had developed prototype optical sensors that provide stand-off detection of methane leaks with detection capabilities comparable to commonly-used flame ionization detectors.[2,3] The Remote Methane Leak Detector (RMLD), shown in use by Figure 2, is based on the established spectroscopic measurement technology known as Tunable Diode Laser Absorption Spectroscopy (TDLAS).[4]

TDLAS sensors rely on well-known spectroscopic principles and sensitive detection techniques coupled with advanced telecommunications-style diode lasers, and often with optical fibers. The principles are straightforward: Gas molecules absorb energy in narrow bands surrounding specific wavelengths in the electromagnetic spectrum. At wavelengths slightly different than these “absorption lines”, there is essentially no absorption. By (1) transmitting a beam of light through a gas mixture sample containing a quantity of the target gas, (2) tuning the beam’s wavelength to one of the target gas’s absorption lines, and (3) accurately measuring the absorption of that beam, one can deduce the concentration of target gas molecules integrated over the beam's path length.

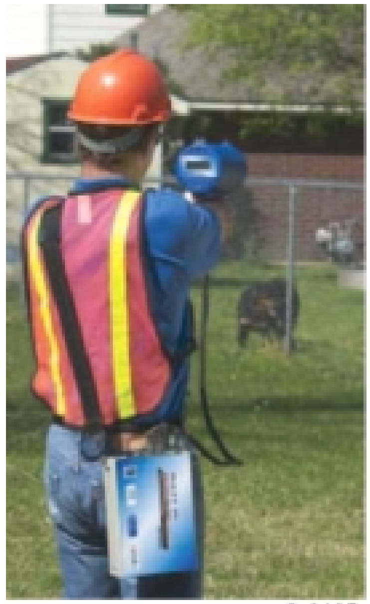
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Figure 2. Photograph of PSI's natural gas leak detector during field testing.

Typically, each TDL system utilizes a laser having a specific design wavelength chosen to optimize the sensitivity to a particular target gas while minimizing sensitivity to other gases. In the RMLD, the wavelength is near 1.653 µm, one of methane's strongest near-IR absorption lines. Fast, sensitive detection of methane is accomplished using the technique of Wavelength Modulation Spectroscopy (WMS),[5] wherein the laser's fast tuning capability is exploited to rapidly and repeatedly scan the wavelength across the selected gas absorption line. While this periodic wavelength modulation occurs, the fraction of emitted laser power transmitted through the gas mixture is monitored with a photodetector. When the wavelength is tuned to be off of the absorption line, the transmitted power is higher than when it is on the line. Because each cycle of the modulation causes the wavelength to cross the absorption feature twice, the resulting amplitude modulated signal is periodic with a fundamental frequency of twice the wavelength modulation frequency. The fundamental component is called the 2f signal. Phase sensitive (lock-in) detection accurately measures the amplitude of the 2f signal, which depends on both the power of the transmitted beam and the path-integrated concentration of the absorbing gas. 2f signals representing absorption of 1/100,000 of the average received laser power are detected routinely by this technique. The average value of the received laser power is measured separately and utilized to normalize the 2f signal. The resulting ratio depends only on path-integrated concentration.

The walking survey tool includes an optical transceiver (the blue handheld component shown in Figure 2) and a controller (shown with a shoulder strap in Figure 2). All of the circuitry and processing hardware required to operate the laser and implement WMS is contained on a single 6 inch square printed circuit board which draws only 1.5 W of power installed within the controller unit. The laser source is mounted on the board. The laser output light is transmitted via optical fiber to the transceiver. The transceiver transmits an eyesafe laser beam onto a topographic target (such as pavement, grass, building walls, etc.) located up to 100 ft from the operator, and receives some of the laser light reflected by the target. Using digital signal processing (DSP) technology, the controller processes the received light signal to indicate, with a sensitivity of 5 ppm-m and 10 Hz response, the presence of natural gas located between the operator and the target.

Figure 3 shows a time-trace of the sensor's output in a common leak detection scenario. The operator stood in the street in front of the home and directed the sensor output from his feet (t = 0 seconds) through the front yard (10 - 30 seconds) to the top of a hill behind the house (30 to 40 seconds, at the maximum range of 30 m), and back. There is a small leak from a buried service line in the front yard (approximately 10 m from the operator). Near 20 and 45 seconds, as the sensor scanned twice through the leak vicinity. The presence of methane diffusing from the soil is clearly indicated as a distinct rise above the background.

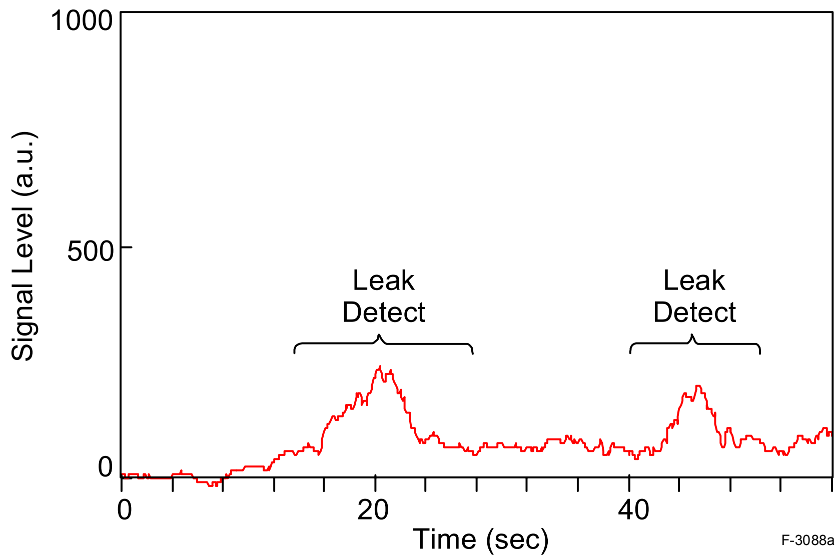

Figure 3. Time history of residential natural gas service leak detection scenario.

The data of Figure 3 provided the foundation for improvements accomplished in Task 1 of the current project. At the project onset, the sensor electronics were configured with a simple threshold alarm to alert an operator of a leak. The data of Figure 3 illustrate, however, that it is difficult to establish a simple threshold set point above which an alarm activates because methane in the ambient air contributes a background signal that may be as large as a small leak signal. As described below, developing techniques to discriminate a leak from the background was a significant achievement that lead to successful use of the RMLD during RMOTC tests and to leak surveyor acceptance of the technology.

Project Overview

The project reported herein comprised four specific and distinct tasks:

Task 1. Develop and install enhanced detection algorithms providing the speed and sensitivity needed to accommodate the scanned laser beam;

Task 2. Evaluate the feasibility of concurrently sensing ethane without significant modification of the sensor; and

Task 3. Design and demonstrate a means for scanning the laser beam and the associated detection components.

Task 4. As a supplement to the originally planned project, PSI participated in a DoE demonstration of several gas leak detection systems at the Rocky Mountain.

In the following report sections, each Task is discussed as a stand alone activity, with its own Experimental, Results and Discussion sections. An overall Conclusions section is at the end of this report.

Task 1

Objective: The purpose of this task was to identify causes of operational deficiencies in the handheld RMLD survey tool, correct the deficiencies, and implement improvements in both the handheld tool and the new Mobile survey unit.

Background: Prior to this project, the handheld survey tool was configured with a threshold alarm. In operation, the user directed the laser beam at a distant topographic target. The unit received laser light backscattered from the target and deduced the path-integrated concentration of methane (reported in units of ppm-m) between the user and the target. When the measured path-integrated concentration exceeded a user-set threshold value, an audible alarm was activated.

Early field tests of two RMLD Advanced Prototype units revealed several deficiencies that would severely limit the effectiveness of a mobile survey tool. These were:

1) When surveying a site known to have a measurable gas leak, the sensor failed to detect the leak even when receiving adequate backscattered laser light.
2) The units were designed to detect backscattered laser light from topographic targets up to 30m (100 ft) away from the transceiver. However, both units indicated that they received inadequate backscattered light from targets as close as 15 m (50 ft).
3) When the optical path is several tens of meters, the average of 2 ppm methane in ambient air activated the threshold alarm, which was typically set to activate at a path-integrated concentration of 50 ppm-m. Setting a higher threshold to preclude this condition confounded detection of small leaks.
4) Highly-reflective or fast-moving topographic scattering surfaces create occasional momentary activation of the threshold alarm due to erroneous calculation of high methane concentration. When combined with the Mobile RMLD spinning turret, this effect significantly increased noise in the concentration measurement.

Task 1 – Experimental

Accomplishments: All of the identified deficiencies were corrected by a combination of minor hardware modifications, software improvements, and changes in operational procedures. The causes of the deficiencies, means for correcting them, and results of the corrections are described next.

Task 1 – Results and Discussion

1) Inability to detect known leaks

Analysis of Cause:

For the sensor to properly detect methane, the laser wavelength must correspond to the methane spectral absorption feature. During assembly and calibration of the sensor, the laser operating parameters are adjusted to set the wavelength appropriately. In the first RMLD built, the Engineering Prototype, once the laser wavelength was set it didn't change significantly over time. However, we found that, in the Advanced Prototypes, over periods of several days the laser wavelength could drift enough to preclude methane sensing.

Modifications Implemented:

We developed a procedure for testing the laser wavelength and adjusting it as needed. For the test, the laser beam is transmitted through a significant concentration of methane, typically contained in a transparent sealed plastic bag or glass cylinder. An algorithm, implemented on a personal computer attached to the serial communications port, causes the laser wavelength to scan across limits spanning the methane spectral absorption feature. As the wavelength scans, the laser absorption signal is measured and recorded. Figure 4 illustrates the measured signal vs wavelength during a scan. Upon completion of the scan, the software identifies the wavelength corresponding to peak absorption, which is the desired operating wavelength. The algorithm then resets the laser operating parameters accordingly.

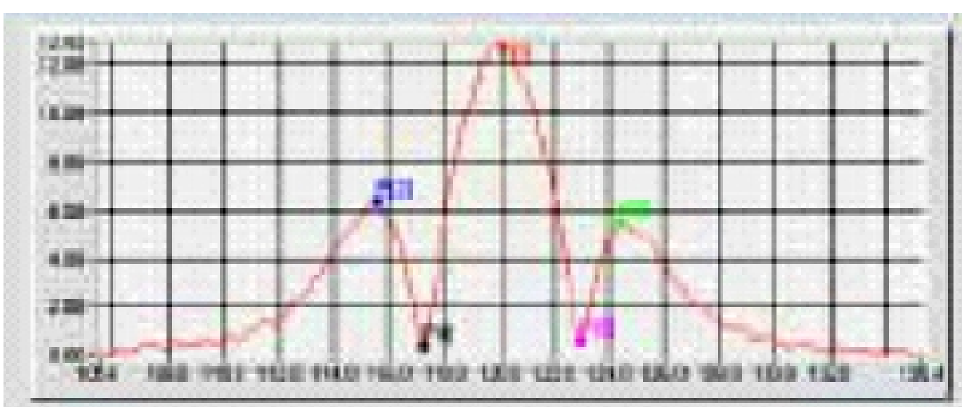

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Figure 4. Computer screen image of laser absorption signal as a function of wavelength.

2) Inadequate backscattered light

Analysis of Cause:

The sensor electronics continually measure the power scattered from the distant topographic target and collected by the transceiver optics. When the received power diminishes below a user-set threshold, the unit activates a low-signal warning and halts measurements. This intent of this action is to preclude generation of false leak detection alarms as a result of poor signal-to-noise ratio. Detailed measurement and analysis of the signal-to-noise ratio showed that the low-signal threshold was set too high. In addition, an improper optical fiber connection caused excessive noise.

Modifications implemented:

- Corrected the optical fiber connection.
- Added a numerical offset to the laser power signal. Although this offset produces a small error in the calculated methane concentration when the received power is low, it reduces the effect of electronic noise. The concentration error is acceptable for the intended use of the survey tool leak sensor rather than a highly accurate gas analyzer.
- Set the low-signal threshold at the proper value based on signal-to-noise considerations. Specifically, the threshold was set so that the sensor continues to operate until the signal is so weak that the noise causes fluctuations in the computed methane concentration that exceed the minimum specified gas sensing limit of 5 ppm-m.
- Added an automatic override of the low-signal warning when the unit senses very high methane concentrations, indicating a large leak at a distance greater than the normal operating range. This capability proved especially valuable during the RMOTC demonstration.

Improvements Achieved:

Table 1 shows the ranges from which the walking survey tool receives adequate backscattered laser power after implementing the improvements described above. For most topographic targets, the maximum range exceeds the specification value of 30 m.

Table 1. Measured Range Limits

Surface	Maximum Range (m)	Surface	Maximum Range (m)
Woodshed	41	Painted Metal Door	14
Old White Paint	35	Dirty Snow Bank	23
Brick	50+	Clean(er) Snow Bank	19
Concrete	43	Clean Asphalt	25
Stucco	46	Sand	33
Boulders	43	Sand on Asphalt	34
Tree	46	Wet Sand	14
Shrub	43	Clean Standing Water	<1
Grass (on hill)	40	Dirty Water	3
Metal Post	>39	Bag w/CH4 on Snow*	50
Wooden Stockade	55	Oblique Bag w/CH4 on Ground*	50

Figure 5 shows the signal strength and measured methane concentration during a walking survey through a site having a known leak. These data show that, outside of the leak, the rms noise in reported concentration is approximately 5 ppm-m, meeting the sensor specification. Furthermore, the noise is independent of signal strength.

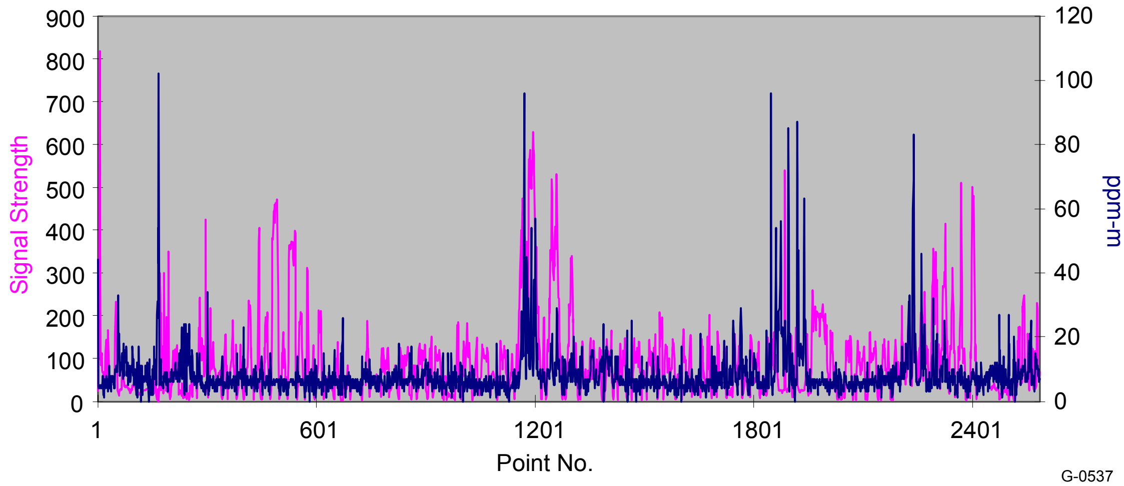

Figure 5. Calculated methane concentration (in ppm-m) and signal strength during walking survey above a leaky pipeline. Data points were recorded at a rate of 10 per second. The laser beam was aimed approximately 20 ft in front of surveyor. Variations in signal strength result from variable topography ranging from asphalt to cement to grass. Large spikes in ppm-m indicate methane plumes.

3) Effects of Ambient Methane

Analysis of Problem:

Ambient air is known to contain methane at concentrations averaging about 2 ppm. When the laser beam strikes a target 25 m distant, the ambient methane contributes a signal of nominally 50 ppm-m, ten times the minimum detection limit. Use of a simple threshold alarm makes it difficult to detect small leaks at a distance, thus limiting the sensor efficacy.

Modifications Implemented:

Because a surveyor does not aim at a fixed location, but continually scans across an area, leak plumes create temporally fluctuating concentration signals as shown in Figure 3. In contrast, the path-integrated ambient methane concentration, which changes with distance to the topographic target, varies relatively slowly. Therefore, rapid fluctuations in methane concentration indicate a leak.

To facilitate the surveyor's detection of rapid fluctuations, we created an audio signal that has a pitch that increases with concentration. Thus, rather than a threshold alarm, the sound emitted by the sensor changes as concentration changes. A surveyor, with a few hours of training, is able to recognize the rapid pitch variations associated with gas leak plumes.

Results Obtained:

This algorithm enabled trained operators to detect leaks with modified sensor electronics as easily as with a traditional flame ionization unit. The algorithm was employed during the RMOTC demonstration. Results of that demonstration are described later in this report.

4) False Alarms

Analysis of Cause:

The concentration measurement algorithm employs two measurements derived from the received laser signal. One measurement, called f1, is proportional to the received laser power, while the second measurement, called f2, is proportional to the product of the received laser power multiplied by the methane concentration. The reported methane concentration is deduced from the ratio f2/f1. Prior to this project, both measurements were collected and averaged for periods of 100 ms prior to computing their ratio. When, during the averaging period, both the concentration and the received power vary significantly, then the ratio of their average values differs from the average of their instantaneous ratios, thus creating an erroneous concentration output.

Modification Implemented:

The data processing algorithm was modified so that f2/f1 is averaged for 10 ms, rather than 100 ms.

Results Obtained:

The algorithm was tested using the Mobile RMLD (MRMLD) spinning turret. Data are presented later in this report showing that, with the new algorithm, the concentration noise in the MRMLD was less than the 5 ppm-m noise level experienced with the handheld sensor prior to implementing the algorithm.

Task 2

Objective: The purpose of this task was to evaluate the feasibility of measuring both ethane and methane components of natural gas using the single laser source in the survey tool. Since ethane is a minor (~2%) component of natural gas but not present in ambient air or other natural sources, sensing it in addition to methane could help distinguish pipeline leaks from biogenic methane.

Background: The sensor detects methane via laser absorption at a wavelength near 1653 nm. It is possible to tune the laser to any wavelength within the range of approximately 1651 nm through 1655 nm. If ethane presents, within this range, spectral absorption features of sufficient strength, then an algorithm could be developed enabling sensing of both ethane and methane without additional hardware.

Task 2 – Experimental

PSI obtained empirical measurements, obtained via FTIR, of the ethane spectrum in the target wavelength range. The data were obtained by Dr. Chris Brown of the University of Rhode Island, and provided to PSI via private communication. Figure 6 shows the ethane absorption for transmission through a path-integrated ethane concentration of 0.2 atm-m (200,000 ppm-m) as a function of wavelength.

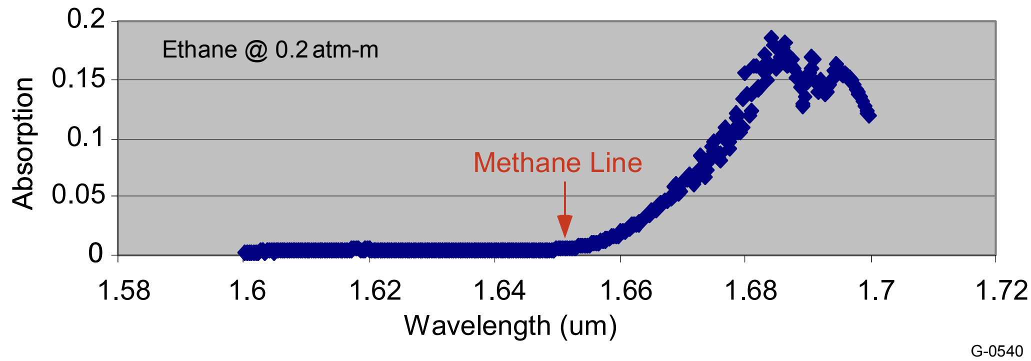

Figure 6. Ethane absorption spectrum. Each diamond represents the position and strength of an absorption line.

Task 2 – Results and Discussion

Although ethane offers several absorption lines in the range accessible by the methane laser, these lines are very weak. To detect the 2% ethane in a 5 ppm-m methane plume requires a capability of sensing 0.1 ppm-m of ethane. This concentration of ethane will yield an absorption of about 10^{-8}, roughly three orders of magnitude smaller than the RMLD detection capability. Based on these data, we suspended further consideration of ethane measurement.

Task 3

Background and Motivation: In October 2002, Physical Sciences Inc. convened a meeting of several sponsors and users of the RMLD. The purpose of the meeting was to identify modes of using the RMLD platform, or extending its capabilities, beyond the handheld leak surveying application for which it was designed. Participants in this user's group included: Graham Midgley, Heath Consultants; George Ragula, PSE&G; Angelo Fabiano, New York Gas Group; Allen Peterson, NYSEG; and Bob Naper, Keyspan Energy. This group recognized the need for a van-mounted mobile system able to scan a street from curb-to-curb and onto sidewalks, as illustrated by Figure 1.

Objectives and Accomplishments: 1) To better describe the vision for a Mobile RMLD product, we created a Preliminary Specification Document; 2) To demonstrate the feasibility of developing the Mobile RMLD sensor described in the Preliminary Specification, we built and tested a breadboard prototype mounted first on a rolling cart and subsequently on a truck.

<u>Task 3 – Specification</u>

The Mobile RMLD Preliminary Specification Document is reproduced here:

1.0 INTRODUCTION

This document describes a mobile laser-based methane detector being developed by Physical Sciences Inc. in conjunction with the US Department of Energy National Energy Technology Laboratory (NETL) and Heath Consultants Inc. The document provides preliminary specifications that will guide the instrument development and testing process, and will serve as a basis for ongoing discussions about the technology among the development team members. It may be modified or refined as the technology development progresses. In its final form this document may be used in conveying to potential customers information that describes the instrument's operating principles, the performance that can be expected, interfaces with other equipment and the operator, and installation requirements. Engineering details of how the instrument meets these specifications are <u>not</u> provided here.

The development program is currently entering a feasibility demonstration phase. This document provides requirements for a laboratory prototype intended to demonstrate the feasibility of using the PSI/Heath Remote Methane Leak Detector (RMLD) in conjunction with a rotating mirror, all mounted on a moving vehicle, to scan the area ahead of the vehicle and map natural gas leaks.

2.0 PRODUCT DESCRIPTION

The RMLD is an optical tool, based on the established spectroscopic measurement technology known as Tunable Diode Laser Absorption Spectroscopy or TDLAS. The tool illuminates a distant surface with laser light, measures the amount of methane along the line of sight transited by the laser beam, and alarms when the methane amount exceeds a preset threshold. Unlike other types of portable gas detectors, this laser-based device does not need to be immersed within the gas leak.

3.0 APPLICATIONS

Municipal natural gas pipeline leak surveying is the principal application for the detector. Natural gas local distribution companies (LDCs) continually survey gas pipelines to detect small leaks and correct them before becoming dangerous. These surveys are conducted either by LDC in-house leak survey teams or by professional survey service companies, who would be the end-user customers for the product.

LDC service pipelines include primarily the main and the secondary lines which branch off the mains to provide individual service. Routine annual, tri-annual, or five-year surveys are scheduled for each pipe segment. However, in many instances, mains are made of cast iron. In most mid- to northern-latitude regions, these pipeline sections must be inspected every one to two weeks throughout the winter. This is a heavy survey burden requirement often requiring supplemental seasonal staff.

Currently, the leak surveying process is labor intensive, requiring an individual to either drive or walk over every buried natural gas pipe. Hand-held flame-ionization detectors (FIDs) sense any leaking gas. The RMLD is intended to replace FID's with laser-based devices that can rapidly survey off-road pipelines, such as those extending from roads to homes, has great appeal. The laser beam would be projected from the road above the path of the pipeline to the home, and indicate the presence or absence of gas. If no gas is detected, the survey progresses to the next site. If gas is detected, the survey crew would then walk the length of the pipe to localize the leak.

The mobile RMLD will be fixed on a survey truck, and will be utilized to map gas leaks from pipes buried beneath the road. A rotating turret on the truck, housing several mirrors, will cause the RMLD to scan an area ahead and to each side of the vehicle while the vehicle is moving. A computer on-board the vehicle will record data.

4.0 PERFORMANCE SPECIFICATIONS AND KEY FEATURES

4.1	Optical Path	Scans 90 degree arc 10 m ahead of vehicle
4.2	Spatial Resolution	1 meter in forward and transverse directions
4.3	Forward Velocity	10 – 20 m/s
4.4	Measurement Ranges	0 - 1000 ppm-m
4.5	Sensitivity	5 ppm-m
4.6	Accuracy	± (20% of reading or minimum sensitivity, whichever is greater)
4.7	Response Time	0.01 s
4.8	Power Requirements	12 Vdc
4.9	Size and Weight	Vehicle Mounted - TBD
4.10	Calibration and Fault Monitoring	Optics provide a means for either continuous or periodic insertion into the measurement path of a sealed calibration cell containing a known concentration of methane. Software then automatically checks calibration. A significant calibration change generates a fault condition.
	Frequency	As required by user.

5.0 OPERATING ENVIRONMENT

5.1	Location	Outdoors in municipal or industrial settings
5.2	Hazardous Area Classification	Intended for use in general purpose, non-hazardous environments.
5.3	Ambient Conditions:	

- Temperature: -20° to +120°F
- Humidity: 0 - 100% RH, condensing
- Wind: 0 - 50 mph

6.0 HOUSING AND MARKINGS

6.1	Enclosure and Shock Protection	Components are enclosed in a rigid plastic housing, including a plastic window for laser beam transmission and reception. Components are attached to housing via shock absorbing materials to protect from 3 foot drops.

6.2	Servicing	Housings permit accessibility to internal components.
6.3	Markings	All housings indicate on permanent exterior markings: manufacturer, make and model number, serial number, date of manufacture, and all warnings.

7.0 INTERFACES

7.1	Diagnostic Interface	Multi-conductor cable connection accessible to service personnel for monitoring internal signals. Accessible only upon by opening housing.
7.2	Digital Interfaces	One serial data port. RS-232 format.
7.3	Concentration Gauges	One visual concentration gauge. One audible signal with frequency proportional to concentration. One Flashing red LED with flash frequency proportional to concentration. Alphanumeric readout or LED visual gauge of concentration in ppm-m.
7.4	Fault Indicator	Flashing yellow LED. Activated when any monitored system parameter falls out of acceptable range.
7.5	Buttons	For zeroing and calibration.
7.6	Low-Signal Indicator	
7.7	Linelock Indicator	
7.8	Low Battery Indicator	
7.9	Ready Indicator	

8.0 QUALITY ASSURANCE

8.1	Standards	All design, components, workmanship, and documentation shall conform to standard industrial practice for high-quality instrumentation used in petrochemical plants.
8.2	Component Level Testing	TBD
8.3	Functional Test	Factory check before delivery to assure compliance with functional test specifications.
8.4	Engineering Documentation	Functional Specification Theory of Operation Sequence of Operation Manufacturing Test Plan Mechanical Assembly Drawings Mechanical Control Drawings Bill of Materials PWB Drawing Packages: Board Outline, Board Fab, Assy; Electrical

		Schematics ROM Object File Installation and Test Manual
8.5	Software	Requirements Document Top Level Design Description Hardware/Software Interface Description Code Listings
8.6	User Documentation	Operations and Maintenance Manual Recommended Spare Parts
8.7	User Training	TBD

Task 3 – Experimental

Benchtop Prototype Design and Assembly

PSI engineers designed and built a benchtop MRMLD unit, utilizing a handheld sensor platform and a battery-powered spinning mirror, to simulate a configuration that would be mounted on a van as illustrated by Figure 1. This, of course, is not a perfect simulation of a MRMLD product, as the spinning mirror causes the RMLD laser beam to trace a full circle around the vehicle rather than repetitively scanning a 90 degree arc in front of the vehicle. Although repetitive scanning can be achieved by replacing the single tilted mirror with a more complex segmented mirror (and may be a task to be pursued in future efforts), the relatively simple single mirror provided the data needed to evaluate feasibility of the concept.

Figure 7 illustrates the configuration of the MRMLD prototype. A 12 Vdc motor powers the spinning mirror. We chose the motor for its ability to operate from an automotive power supply while providing enough torque to spin the mirror at a constant speed despite wind resistance. Via a rubber belt, the motor turns a spindle supported by a ball bearing assembly. The motor and bearing reside on the top of the mounting platform, as shown in Figure 7, while the drive belt and pulleys are below the plate. We chose pulley diameter ratios to yield a mirror spin rate of 120 turns per minute

Just below the pulleys are mirror support connector pieces and the mirror itself. The mirror is an industrial quality first surface aluminized 4.5 inch x 6.0 inch flat mirror. The mirror tilt relative to horizontal is 31.7 degrees. The laser beam, transmitted vertically from the RMLD transceiver, reflects from the mirror at an angle of 63.4 degrees relative to the vertical. We chose this angle to support tests of the unit mounted on a rolling cart. When the mirror is 5 feet above ground, the transmitted laser beam, after reflection from the mirror, strikes the ground 10 feet horizontally from the mirror. As the mirror spins at 120 rpm, the transmitted laser beam scans a 10 ft radius circle. Thus, the beam traverses the ground at 125 ft/s.

Note that the assembled unit pictured in Figure 7 has a black shroud surrounding much of the open area. This shroud blocks the laser beam during 270 degrees of its sweep, thus exposing only 90 degrees of the ground to the RMLD beam. We installed this shroud to better simulate the anticipated use of the MRMLD, allowing it to sense methane only in the open 90 degree arc.

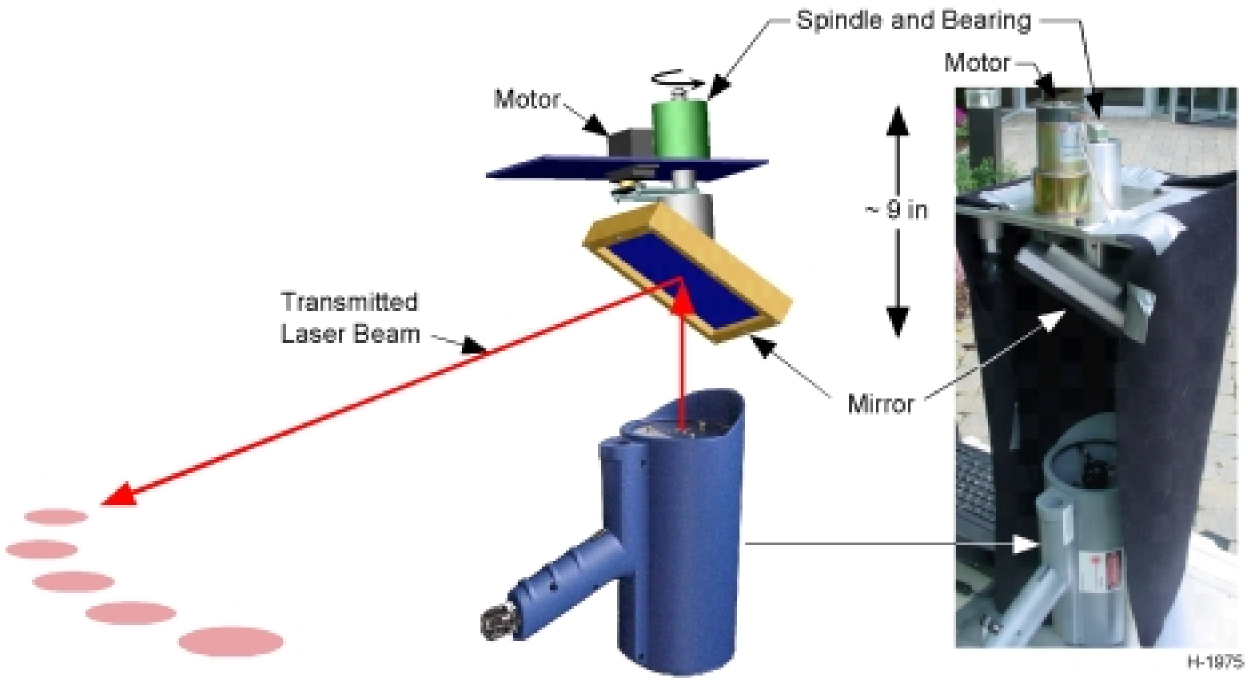

Figure 7. Prototype mobile RMLD configuration. Left: Design drawing. Right: Assembled unit mounted on a cart.

Benchtop Prototype Evaluation Procedures

To characterize the MRMLD benchtop prototype unit's performance, we initially mounted it on a cart and rolled it past a simulated methane leak. Figure 8 shows pictures of the device mounted on the cart and on the roof of a vehicle. Data output from the unit were recorded on a portable computer at a rate of 10 points per second. A 12 V battery powered the system.

Figure 8. Prototype mobile RMLD photographs.

We initially evaluated the sensitivity of the MRMLD in an outdoor test with a controlled methane leak. Methane from a tank was set to flow at a rate of 2 scfh (57 l/hr). We manually pushed the MRMLD past the region of this leak while recording the concentration output.

In a privately-funded follow-on activity, we mounted the MRMLD unit in the cargo component of a box truck with its beam directed out of the back. Again, a simulated leak site was created from a tank of methane. Concentration data were recorded as the truck drove past the leak at various speeds. Figure 9 pictures the sensor and leak configurations.

Figure 9. Configuration of MRMLD in the back of a box truck, and photograph of leak site.

Task 3 – Results and Discussion

Figure 10 shows an example of data recorded with the Benchtop prototype MRMLD mounted on the cart. Prior to entering the leak area, the unit detects only ambient methane of about 4 ppm-m with an rms noise of about 1 ppm-m. ***This noise level is comparable to that of the handheld sensor and is meets the requirements for the MRMLD mission.*** Upon entering the leak area, approximately 6 seconds after the start of data acquisition, a spike in concentration output occurs each time the spinning mirror directs the laser beam at the gas plume. The spikes increase in amplitude as the cart passes close to the center of the plume.

Figure 11 shows data acquired from the back of the truck with the methane leak rate set at 100 l/h. We note that these data were acquired with the spinning mirror de-activated. These data provided guidance for the preferred means of using the RMLD at the RMOTC demonstration, described in Task 4 below.

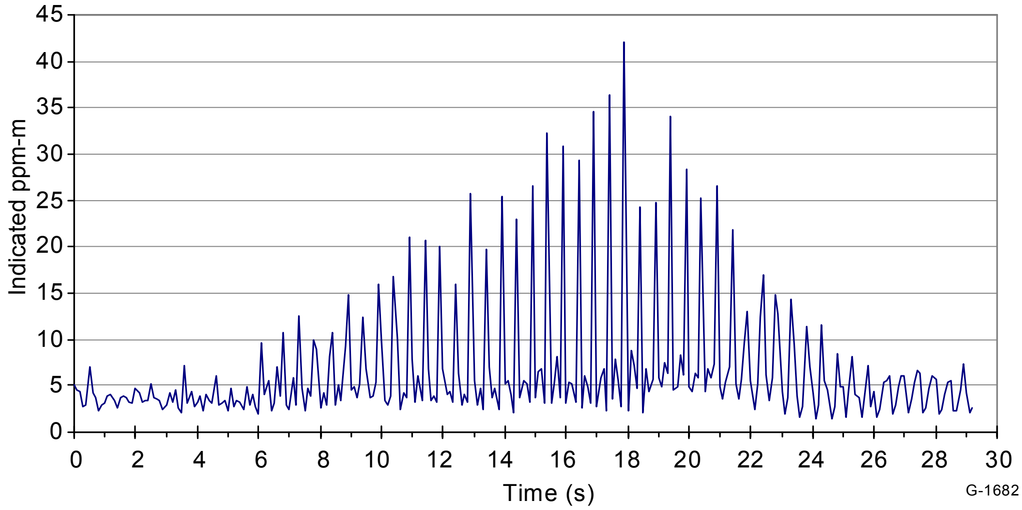

Figure 10. Concentration recorded by cart-mounted MRMLD when moving past a 2 scfm leak.

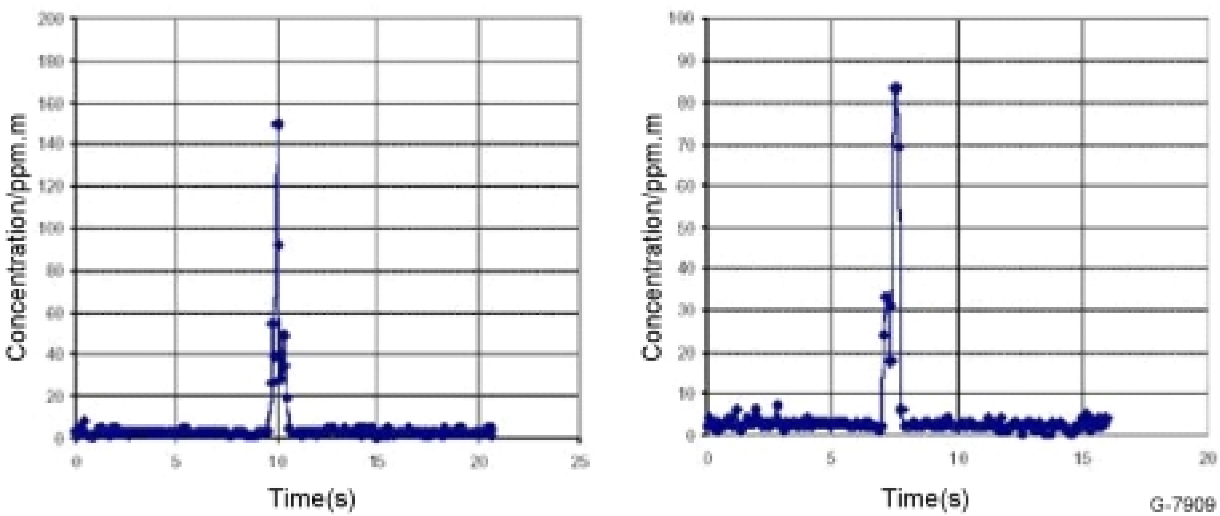

Figure 11. Concentration data obtained while driving past the leak of Figure 9. Left: Speed = 10 km/hr. Right: Speed = 20 km/hr

The data of Figures 10 and 11 illustrate that the combination of the spinning mirror hardware and the high-speed data acquisition algorithms developed in Task 1 enable successful gas leak detection from a moving platform. In both cases, the RMLD laser beam scanned the ground at a speed comparable to the speed that would be encountered with the MRMLD unit mounted and operated as illustrated by Figure 1. The gas flow rates in these evaluations were comparable to those that leak surveyors would need to sense when using the sensor in a municipal setting. Thus, we have achieved our objective of demonstrating the technical feasibility of developing a Mobile RMLD. However, as described in the Conclusion to this report, much work remains to develop procedures for using this sensor in a complex municipal setting.

Task 4

Objective: During the week of September 13, 2004, PSI and our cost-sharing partner Heath Consultants participated in a NETL-sponsored demonstration of several mobile and airborne leak detection systems under development. The demonstration was intended to evaluate the efficacy of these systems for locating leaks from gas distribution pipelines. This demonstration involved locating leaks that were up to several hundred feet from the road on which PSI could travel. The survey route was 7.4 miles long and followed a simulated gas transmission pipeline. Gas leaks were manually created at several locations along the simulated pipeline route. Our job was to find the leaks.

Task 4 – Experimental

To optimize the likelihood of successful detection, PSI deployed a handheld RMLD equipped with the high-speed data acquisition software and variable-pitch audio algorithm developed in Task 1 of this project. These algorithms were very successful at aiding the user to identify possible leaks while driving past them at approximately 10 mph. The surveyor simply aimed the RMLD out of the rear window of a Chevy Suburban truck towards the region where a leak might occur. When the audio indicated a possible leak, a more detailed survey of the area with the vehicle stopped enabled leak verification and location.

During these tests, data were acquired with the surveyor sitting in the rear set of the vehicle looking sideward, viewing the terrain at the limit of handheld sensor range (about 100 feet) through the open rear windows. We used the audio tone as a rapid indicator of methane cloud detection. We also recorded numerous instrument performance indicators, returned signal levels and the detected concentration on a laptop computer in the front seat of the vehicle. Also operational in the vehicle was a GPS unit (Garmin Etrex, WAAS enabled) connected to a second laptop running a DeLorme topographical mapping software program. The Virtual Pipeline route, markers and road crossings were inserted into this display prior to the RMOTC testing. An example of a map created for the RMOTC tests is shown in Figure 12. These tools permitted the survey vehicle location to be instantaneously displayed with respect to the pipeline and a track of the entire driven route to be shown. When a leak was detected, a compact laser rangefinder (Bushnell Yardage Pro Sport Rangefinder) was used to estimate the range to the leak. The location of the survey vehicle when a leak was observed was entered onto the GPS map. We entered the detected leaks onto the test form provided each day, making note of the relative wind direction, magnitude of leak and other salient characteristics.

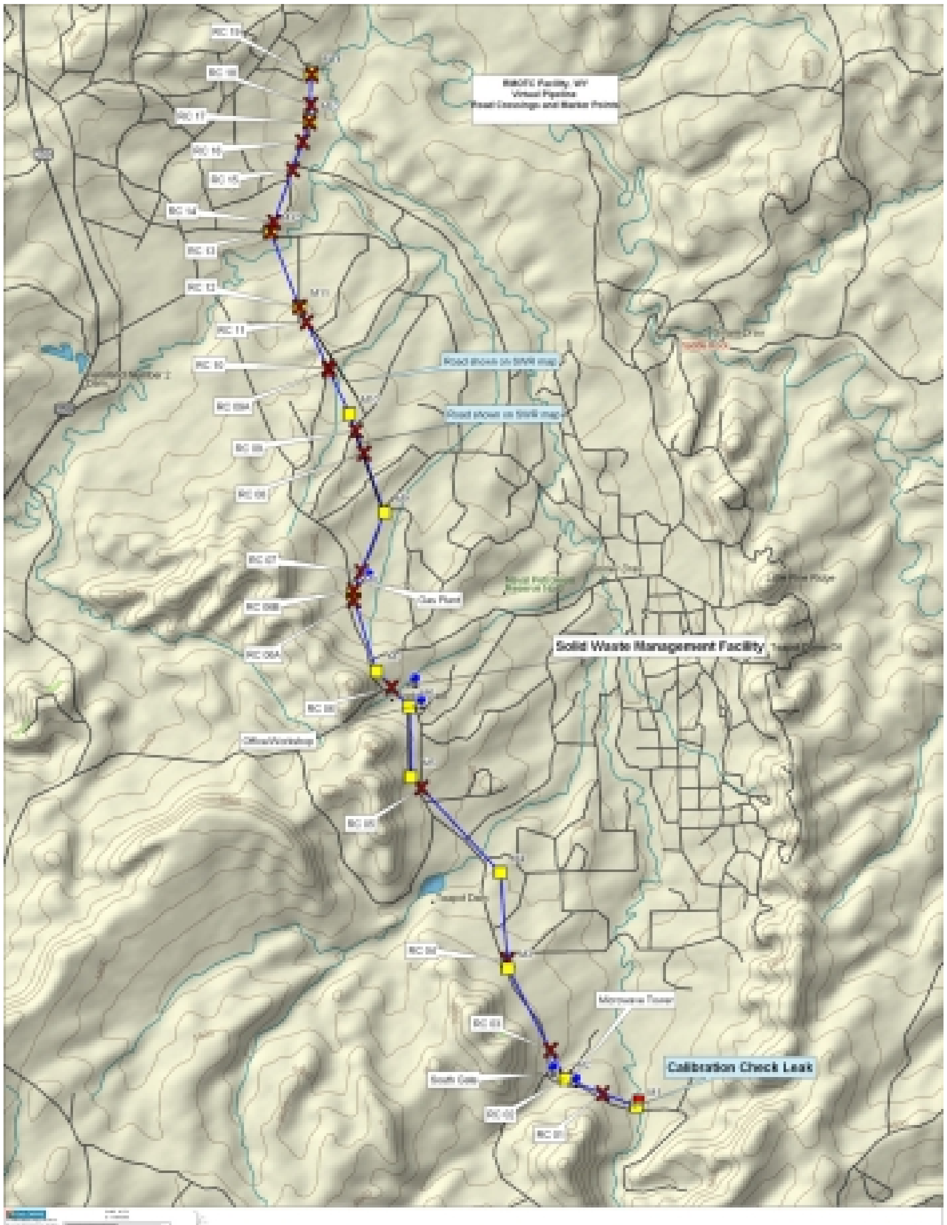

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Figure 12. Virtual pipeline course on topographic map with markers, crossings and roads indicated.

Task 4 – Results and Discussion

Data Acquired

PSI participated in morning and afternoon tests Monday through Thursday, always traveling the same route shown in Figure 13. The data from each day are documented below in the forms of tables that list the leaks detected during each run, plots of methane concentration versus time for each run, and topo maps with Virtual Pipeline and markers indicated along with the detected leaks. The leaks are indicated as on the road, but the notes would permit more accurate location. Figure 22 is an expanded view of an area where two leaks were detected. These were easily resolved in our ground operations.

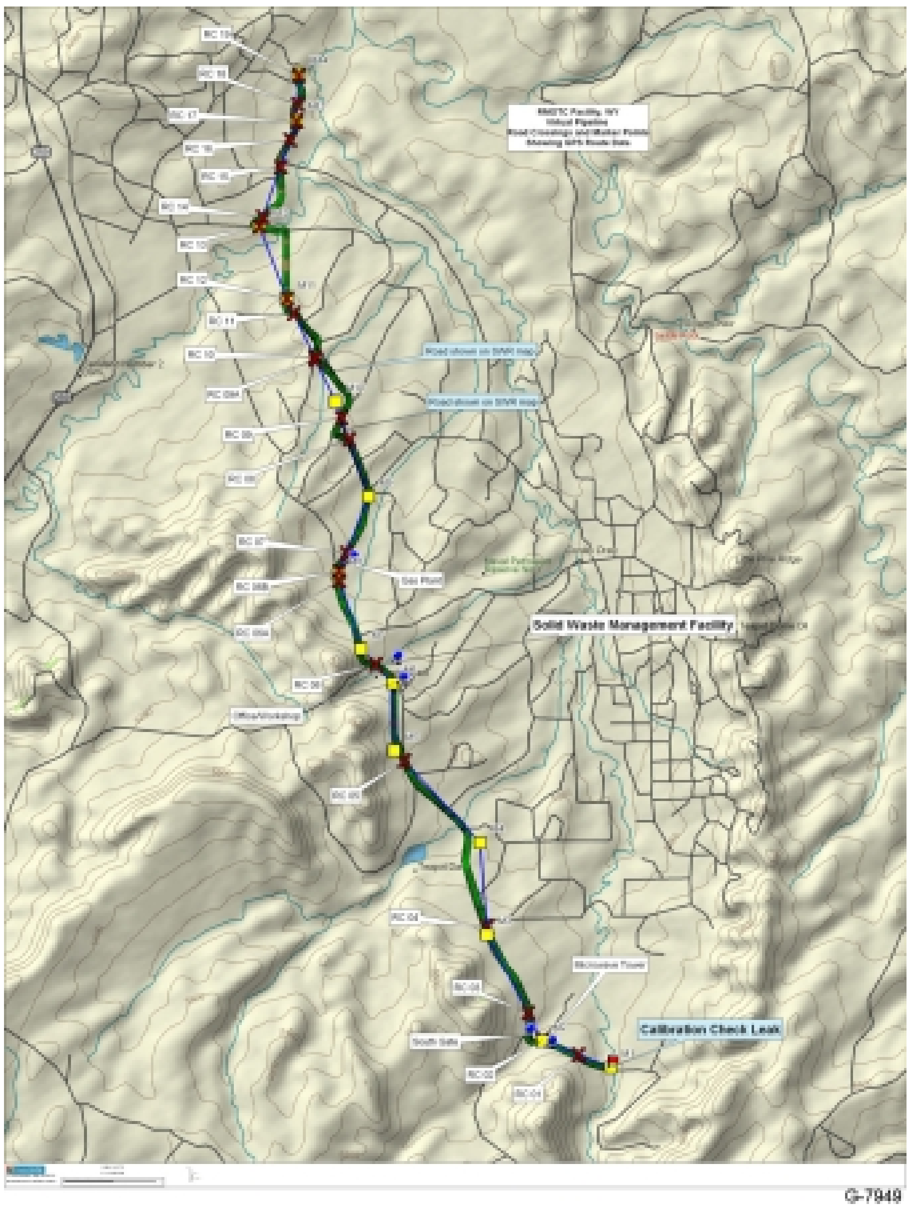


Figure 13. Topographical map as in Figure 12 with path traveled during testing shown in green.

Monday, September 13

Table 2. Enhanced Methane Positions September 13 AM

Time	NAD 27 GPS Latitude (DD MM SS.S)	NAD 27 GPS Longitude (DD MM SS.S)	Assessment of Leak	Comments
9:47 a.m.	N 43 14 53.3	W 106 11 10.92	Easy to find	5,000' SCFH calibration leak test run
10:05 a.m.	N 43 16 14.88	W 106 12 19.57	Large	
10.25 a.m.	N 43 17 7.67	W 106 12 55.23	Large	
10:31 a.m.	N 43 17 44.2	W 106 13 16.7	Large	
10:41 a.m.	N 43 18 13.8	W 106 13 5.5	Relatively small	
10:43 a.m.	N 43 18 56.41	W 106 13 28.19	May be plume from previous	
11:04 a.m.	N 43 20 12.29	W 106 13 37.47	Relatively small	
11:10 a.m.	Done			

Table 3. Enhanced Methane Positions September 13 PM

Time	NAD 27 GPS Latitude (DD MM SS.S)	NAD 27 GPS Longitude (DD MM SS.S)	Assessment of Leak	Comments
4:00 p.m.	N 43 14 53.18	W 106 11 12.24	Large	5,000' SCFH calibration leak Wind from NW
4:15 p.m.	N 43 16 15.26	W 106 12 20.04	Narrow	60' E. of road Wind from W.
4:33 p.m.	N 43 17 44.11	W 106 13 16.70	Relatively small leak	20' E. of road Gusty low wind from NW
4:43 p.m.	N 43 18 13.00	W 106 13 5.32	Large leak 1st seen 200' back south of leak	60' NW of road Gusty wind from NW
4:55 p.m.	N 43 18 55.70	W 106 13 28.55	Small leak Wind blowing leak downstream	90' NW of Road Gusty wind from NW
5:16 p.m.	N 43 20 12.12	W 106 13 37.64	Small leak Wind blowing leak downstream	60' NW of Road Mild gusty wind from NW
5:27 p.m.	Done			

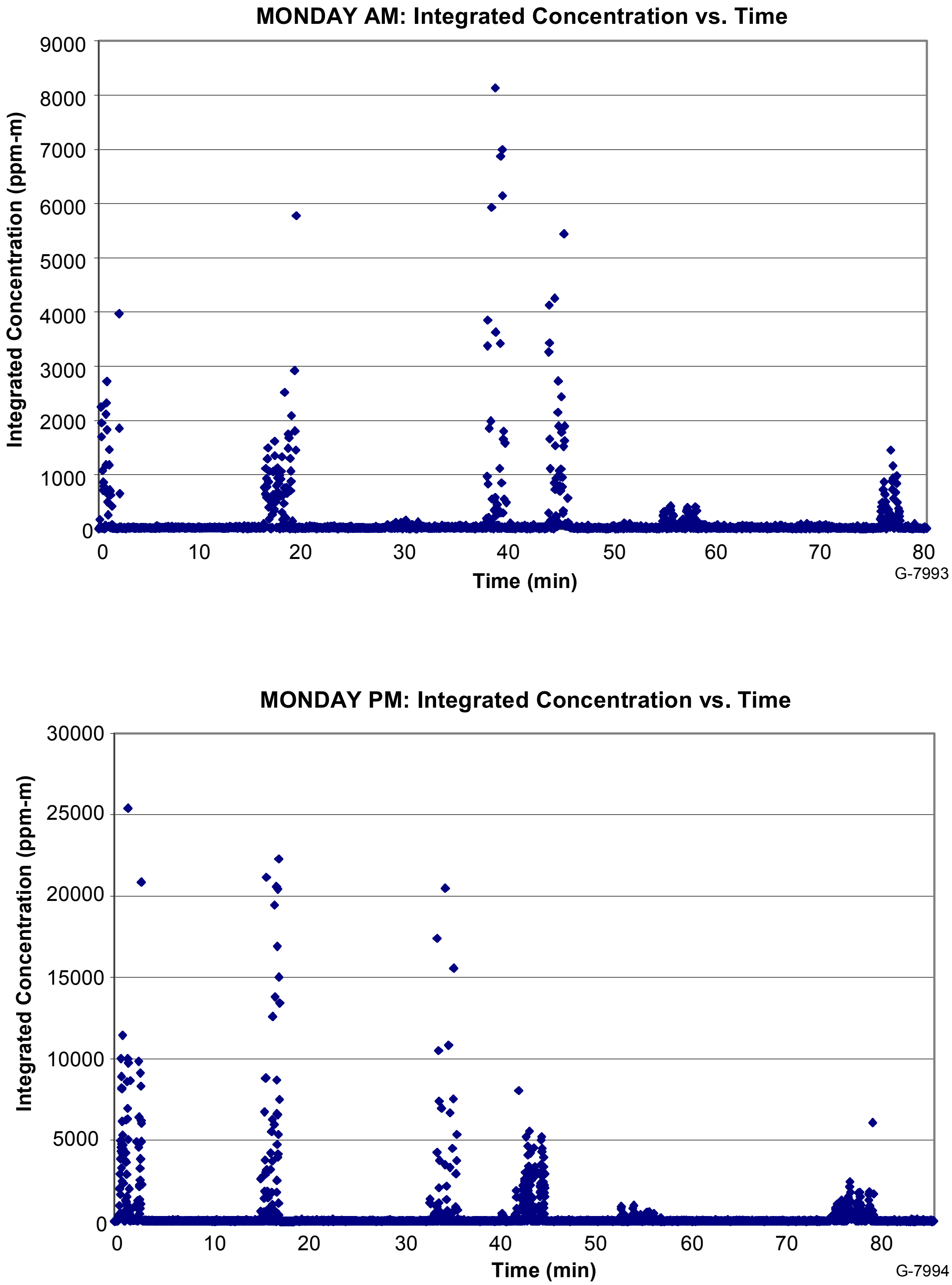


Figure 14. Path integrated concentration versus time for September 13.

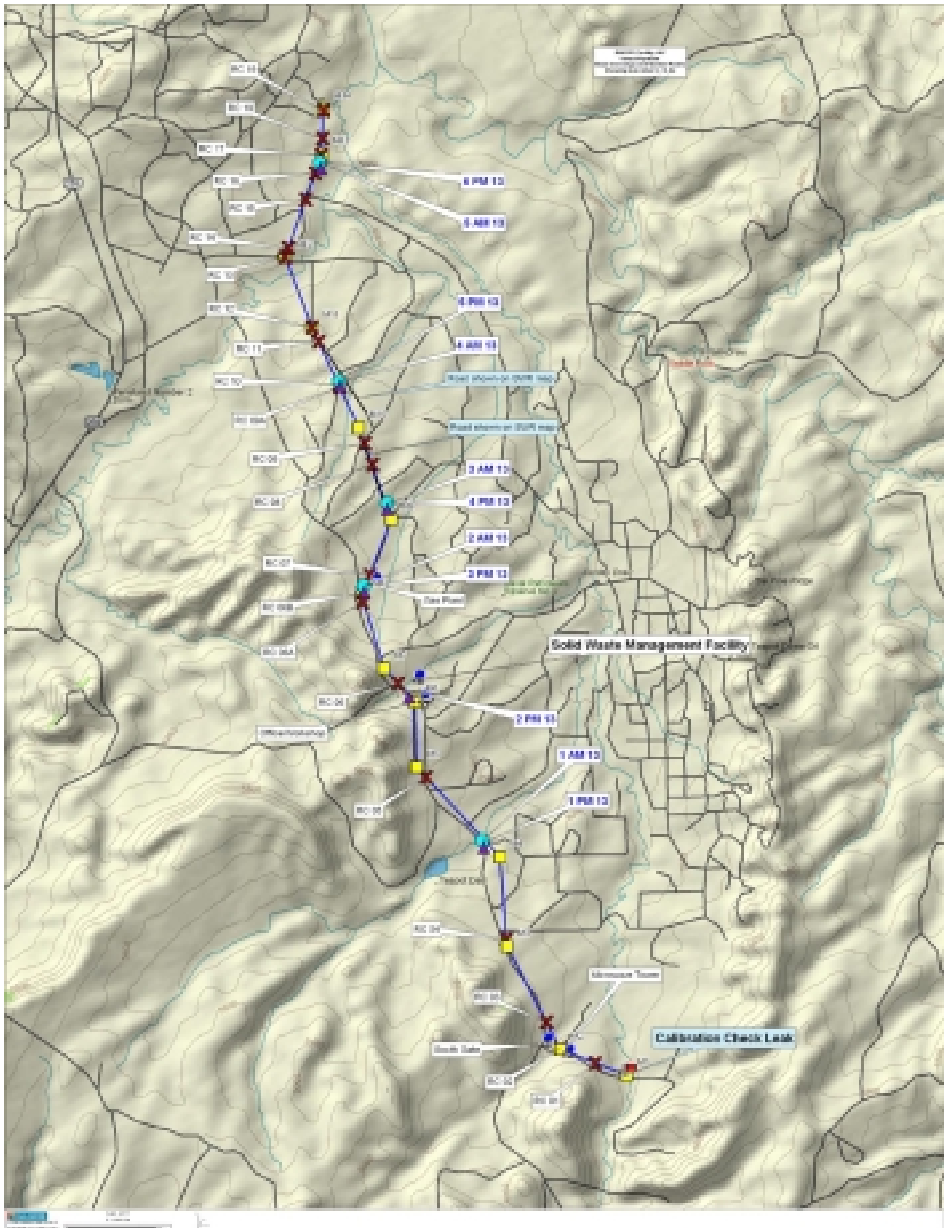


Figure 15. Positions of survey vehicle when enhanced methane was observed on Monday, September 13, ● AM, ▲PM.

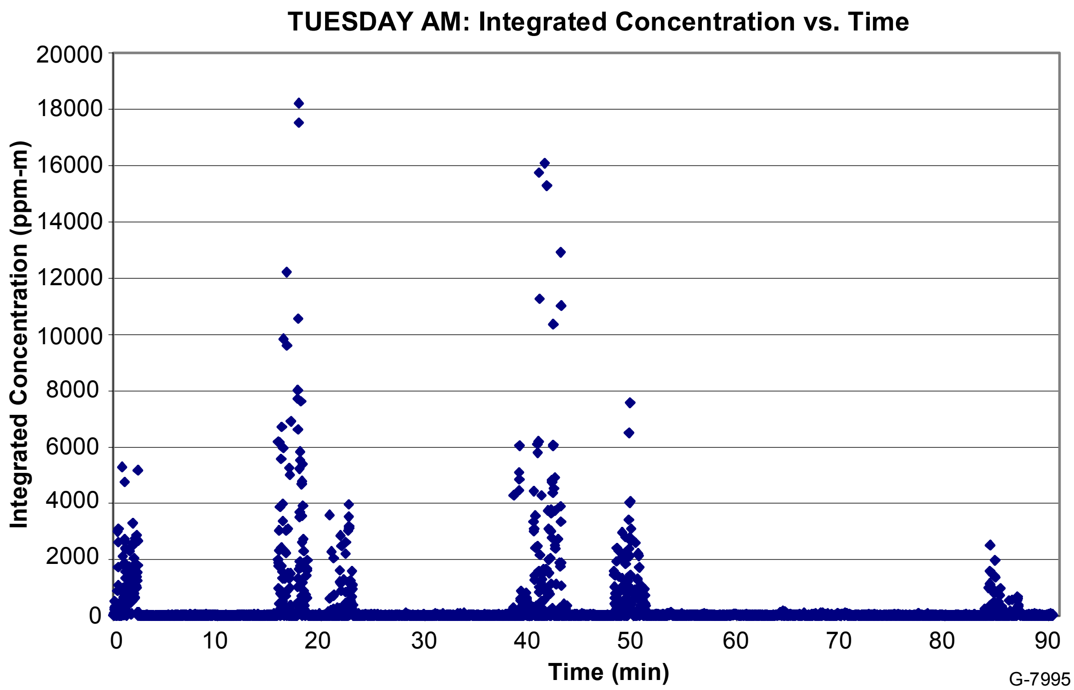
TUESDAY, September 14

Table 4. Enhanced Methane Positions September 14 AM

Time	NAD 27 GPS Latitude (DD MM SS.S)	NAD 27 GPS Longitude (DD MM SS.S)	Assessment of Leak	Comments
10:40 a.m.	N 43 14 53.04	W 106 11 12.12	Large leak	1,000' SCFH Calibration leak
10:56 a.m.	N 43 16 15.38	W 106 12 20.13	15' wide leak	45' east of road 25 mph from SW
11:00 a.m.	N 43 16 19.37	W 106 12 25.34	Small, but at limit of test range Low vertical angle	60' NE of road 25 mph from SW
11:18 a.m.	N 43 17 44.26	W 106 13 16.81	More localized 200'+ downwind	50' NNE of road Gusts from SW
11:28 a.m.	N 43 18 13.52	W 106 13 5.45	Wide leak Wind carried?	30-75' probably dispersed by wind Gusty from SW
11:34 a.m.	N 43 18 26.39	W 106 13 12.91	Potential prior leak – see 11:28 entry	Gusty from SW
11:45 a.m.	N 43 18 56.10 (.56)	W 106 13 28.40 (.14)	Small Leak Intermittent also seen downwind 120 ppm at 300'	100' W from road 120' gusty from SW light rain
12:03	N 43 20 12.16	W 106 13 37.44	Narrow plume also downwind 300 ft.	60' NW of road Gusty from SW
12:08	Done			

Table 5. Enhanced Methane Positions September 14 PM

Time	NAD 27 GPS Latitude (DD MM SS.S)	NAD 27 GPS Longitude (DD MM SS.S)	Assessment of Leak	Comments
5:31 p.m.	N 43 14 53.15	W 106 11 12.44	Large leak	1,000' SCFH calibration leak
5:52 p.m.	N 43 16 14.96	W 106 12 19.56	Large leak	50' NE of road Wind from W.
5:56 p.m.	N 43 16 19.22	W 106 12 25.15	Large leak	80' NE of road off bushes - wind from W.
6:18 p.m.	N 43 17 38.42	W 106 13 17.39	Possible intermittent	70' E of road Near Gas Plant Wind N-NW
6:21 p.m.	N 43 17 44.29	W 106 13 16.66	Easy too see & constant	70' E of road Wind from N – NW
6:31 p.m.	N 43 18 13.20	W 106 13 5.35	Large leak Also seen 300' downwind	75' W of road Wind out of N
6:56 p.m.	N 43 20 12.13	W 106 13 37.67	Large + 75' downwind	55' NW of road Wind from N-NE
7:02 p.m.	Done			



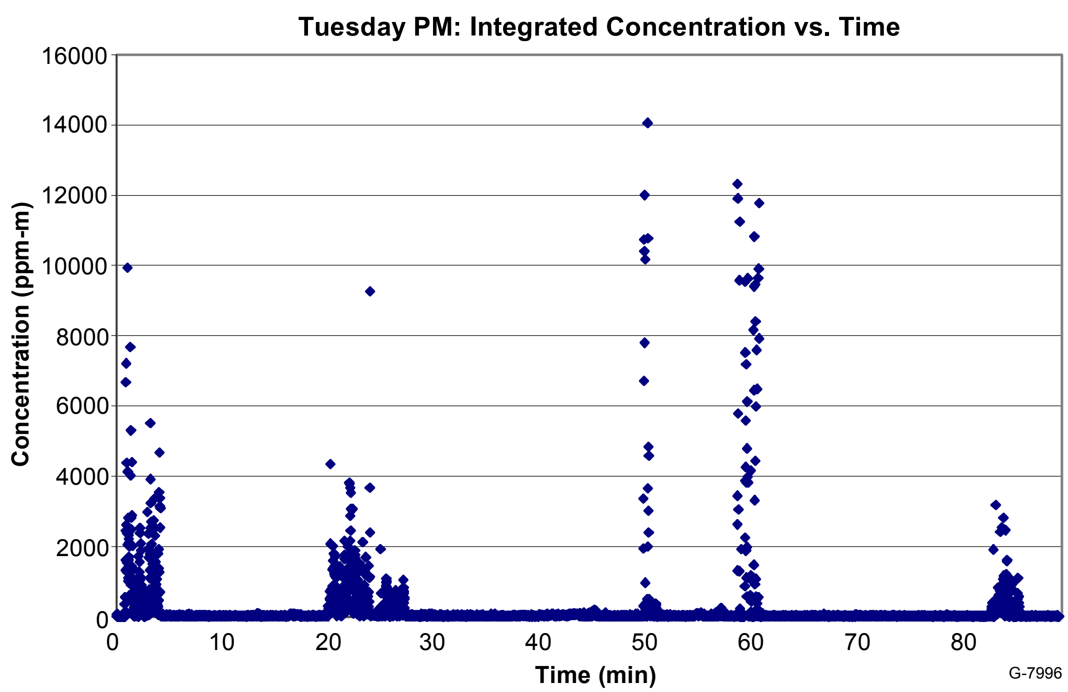


Figure 16. Path-integrated concentrations versus time for September 14.

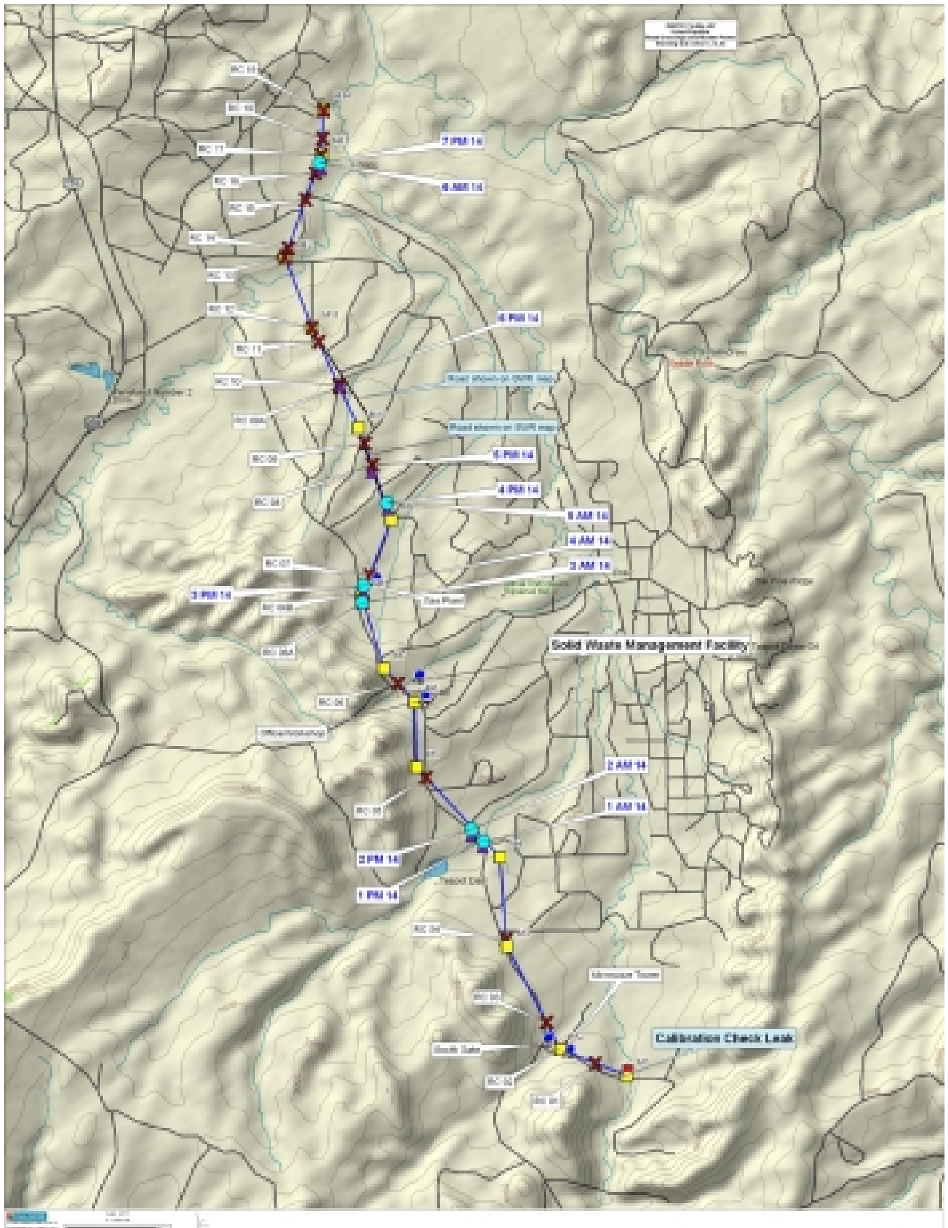


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Figure 17. Positions of survey vehicle when enhanced methane was observed on Tuesday, September 14, ● AM, ▲PM.

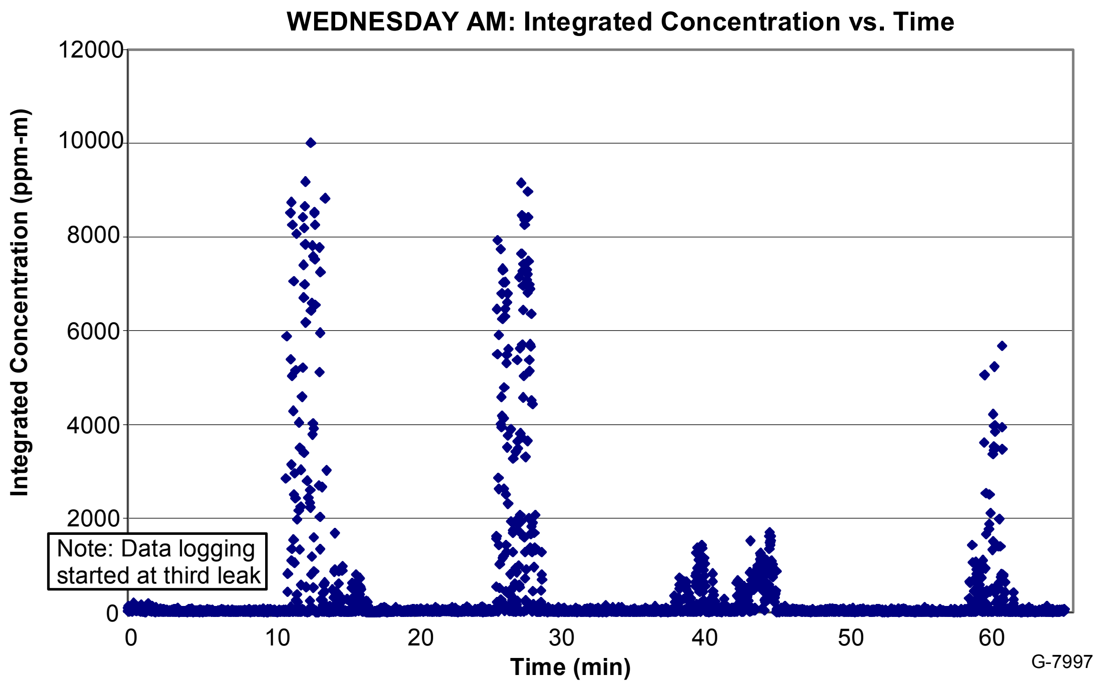
WEDNESDAY, September 15

Table 6. Enhanced Methane Positions September 15 AM

Time	NAD 27 GPS Latitude (DD MM SS.S)	NAD 27 GPS Longitude (DD MM SS.S)	Assessment of Leak	Comments
7:59 a.m.	N 43 14 53.18	W 106 11 12.38	Smaller than prior days 4,000-8,000 ppm-m	500 SCFH calibration leak 50' N of road
8:17 a.m.	N 43 16 15.41	W 106 12 20.03	Smaller than prior 2,000-3,000 ppm-m	33' NE of road Gusty wind from SE
8:22 a.m.	N 43 16 19.48	W 106 12.25.54	Lower level 1,500 – 2,500 ppm-m disbursed over 100'	80' NNE of road Constant from SE
8:33 a.m.	N 43 17 2.59	W 106 12 51.49	Low level 100-300 ppm-m	60' W of Road Gusty from SE
8:45 a.m.	N 43 17 44.33	W 106 13 16.63	Large leak 7,000-9,500 900 ppm-m on downwind 80 yards from leak 300 ppm-m @ 112 yards from leak 0 @ RC 07	40' NE of road Gusty from SE
Just beyond M9 (100') low level just above noise possible wind carried from prior leak				
9:00 a.m.	N 43 18 13.11	W106 13 5.36	Large leak 7,000-9,500 ppm-m Dirt patch Blowing	60' SW of road Gusty from SE
9:13 a.m. to 9:20 a.m.	N 43 18 56.67	W106 13 28.21	Small Leak 200-1,500 ppm-m Close to range of instrument. consistent at 1,200 ppm-m then low again. Possibly intermittent or wind	60' – 120' W of road Gusty from SE
9:34 a.m.	N 43 20 12.49	W 106 13 37.47	Moderate localized 3,500 – 4,000 ppm-m Gas also seen downwind	60' NW of road Strong gusts from SE
9:40 a.m.	End			

Table 7. Enhanced Methane Positions September 15 PM

Time	NAD 27 GPS Latitude (DD MM SS.S)	NAD 27 GPS Longitude (DD MM SS.S)	Assessment of Leak	Comments
5:29 p.m.	N 43 14 53.15	W 106 11 12.22	4,000-5,000 ppm-m	500 SCFH calibration leak Gusty wind from N-NE
5:49 p.m.	N 43 16 15.83	W 106 12 20.62	Twice saw 180 ppm – m fleeting	Either residual or intermittent
5:54 p.m.	N 43 16 19.38	W 106 12 25.48	1,200-10,000 ppm-m	Gusty from W
6:16 p.m.	N 43 17 44.23	W 106 13 16.65	Large 5,000-18,000+ ppm-m	51' NE of road Gusty from NW
6:25 p.m.	N 43 18 13.18	W 106 13 5.46	Narrow/localized 8,000-20,000 ppm-m	60' W of road Mild from NW
6:30 p.m.	N 43 18 18.74	W 106 13 8.21	Small 100-300 ppm-m	100' NW of Road Mild from NW
6:38 p.m.	N 43 18 36.58	W 106 13 14.62	Small 200-500 ppm-m (Orange) 150 consistent	120' WNW of road Mild from NW
6:48 p.m.	N 43 18 56.17	W 106 13 28.51	Large HSL – good 6,000 ppm-m	100 to bushes NW of road No wind 126' to bill for solid return
7:02 p.m.	N 43 19 44.29	W 106 13 50.01	Low Level 180 ppm – m	60' NW of road No wind extended area
7:13 p.m.	N 43 20 12.44	W 106 13 37.50	Large 20,000 – 25,000 ppm-m 5,000 lower limit Local: middle of oilfield, plowed patch	61' WNW NW of road No wind
7:20 p.m.	Done			



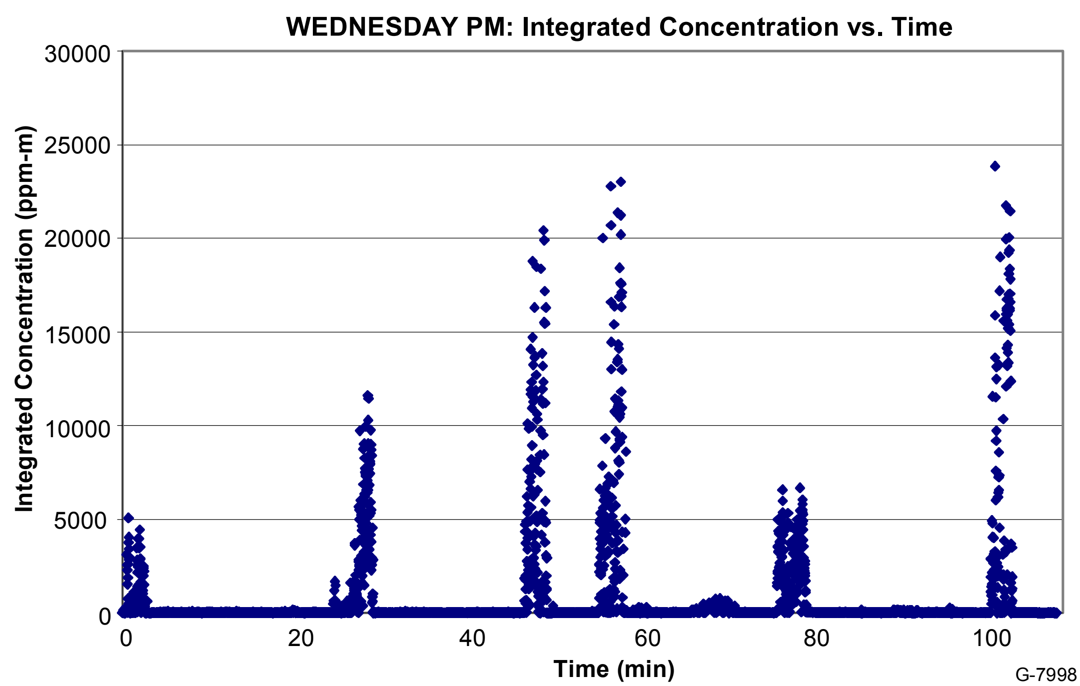


Figure 18. Path-integrated concentration versus time for September 15.

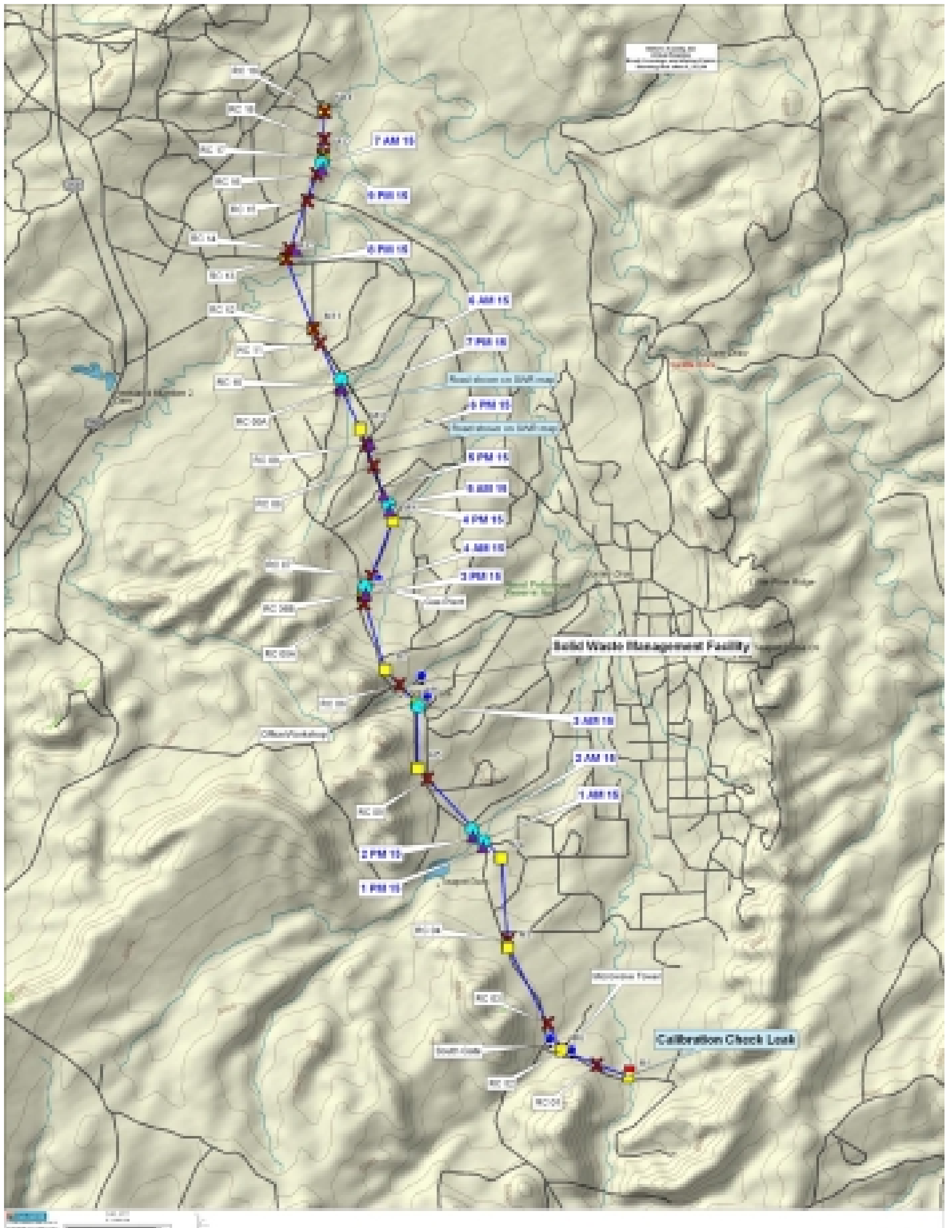


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Figure 19. Positions of survey vehicle when enhanced methane was observed on Wednesday, September 15, ● AM, ▲PM.

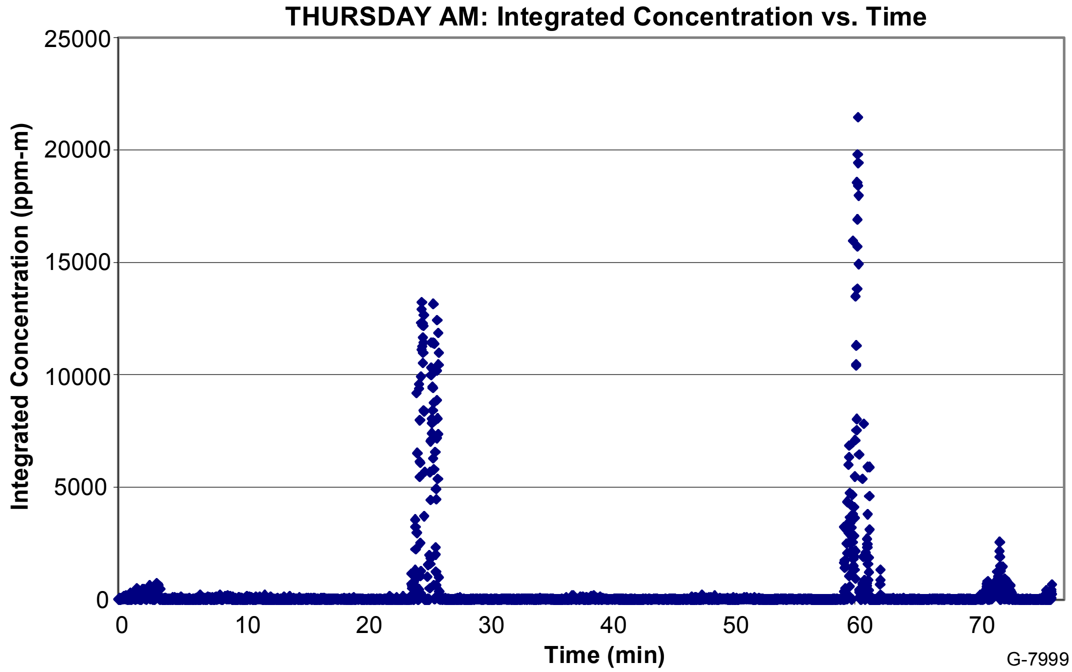
THURSDAY, September 16

Table 8. Enhanced Methane Positions September 16 AM

Time	NAD 27 GPS Latitude (DD MM SS.S)	NAD 27 GPS Longitude (DD MM SS.S)	Assessment of Leak	Comments
7:28 a.m.	N 43 14 53.12	W 106 11 12.07	500 ppm-m	100 SCFH calibration leak Wind from SE
7:36 a.m.	N 43 15 03.44	W 106 11 49.47	Low level 100-150 ppm m Extended	130' NE of road Wind from SE
7:52 a.m.	N 43 16 15.12	W 106 12 19.83	Large/narrow 5,000-1,000 ppm-m	60' NE of road Mild to None
8:05 a.m.	N 43 17 2.47	W 106 12 51.56	Small/Int (wind) 100-150 ppm – m 120 average	60' W of road Gusty from SW
8:18 a.m.	N 43 17 44.34	W 106 13 16.56	Unclear <50 ppm –m edge of detection (50-100)	70' E of road Gusts from SE
8:29 a.m.	N 43 18 13.48	W106 13 05.56	Strong leak dispersed by wind +/-15,000 ppm-m (100 ft. area)	60' W of road Very gusty from S
8:40 a.m.	N 43 18 56.95	W 106 13 28.10	Spread out 800-2,000 ppm-m	60' W of road Mile gusty from SW
8:46 a.m.	N 43 19 12.29	W 106 13 41.71	Narrow plume 42' 500 ppm–m Edge of Range Due to terrain	100' E of road Gusts from SE
9:00 a.m.	N 43 20 12.32	W 106 13 37.60	Variable strength 8,000-15,000 ppm-m	40' W of road Mild wind
9:07 a.m.	Done			

Table 9. Enhanced Methane Positions September 16 PM

Time	NAD 27 GPS Latitude (DD MM SS.S)	NAD 27 GPS Longitude (DD MM SS.S)	Assessment of Leak	Comments
4:32 p.m.	N 43 14 53.11	W 106 11 12.15	800 ppm-m	100 SCFH calibration leak Gusty from NW
4:51 p.m.	N 43 16 15.21	W 106 12 19.79	Large seen downwind 200'+ 10,000 ppm-m	54' NE of road Gusty from WNW
4:55 p.m.	N 43 16 19.43	W 106 12 25.37	Medium 2,000-3,500 ppm-m	60' NE of road Gusty from WNW
5:07 p.m.	N 43 17 2.39	W 106 12 51.64	Small 60-250 ppm-m	54' W of road Mild from NW
5:22 p.m.	N 43 18 13.25	W 106 13 05.37	Large 3,000-8,000 ppm-m	66' W of road slight from NW
5:29 p.m.	N 43 18 35.48	W 106 13 15.26	Small 100-300 ppm-m	100' + W of road Gusty from NW
5:36 p.m.	N 43 18 55.84	W 106 13 28.56	Medium 1,000-4,000 ppm-m	90' W of road Gusty from W
5:46 p.m.	N 43 19 43.77	W 106 13 50.48	Tiny 50-100 ppm-m	72" W of road Moderate from W
5:52 p.m.	N 43 20 12.41	W 106 13 37.46	Medium 1,000-5,000 ppm-m	54' NW of road slight from WNW
5:57 p.m.	Done			



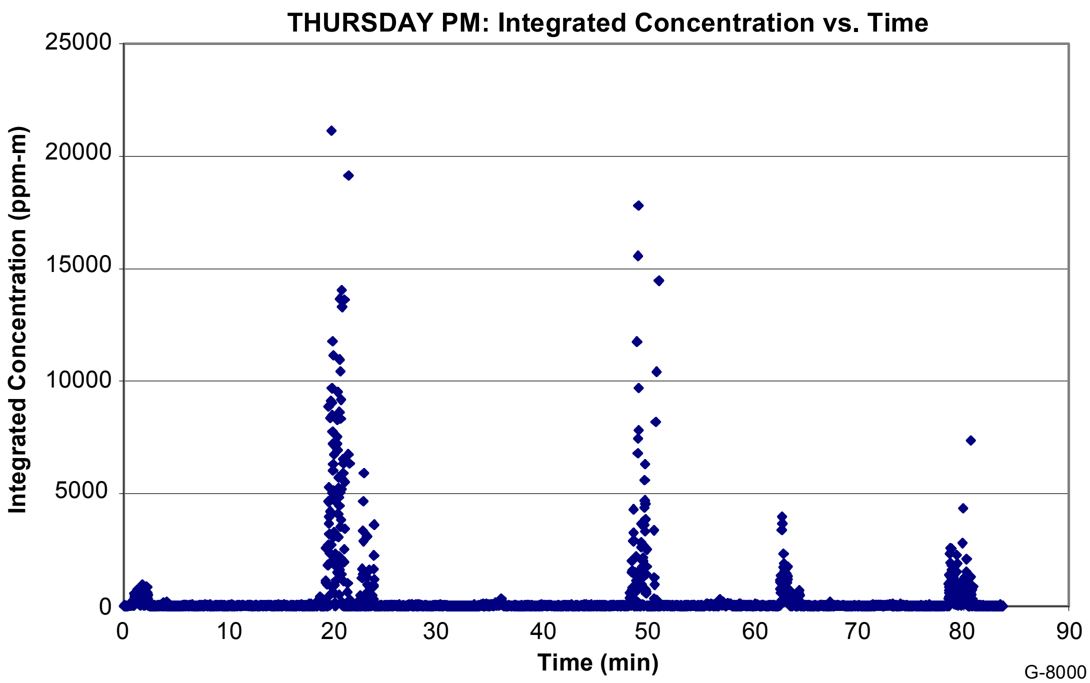


Figure 20. Path-integrated concentration versus time for September 16.

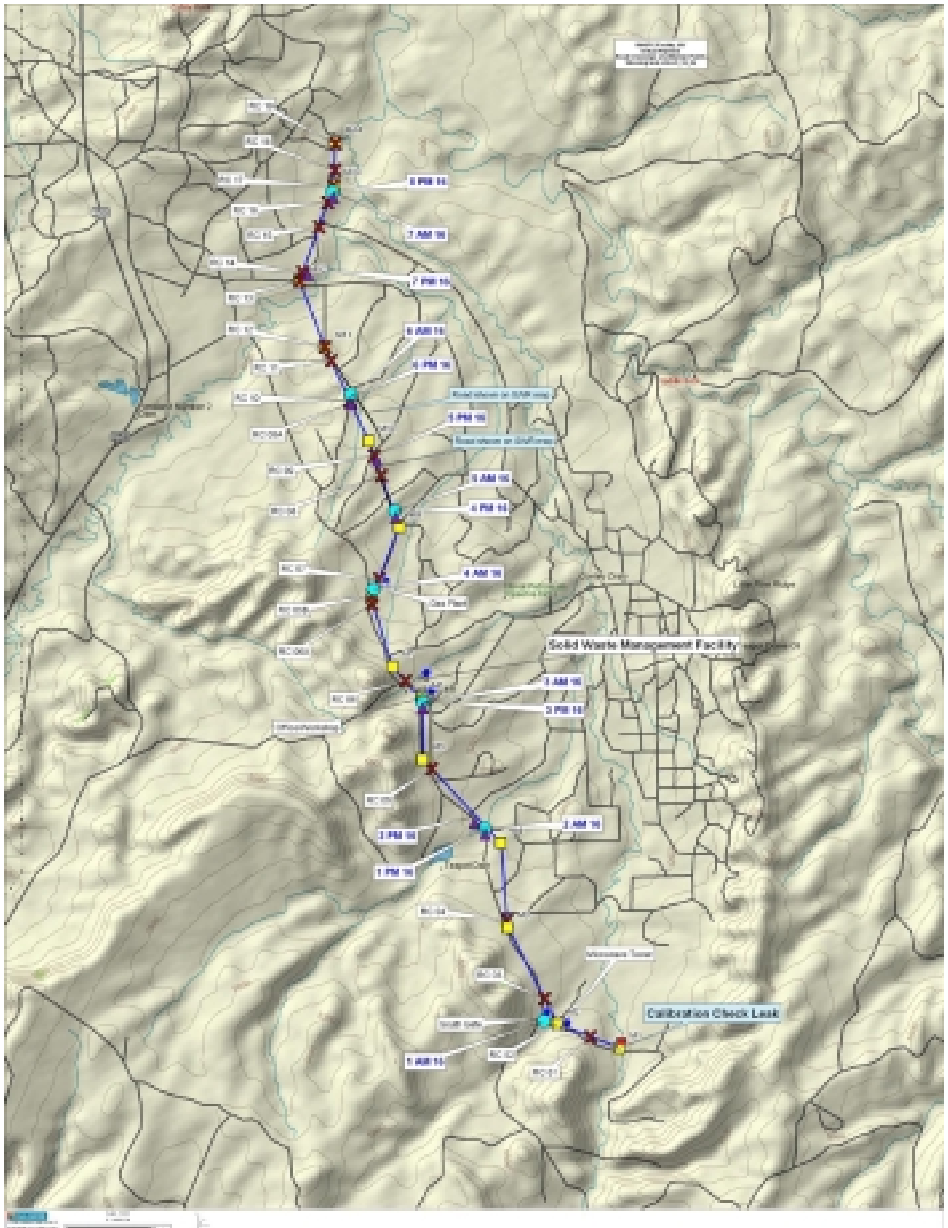


Figure 21. Positions of survey vehicle when enhanced methane was observed on Thursday, September 16, ● AM, ▲PM.

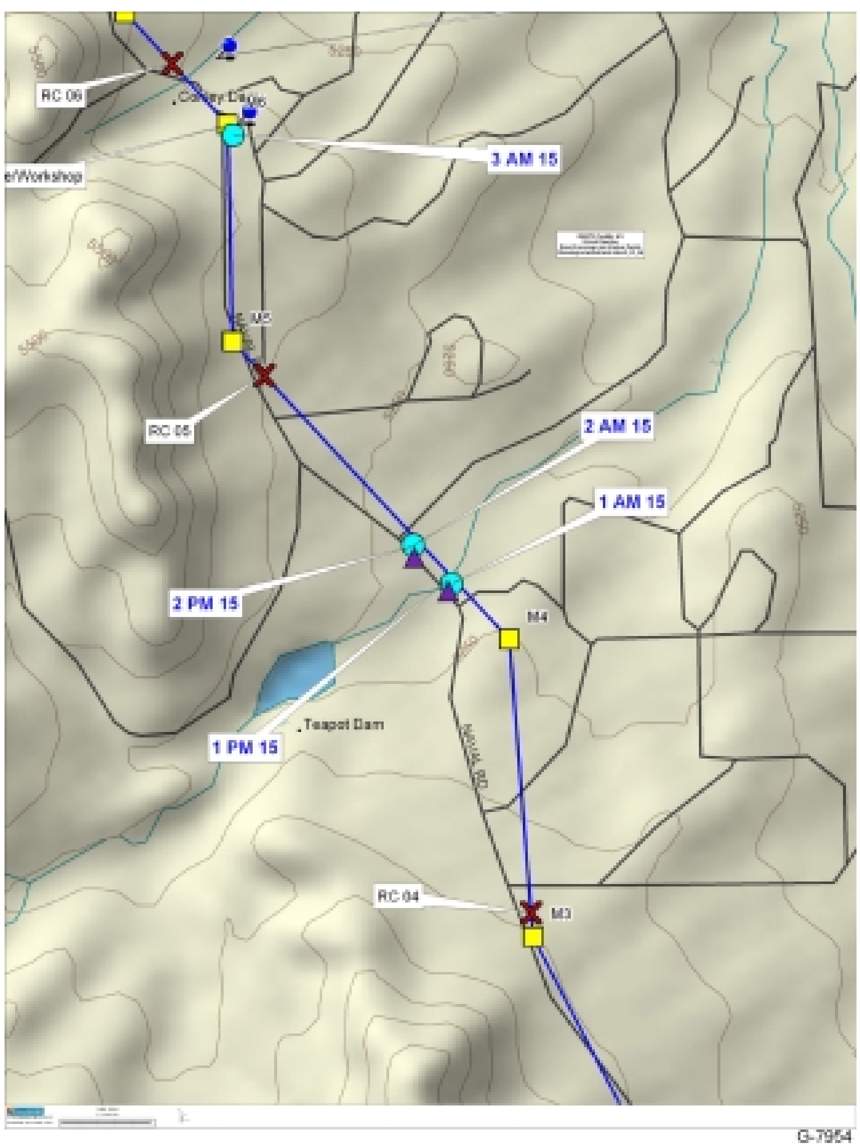


Figure 22. Positions of two adjacent leaks present both Wednesday AM and PM show resolving power.

Data Analysis

The results of the RMOTC tests are summarized in tabular form by Table 10 and its notes. Figure 23 displays the data graphically.

There are 88 leaks identified in Table 10 that were active during our testing period. Nine of the 88 were at the calibration site. Thirty leaks (at Leak Sites 2C, 2D/1F, P2, 6, and P3) were located 100 ft or more from the road, beyond the RMLD's specified detection range. Fourteen of those 30 were at or just beyond the 100 ft range and had small leak rates, 15 scfh or less. The data plotted in Figure 23 indicate that detection of these smaller leaks becomes increasingly challenging as distance increases beyond 70 ft. Eight leaks (at Leak Site P5) had flow rates of

Table 10. Leak Detection Table

Site	Range	9/13			9/14			9/15			9/16			9/17		Fraction Found
		Rate	**am**	**pm**	**Rate**	**am**	**pm**	**Rate**	**am**	**pm**	**Rate**	**am**	**pm**	**Rate**	**am**	
cal	**36**	**5000**	**Y**	**Y**	**1000**	**Y**	**Y**	**500**	**Y**	**Y**	**100**	**Y**	**Y**	**15**	**Y**	**9/9**
P5	**39**	**1**	**N**	**N**	**1**	**N**	**N**	**1**	**N**	**N**	**1**	**N**	**N**	**---**	**---**	**0/8**
3	**44**	**1000**	**Y**	**Y**	**2000**	**Y**	**Y**	**100**	**Y**	**?[f]**	**2000**	**Y**	**Y**	**---**	**---**	**7/7**
5	**59**	**2900**	**Y**	**Y**	**5000**	**Y**	**Y**	**5000**	**Y**	**Y**	**---**	**?[f]**	**---**	**---**	**---**	**6/6**
P4	**66**	**500**	**Y**	**Y**	**500**	**Y**	**Y**	**500**	**Y**	**Y**	**500**	**Y**	**Y**	**---**	**---**	**8/8**
2E	**74**	**---**	**---**	**---**	**---**	**---**	**---**	**---**	**---**	**---**	**15**	**Y**	**Y[a]**	**---**	**---**	**2/2**
2A	**76**	**---**	**---**	**---**	**---**	**---**	**---**	**---**	**---**	**---**	**---**	**---**	**---**	**---**	**---**	**---**
P1	**78**	**1000**	**Y**	**Y**	**1000**	**Y**	**Y**	**1000**	**Y**	**Y**	**1000**	**Y**	**Y**	**---**	**---**	**8/8**
2B	**78**	**15**	**Y[a]**	**N**	**---**	**---**	**---**	**---**	**---**	**---**	**---**	**---**	**---**	**---**	**---**	**1/2**
4	**90**	**100**	**N[b]**	**N[b]**	**500**	**Y**	**Y**	**2000**	**Y**	**Y**	**1000**	**N[b]**	**Y**	**---**	**---**	**5/8**
1F[c]	**100**	**---**	**---**	**---**	**---**	**---**	**---**	**15**	**N**	**N**	**---**	**---**	**---**	**---**	**---**	**0/2**
2D[c]	**100**	**---**	**---**	**---**	**15**	**N**	**N**	**---**	**---**	**---**	**---**	**---**	**---**	**---**	**---**	**0/2**
P3[c]	**116**	**10**	**N**	**N**	**10**	**N**	**N**	**10**	**N**	**Y**	**10**	**N**	**Y**	**---**	**---**	**2/8**
2C[c]	**122**	**---**	**---**	**---**	**---**	**---**	**---**	**15**	**N**	**N**	**---**	**---**	**---**	**---**	**---**	**0/2**
6[c,d]	**170**	**500**	**Y**	**Y**	**100**	**N**	**Y**	**1000**	**Y**	**Y**	**500**	**Y**	**Y**	**---**	**---**	**7/8**
P2[c]	**240**	**100**	**N**	**N**	**100**	**N**	**N**	**100**	**N**	**Y**	**100**	**N**	**Y**	**---**	**---**	**2/8**

Notes to Table 10:

a) The PSI team recognized and noted brief intermittent very small gas detection signals at Leak Sites 2B and 2E during survey. The surveyors subjectively chose to not report these signals as positively-identified leaks. Subsequent data review shows a distinct rise in signal above the background at these sites. With knowledge that these were actual leaks, we now record them as successfully identified. In actual practice, when a questionable signal of this sort is detected, the surveyor would leave the vehicle and perform a more detailed investigation on foot.

b) Our data show no indication of gas at Leak Site 4 on Monday AM, Monday PM, and Thursday AM. We readily identified Leak Site 4 at other times. On Monday, the combination of relatively small leak rate, location on a ridge above the road limiting opportunities for laser backscatter, and wind blowing from SW (perpendicularly away from the road), may have precluded detection of the leak plume. On Thursday, wind was again SW in the morning by NW, parallel to the road, in the evening. The NW wind facilitated detection.

c) Leak Sites 2C, 2D/1F, P2, 6, and P3 were too far from the road for normal detection with PSI equipment which has a nominal range of 100 ft. It appears that the NW wind Wednesday PM and Thursday PM enabled detection of P2 and P3. Photographs of 2D and P3 suggest that optical access to the leak site may have been obstructed by brush.

d) The very high rate of Leak 6 and favorable winds made its plume generally detectable despite the leak source distance from the road.

e) Photos of P5 appear to place the leak on a ridge above the road surrounded by brush. The very small leak rate and possible obstruction of the laser beam precluded detection of this leak.

f) Although these leak sites are listed as inactive, we detected and our data files recorded small but distinct and momentary signals at or near them.

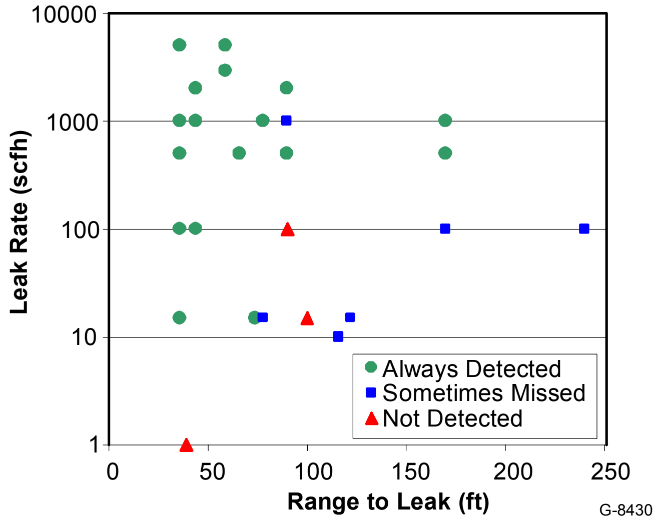


Figure 23. Graphical leak summary.

only 1 scfh, yielding gas concentrations of less than 3 ppm at 10 ft from the source. Plumes from these leaks are below the 10 ppm-m RMLD detection threshold when operating on a mobile platform. Of the remaining 41 leaks, four were not detected by our equipment, including: the 15 scfh leak at site 2B on Monday PM, and three of eight passes at Leak Site 4. Thus we detected 37 of the 41 leaks within our specified performance range, a 90% success rate. Table 10 Note b offers an explanation for missing the leaks at Site 4. Unexpectedly, during favorable wind conditions we were able to detect plumes from Leak Sites 6 and P2, despite the leak sources being located well beyond reach of the sensor. Although we cannot probe leak sources beyond 100 ft from the sensor, we can detect plumes from leak sources farther away when the natural gas from these sources is transported to within 100 ft.

Some of our reported detection events cannot be correlated with the leak locations. On three occasions we detected methane in the vicinity of N43 17 3, just north of a building. This location was independently tested and determined to be a real (but unplanned) leak source. Other events, noted in our reports as small and momentary, include: 1) a distinct signal, reported in our Equipment Provider Test Report Table 3.3.2 and plotted in the Wednesday PM data record, located at N43 18 18.7, just north of P1 (this may have been a gust associated with P1); and 2) fleeting signals recorded on Wednesday PM at the site of Leak 3 and Thursday AM at Leak 5, despite the leaks (which had previously been quite large) being shut off at the time. During a survey of real pipeline, these events would have warranted a closer walking inspection

Conclusions

The work completed in this project successfully demonstrated the feasibility and value of adapting the walking survey tool optics and control electronics to a mobile platform for use in surveying transmission pipeline leaks. The advanced data processing and user interface algorithms developed in Task 1, combined with the spinning mirror hardware designed and assembled in Task 3, easily detected methane leaks from moving platforms including a manually pushed cart and a truck traveling faster than 20 km/hr. The gas flow rates of the detected leaks were comparable to those that leak surveyors would need to identify in municipal settings, verifying that the mobile sensor possesses the inherent sensitivity required to be useful for locating municipal gas distribution pipeline leaks. Enhancements to the leak detection algorithms and procedures developed in this program also resulted in a very successful use of the modified handheld RMLD from a moving vehicle at the RMOTC site for identifying leaks from a virtual gas transmission pipeline. The RMOTC experience has taught that the sensor, even without a continuously spinning mirror, is generally an effective mobile tool for both transmission and distribution pipeline leak surveying.

There are improvements to the MRMLD configuration, and more extensive testing, needed to make it ready for acceptance by the leak survey community. We learned from the RMOTC tests that, to optimize leak detection probability, the survey vehicle would preferably drive within a nominal 100 ft (the maximum range of the current design) of the pipeline. Leak detection and location will also be enhanced by performing a walking survey, using a handheld RMLD, at sites where the MRMLD indicates possible but unconfirmed detection signals. Because the sensor operates like a flashlight and detects gas in the path between the light source and the surface it illuminates, the MRMLD beam needs to pass through a leak plume and scatter from a surface beyond the plume. Therefore, it is preferable to locate a beam aiming device, e.g., a movable mirror, atop the survey vehicle and have it point the beam at a shallow angle towards the ground just beyond the pipeline. Ideally, the MRMLD would be mounted on a platform equipped with a GPS tracking system that automatically aims the laser beam at or across the pipeline, thus replacing the two individuals who, at RMOTC, 1) aimed the transceiver from the back seat of the vehicle and 2) recorded the data. Such an automated system would enable a single operator to survey an extended pipeline from a vehicle, and is ultimately likely to be a more flexible and robust approach to implementing a Mobile RMLD than the fixed-angle continuously spinning mirror system demonstrated in the current project.

Additional effort is needed to package a system incorporating the features described above for permanent installation on a vehicle, and for understanding the optimum procedures for operating such a device in the presence of physical obstructions. PSI recommends that future technology development of a Mobile RMLD platform include this type of configuration along with extensive field testing similar to that performed at RMOTC.

The work accomplished in Tasks 1 through 3 was documented and presented to DoE Technical Points of Contact during a site visit on 17 July 2003. A copy of the presentation material is attached hereto as Appendix A. The work accomplished in Task 3 was presented and published in the Proceedings of the Natural Gas Technologies III Conference, sponsored by the Gas Technology Institute, which was held in Phoenix, AZ during February 2004. A copy of this presentation is attached hereto as Appendix B. The work and results of the supplemental RMOTC demonstration project were documented in a technical paper presented at the Natural Gas Technologies IV Conference held in Orlando, FL during January 2005. A copy of paper is attached hereto as Appendix C.

References

1. www.aga.org/statsstudies/gasfacts/2131.html

2. M.B. Frish, M.A. White, and M.G. Allen, "Handheld laser-based sensor for remote detection of toxic and hazardous gases," SPIE Paper No. 4199-05, November 2000.

3. R.T. Wainner, B.D. Green, M.G. Allen, M.A. White, J. Stafford-Evans, and R. Naper, "Handheld Battery-Powered Near-IR TDL Sensor for Standoff Detection of Gas and Vapor Plumes," *Appl. Phys. B*, 75(2-3), 249-254 (2002).

4. M.B. Frish and F. Klein, "Trace Gas Monitors Based on Tunable Diode Laser Technology: an Introduction and Description of Applications," 5th International Symposium on Gas Analysis by Tunable Diode Lasers, Freiburg, Germany, VDI Berichte 1366 (1988).

5. M.B. Frish, "Overview of Sensitive Detection and Multiplexing Techniques for Tunable Diode Laser Absorption Spectroscopy," OSA *Trends in Optics and Photonics Vol. 31, Advanced Semiconductor Lasers and Their Applications*, Leo Hollberg and Robert J. Lang, Eds., Optical Society of America, Washington, DC (2000).

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Appendix A

Extended Performance Handheld and Mobile Sensors
for Remote Detection of Natural Gas Leaks

Phase II Briefing

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PSI Physical Sciences Inc.

VG03-220

Extended Performance Handheld and Mobile Sensors for Remote Detection of Natural Gas Leaks

Phase II Briefing

Mickey Frish, David Green, Rick Wainner,
Francesca Scire-Scappuzzo, and Mark Allen

Physical Sciences Inc.

Presented to:
National Energy Technology Laboratory (NETL)
Pittsburgh, PA

17 July 2003

PSI Physical Sciences Inc.

HEATH CONSULTANTS

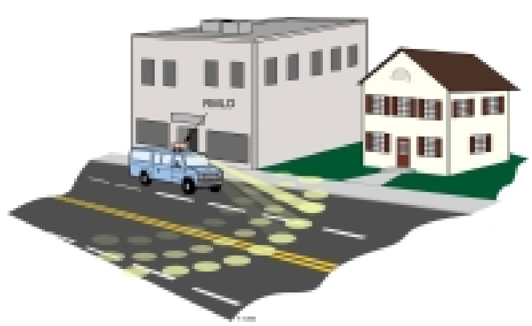
Physical Sciences Inc. 20 New England Business Center Andover, MA 01810

Phase I User Community Input

VG03-220-1

Participant	Comments
Graham Midgley	Mobile curb to curb survey; achieve sensitivity comparable to OMD, FID at range.
George Ragula	No need for longer range; OMD covers mobile; increase sampling speed of existing RMLD for roadside survey.
Angelo Fabiano	Extend RMLD to mobile curb to curb survey; maintain sensitivity. Natural background interference.
Allen Peterson	Interest in moving survey (Segway): increase RMLD sampling speed. Greater range of little benefit except for fenceline and transmission applications.
Bob Naper	Mobile survey tool needed; OMD limited to path of travel; cover street and curb; removable unit to permit walking survey.

- Group identified need for a van-mounted mobile scanning RMLD system



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Task 1

Enhanced Algorithm Development

Status - December 2003

VG03-220-3

- **Preliminary field tests at PSE&G, South Plainfied, NJ, revealed several deficiencies in handheld RMLD survey tool:**
  - "inadequate signal" warning at short range overrode measurement function
  - gas not detected at known leak site
  - ambient methane obscuring leaks at longer ranges
  - occasional false alarm from highly-reflective or fast-moving backgrounds (e.g., cars)

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Inadequate Signal Warning

VG03-220-4

- **The “warning” halts gas measurement and indicates an error when received laser power falls below a pre-set threshold**
  - intended to prevent electronic noise from triggering false alarms
  - poor reflectance of wet, icy, and snowy surfaces activated warning
  - originally programmed as a non-adjustable parameter
- **Solutions: 1) Improved algorithms**
  - field data show that warning threshold was set too high
  - ability to sense ambient methane over long optical paths added as secondary test of signal strength
  - added a small numerical offset to received laser power to reduce electronic noise effect on computed gas concentration
  - warning thresholds now set lower; offset now adjustable via RS-232
- **Solutions: 2) Improved optical fiber connection**
  - original fitting connecting the internal fiber to the external fiber allowed misalignment
  - replaced with improved fitting

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Lack of gas leak detection

VG03-220-5

- **Due to a combination of low signal and mistuning**
- **Tuning:**
  - laser wavelength is tuned to the methane absorption line by a combination of temperature and current
  - significant mistuning will result in calibration error or loss of methane signal
  - RMLD AP tested in NJ were subsequently found to be tuned improperly
  - slow drift of tuning characteristic was subsequently verified
- **Solution:**
  - software developed, initially for use on a PC attached via RS-232, that automatically checks and corrects tuning
  - methane bag provides tuning signal

G-0536

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Improvements Achieved

VG03-220-6

- Improved algorithms and proper tuning yield approximately 10 fold improvement in sensitivity (as measured by signal-to-noise ratio)
- 5 ppm-m accuracy is achieved at 25 to 30 m range from dry surfaces
  - angle of incidence is not a factor
- Highly reflective surfaces, such as water or ice, reduce the returned laser power and may limit range
- Snow absorbs laser power, and may limit range
  - data indicate marginally acceptable signals from snow at 25 m

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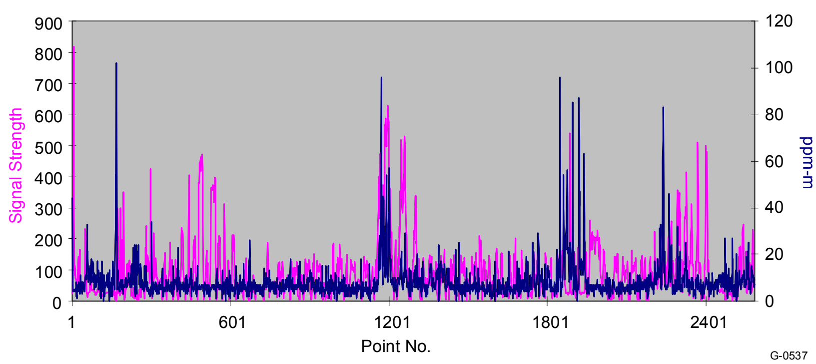
Walking Survey through Known Leak

VG03-220-7

- **Spot aimed 20 ft ahead of surveyor**



G-0537

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Measured RMLD Range Limits

VG03-220-8

- **030312, Cloudy, 50F, 3PM**

Surface	Range (m)	Surface	Range (m)
Woodshed	41	Painted Metal Door	14
Old White Paint	35	Dirty Snow Bank	23
Brick	50+	Clean(er) Snow Bank	19
Concrete	43	Clean Asphalt	25
Stucco	46	Sand	33
Boulders	43	Sand on Asphalt	34
Tree	46	Wet Sand	14
Shrub	43	Clean Standing Water	<1
Grass (on hill)	40	Dirty Water	3
Metal Post	>39	Bag w/CH4 on Snow*	50
Wooden Stockade	55	Oblique Bag w/CH4 on Ground*	50

* Methane cloud (baggie) increases range as F2 overrides low F1.

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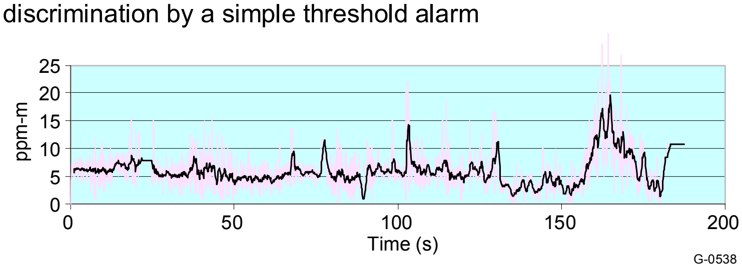
Ambient Methane

VG03-220-9

- Data acquired 2/25/03 – a cold and windy day – suggests leaks at long range will rise above the background, but not enough for discrimination by a simple threshold alarm



- Variable tone audio signal, rather than threshold alarm, enable user interpretation
  - tone pitch proportional to concentration
  - temporally varying tone indicates gas leak
  - user intuitively compensates for changes in range and ambient methane
  - basis for objective algorithm when combined with a rangefinder (not part of NETL program)

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RMLD AP outdoor performance

030311 cloudy 45F 5-15mph SW wind 4PM

VG03-220-10

- **Valid Return signals from >100', 130' inside garage**
- **5 Glenmere along cross street**
  - snow covered along stockade fence
  - bare very wet soil at ends of fence 5' from street showed methane (dead veg)
  - audio flutter gives clear leak indication
  - stare: variable with time (percolation) and wind
  - decreases with height. Decrease more rapidly above 1'. Boundary layer
  - vertical sweep shows profile – tell where pipe is located
- **Detection level (W end stockade looking E along cross street)**
  - at 100' barely detect as change in horizontal sweep
  - at 65' clear if know where you want to look
  - at 50' obvious when blindly hit plume
  - at 30' follow structure of plume
- **Saw indications of gas above meter set under window**
- **Different types snow shortened range**
- **Standing water gives no return signal**
- **No apparent solar effects (even for looks into solar direction low in sky)**

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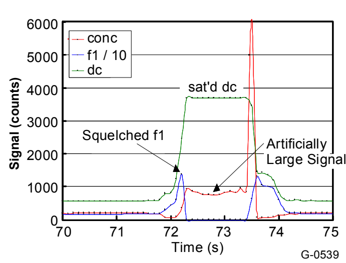
False Alarms

VG03-220-11

- Rapidly changing background in presence of ambient methane causes false alarms due to signal processing algorithm
  - most notable in mobile RMLD



- **Cause:**
  - TDLAS sensor measures two fundamental signals:
    - f1(t) is indicative of received laser power, and
    - f2(t) = Ac(t)f1(t) where c(t) is the path-integrated methane concentration (ppm-m) and A is a calibration constant.
  - f1 and f2 are acquired for 100 ms periods
  - reported methane ppm-m = $A(f2_{avg}/f1_{avg})$ where avg indicates the 100 ms average.
  - when both c(t) and f1(t) vary during the averaging period, then ppm-m = $A[c(t)f1(t)]_{avg}/f1_{avg}$ $\neq$ ***(f2/f1)$_{avg}$***
- **Solution**
  - reduce averaging period to <10ms, compute instantaneous concentration, then average results.

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Alarm Algorithm

VG03-220-12

- Threshold alarm will be evaluated
  - when measurement exceeds threshold, activate and hold alarm
- Evaluation of appropriate threshold level and response time is in progress
- Gas plume dynamics impact algorithm optimization:

  $G = C\,(t_{exp}/t_{avg}) = C\,(d/\omega r)/t_{avg}$ when **$t_{exp} < t_{avg}$**

  $= C$ when **$t_{exp} \geq t_{avg}$**

  where:

  G = indicated methane level
  C = path-integrated methane concentration (ppm-m)
  t_{exp} = interval of RMLD beam exposure to gas
  t_{avg} = RMLD sample averaging time
  d = lateral gas plume dimension (m)
  ω = angular velocity of RMLD beam circle
  r = radius of RMLD beam circle

  Noise = $N \propto (t_{avg})^{-1/2}$

  $G/N \propto (t_{avg})^{-1/2}$ for localized plumes where $t_{exp} < t_{avg}$

  $G/N \propto (t_{avg})^{1/2}$ for extended plumes where $t_{exp} \geq t_{avg}$
- Field tests needed to find optimum algorithm

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Task 2

Ethane Detection

Motivation and Objectives

VG03-220-14

- **Motivation**
  - natural gas contains about 2% ethane, while ambient air has none
  - sensing of ethane can discriminate gas leaks from anthropomorphic sources of methane (i.e., swamp gas)
  - no need to distinguish between small leaks and ambient gas
- **Objectives**
  - evaluate feasibility of combining ethane and methane sensing in single RMLD, using only one laser
  - requires strong ethane absorption lines within a few nm of the RMLD methane line
  - must sense ~ 0.1 ppm-m ethane
- **Tasks**
  - acquire ethane absorption spectra via FTIR measurements and literature search
  - compare lines with wavelengths accessible by methane lasers
  - compute ethane detection limits

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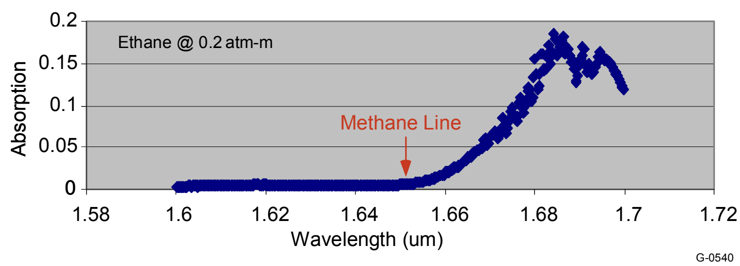
Results

VG03-220-15

- **Located published FTIR data**
  - Dr. Chris Brown, University of Rhode Island, private communication



- **Methane laser tunable from about 1.650 to 1.656 µm**
- **Ethane lines in accessible wavelength region yield absorbance of about 1 x 10^{-8} for 0.1 ppm-m**
  - several orders of magnitude too weak!
  - minumum detectable ethane ~ 100 ppm-m, corresponding to ~ 5000 ppm-m methane leak

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Appendix B

Mobile Remote Methane Leak Detection Demonstration

Presentation for Natural Gas Technologies III Conference

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VG03-361

Mobile Remote Methane Leak Detection Demonstration

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9030 Monroe Road
Houston, TX 77061
USA

Abstract

VG03-361-1

We have built and tested a prototype natural gas leak survey tool, designed to survey across streets and to building walls from a moving vehicle. The compact, affordable, self-contained standoff detection system is based on tunable diode laser absorption spectroscopy (TDLAS), and utilizes the same proven technology platform as our handheld gas leak survey tool, the Remote Methane Leak Detector (RMLD), that will soon be released for commercial sale. The technology platform projects an infrared laser beam onto a topographic target such as a road surface or building wall. The sensor collects and processes a fraction of the laser light scattered from the wall to deduce the amount of methane within the path traversed by the laser beam. Excess methane in one location relative to neighboring locations indicates a gas leak.

The mobile unit is not an imaging device, but rather employs a spinning turret that continually sweeps the laser beam across the survey area as the vehicle moves forward. Unlike currently utilized flame ionization (FI) and optical methane (OM) detectors, the vehicle bearing the Mobile RMLD (MRMLD) need not pass through the leak to detect it – it merely needs to pass by the leak. The MRMLD is intended to provide lateral coverage of 10 m and one lateral scan for every meter of forward motion at forward speeds up to 10 m/s, and to detect the same leaks as FI and OM technology. Installed on the back of a truck, the early prototype MRMLD has readily detected simulated gas leaks of 50 liters per hour.

This work was supported by the US Department of Energy, National Energy Technology Laboratory, Morgantown, WV under contract DE-FC26-02NT41603 as part of the Natural Gas Delivery Reliability Program.

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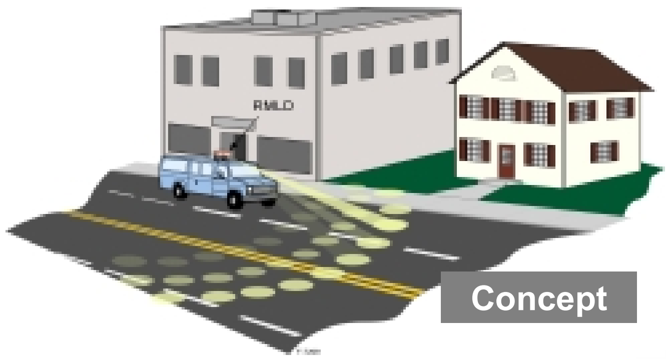
Project Objectives

VG03-361-2

- **Demonstrate the feasibility of developing a low-cost van-mounted laser-based sensor for gas pipeline leak surveying**
  - technology built upon the PSI handheld laser-based Remote Methane Leak Detector (RMLD) technology platform



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Participants

VG03-361-3

- **Mobile Survey System:**
  - Physical Sciences Inc. – Developer
  - Heath Consultants Inc. – Commercializer/Distributor
  - Funding Agencies:
    - US Department of Energy/National Energy Technology Laboratory
- **Walking Survey Tool**
  - Physical Sciences Inc. – Developer
  - Heath Consultants Inc. – Commercializer/Distributor
  - Funding Agencies:
    - US Environmental Protection Agency
    - Northeast Gas Association (formerly New York Gas Group)
    - PGE&G
    - Heath Consultants
    - Physical Sciences Inc.

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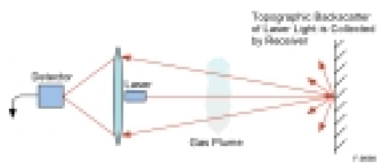
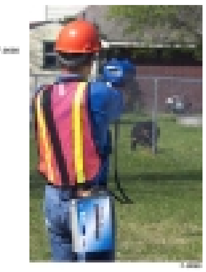
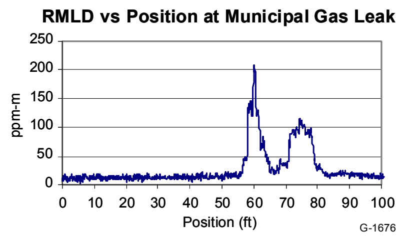
Background - Remote Methane Leak Detector (RMLD)

VG03-361-4

- Based on near-IR tunable diode laser absorption spectroscopy (TDLAS)
- Senses target gas along path between transceiver and a surface up to 30 m (100 ft) distant
- No cross-species interferences
- Shoulder-mounted control unit; handheld transceiver
- Total weight <6 lb
- Eye safe
- Battery-operated, >8 hours between charges







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RMLD Overview

VG03-361-5

- Laser light is projected over a distance onto a reflective target (e.g., grass, wall, etc.)
- A fraction of the light is scattered from the target surface and returns to the source
- Returned light is collected and focused onto a detector
- The presence of methane is encoded within the returned light
- Methane readings are reported in ppm-m

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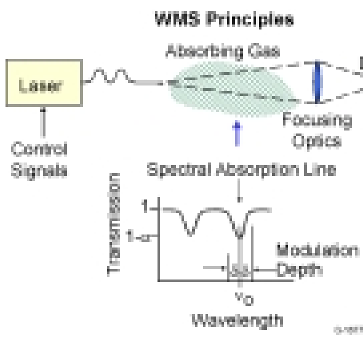
RMLD Technology

VG03-361-6

- **Based Tunable Diode Laser Absorption Spectroscopy (TDLAS)**
  - established trace gas sensing technique used for industrial safety and process control
- **Molecules of the target gas (methane) in the laser light path absorb specific wavelengths (colors) of infrared light**
  - a wavelength is chosen where methane is the only absorbing gas – other gases in the air are invisible
- **Wavelength Modulation Spectroscopy (WMS) signal processing measures the methane absorption,**
  - yields the path-integrated concentration (ppm-m)



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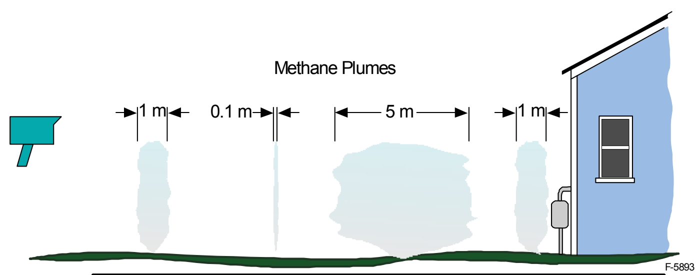
Methane Column Concentration

VG03-361-7

- **RMLD measures concentration x plume length**
  - differs from FID, which measures concentration only
  - detects everywhere along sight line (do not need to be in plume)



FI (ppm)	**10**	**0**	**0**	**0**	**RMLD = 10**
	0	**0**	**0**	**10**	**(ppm-m) 10**
	0	**10**	**0**	**0**	**1**
	0	**0**	**2**	**0**	**10**
	2	**0**	**2**	**2**	**14**

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RMLD Benefits

VG03-361-8

- **Improved walking survey operations:**
  - hard to reach or difficult areas (e.g., over or through fences, under parked vehicles)
  - service leak survey can be performed near or at sidewalk.
- **Sense leaks inside buildings or confined spaces from outside via a closed window or access**
- **Field evaluations during survey operations typically show typical 25% productivity improvement**

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User Interface

VG03-361-9

- **Visual:**
  - LCD display in transceiver with digital readout and bargraph
- **Audio**
  - Headphone provides a variable tone
  - Tone frequency = 10 x methane concentration
  - Minimum frequency = 100 Hz indicates normal operation in absence of methane
  - If transceiver trigger is depressed, tone stops during faults or warnings
  - *Temporal variation of the tone (music) is an excellent intuitive leak signature*

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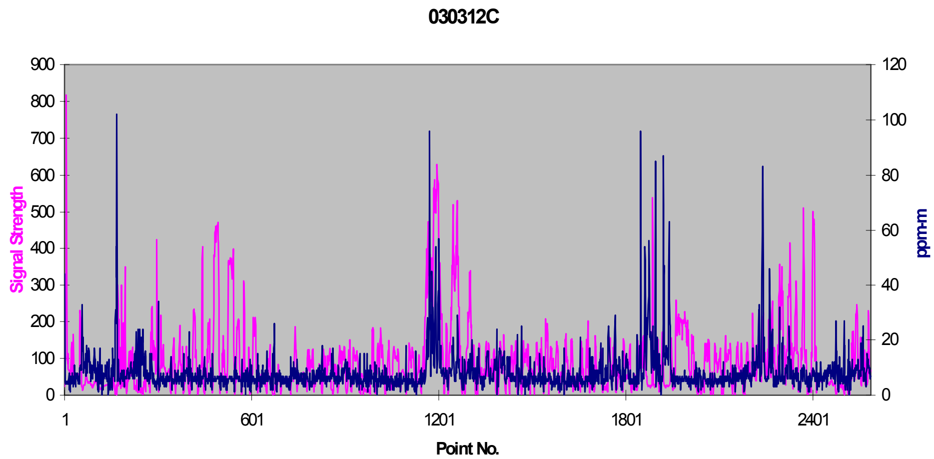
Walking Survey through Known Leak

VG03-361-10

- **Spot aimed 20 ft ahead of surveyor**



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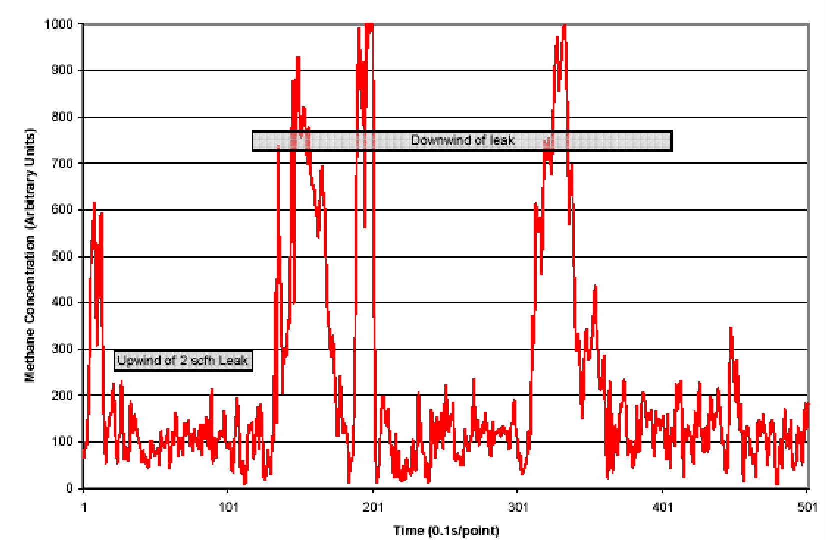
60 liter/hour Simulated Leak

VG03-361-11



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Measured RMLD Range Limits

VG03-361-12

- **030312, Cloudy, 50F, 3PM**

Surface	Range (m)	Surface	Range (m)
Woodshed	41	Painted Metal Door	14
Old White Paint	35	Dirty Snow Bank	23
Brick	50+	Clean(er) Snow Bank	19
Concrete	43	Clean Asphalt	25
Stucco	46	Sand	33
Boulders	43	Sand on Asphalt	34
Tree	46	Wet Sand	14
Shrub	43	Clean Standing Water	<1
Grass (on hill)	40	Dirty Water	3
Metal Post	>39	Bag w/CH4 on Snow*	50
Wooden Stockade	55	Oblique Bag w/CH4 on Ground*	50

* Methane cloud (baggie) increases range as F2 overrides low F1.

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Task 3
Mobile RMLD Motivation

VG03-361-13

- **Users of RMLD identified need for van-mounted mobile curb-to-curb scanning leak detector**
  - Lines/ mains often along side of street
    - Coverage of sidewalk to building wall desirable
  - Optical Methane Detector (OMD), mounted on vehicle bumper, must penetrate leak plume to sense it
- **Sensitivity comparable to OMD or van mounted FI**
- **Removable unit to permit manual leak investigation**
  - single survey tool for mobile and walking survey to reduce capital cost
- **Survey travel speeds up to 40 mph desired**

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Mobile Sensor Description

VG03-361-14

- **Preliminary specifications**
  - forward speed ~ 10 m/s
  - 8 to 10 meter lateral coverage
  - at least one lateral scan per meter of forward motion (i.e. 10 scans/s)
  - minimum sensitivity: detect leaks of 50 liter/hour
  - goal: capable of detecting same leaks as OMD or FID
    - 20 ppm-m x 0.01 s = 0.2 ppm-m-s
  - cost about or less than $20K

- **Mode of operation**
  - continually scans while moving forward
    - may be coupled with GPS to record methane and location concurrently
  - leak, identified as momentary increase above background, triggers alarm
  - upon alarm, surveyor returns to location and conducts detailed survey with handheld RMLD or FID

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Feasibility Demonstration Plan

VG03-361-15

- **Objective**
  - demonstrate the feasibility of utilizing the RMLD platform in a mobile configuration that provides required speed and sensitivity

- **Approach**
  - design and assemble benchtop apparatus simulating operation of mobile unit
  - optimize operating parameters
  - characterize performance in laboratory and mobile settings

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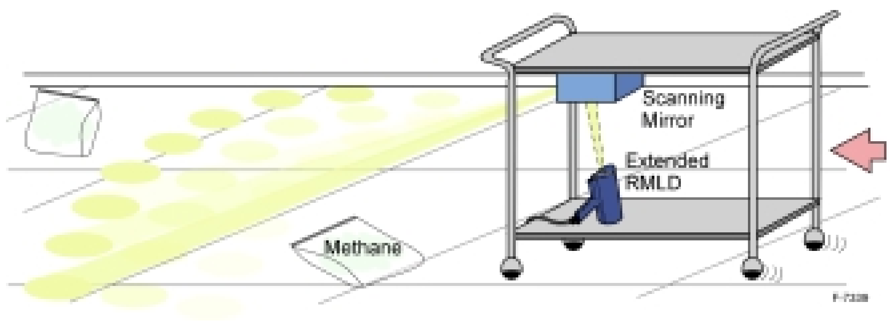
Feasibility Demonstration Concept

VG03-361-16



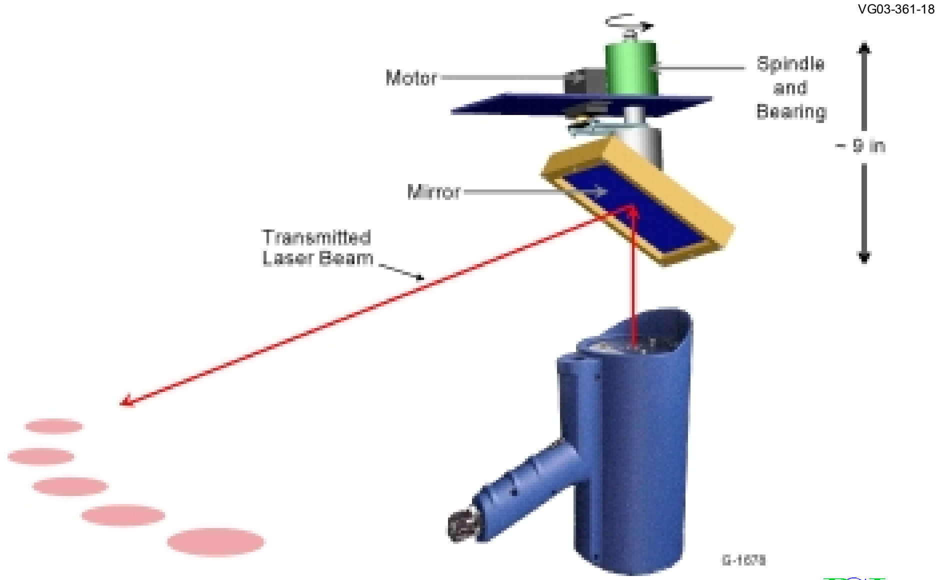
Cart-Mounted Scanning RMLD Description

VG03-361-17

- **Single mirror sweeps beam in circle of adjustable radius and adjustable speed**
  - initial tests with radius of 10 ft and speed 120 rpm
  - lateral speed is 125 ft/s
- **Within RMLD, concentration is computed every 6 ms and 16 samples are combined to provide an average value output every 100 ms**
- **Data output via serial port is acquired by laptop computer which displays and records the data**
- **Recorded data are analyzed manually**

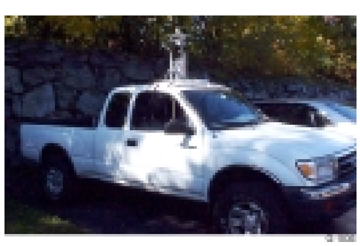
Configuration of Feasibility Demonstrator

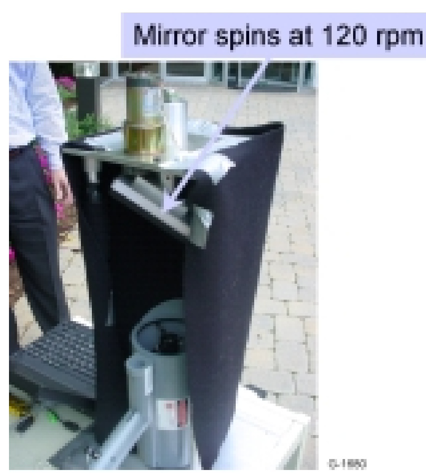
VG03-361-18



Implementation

VG03-361-19

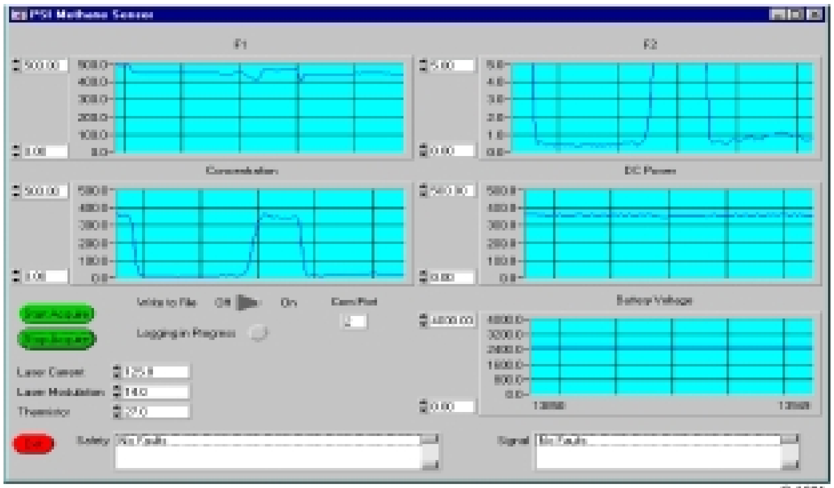




PC Interface

VG03-361-20

- **Displays and records concentration and internal signals**



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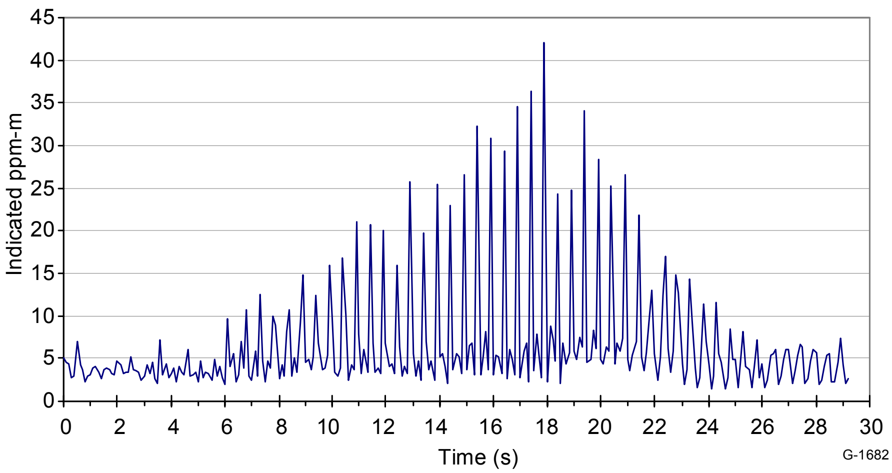
Example Data

VG03-361-21

- **Cart pushed past 2 scfh (57 liter/hour) leak from bottled methane**



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Summary and Future Work

VG03-361-22

- **Feasibility of extending the RMLD platform to a mobile system suitable for detecting municipal leaks has been demonstrated**
  - a simulated leak of 2 scfh yields a signal well exceeding system noise
  - noise/sensitivity below 0.2 scfh (pilot light) level
- **Further development is needed to:**
  - package system for vehicle mounting
  - integrate devices (e.g., PCs or PDAs) for data storage and user interface
  - integrate GPS
  - optimize data acquisition algorithms to accommodate rapidly varying backgrounds

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Acknowledgment

VG03-361-23

- **PSI gratefully acknowledges the funding for this project provided by the Department of Energy, Office of Fossil Energy through the National Energy Technology Laboratory's Delivery Reliability Program**
  - Rodney Anderson
  - Dan Driscoll
  - Magda Rivera
  - Contract Number DE-FC26-02NT41603

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Appendix C

Extending Optical Methane Leak Detection To Mobile Platforms

Paper for Natural Gas Technologies IV Conference

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EXTENDING OPTICAL METHANE LEAK DETECTION TO MOBILE PLATFORMS

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ABSTRACT

We have developed a handheld natural gas leak survey tool and the experimental model or an urban mobile survey tool as previously reported at this conference. We report here data from demonstrations of natural gas leak detection from a mobile platform in support of transmission pipeline monitoring. Data from a wide rate of leak sizes, illumination conditions, and viewing geometries (as collected at the RMOTC facility) will be used to demonstrate technique sensitivity and robustness. We will also present our concept for extending this technology to a high altitude aerial platform that will permit wide area survey. This effort is supported by the DoE NETL at Morgantown, WV.

1. INTRODUCTION

The US natural gas transmission system comprises approximately 250,000 miles of pipeline, 1700 transmission stations and 17,000 compressors. This transmission system serves local distribution companies that operate some 500-1000 gate stations supplying roughly 132,000 surface metering and pressure regulation sites stationed along 1,000,000 miles of distribution pipeline terminating at 61,000,000 end-user customer meters. Maintaining the security and integrity of this system is a continual process of searching for, locating, and repairing leaks.

Leak surveying is very labor intensive, in part because all currently available natural gas detectors must be positioned within a leak plume to detect the leak. Physical Sciences Inc. (PSI), in conjunction with Heath Consultants (Houston, TX) and the Northeast Gas Association (New York, NY), and with funding from PSE&G (NJ), SoCal Gas (CA), and the US EPA and DoE, has developed an optical methane detector that provides stand-off detection of leaks with detection capabilities comparable to commonly-used flame ionization detectors. The Remote Methane Leak Detector (RMLD), shown in use by Figure 1, is based on the established spectroscopic measurement technology known as Tunable Diode Laser Absorption Spectroscopy (TDLAS). The RMLD includes a handheld optical transceiver and a shoulder-mounted controller. The transceiver transmits an eyesafe laser beam onto topographic targets up to 100 ft. distant, and receives some of the laser light reflected by the target. The controller processes the received light signal to deduce the amount of methane in the laser's path. The entire system weighs a total of approximately 6 lbs. Self-contained rechargeable batteries power the device for more than 8 hours continuously on one charge. Field tests of advanced prototype RMLD units have been ongoing by several gas distribution companies since March 2003, with excellent results. Design of production units is currently underway, with market introduction planned for 2004.

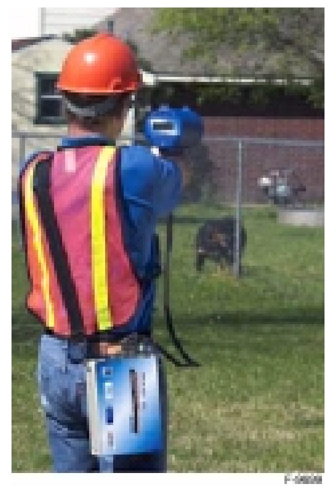

Figure 1. Photograph of PSI's natural gas leak detector during field testing.

2. MEASUREMENT APPROACH

The RMLD combines a telecommunications-style diode laser, fiber-optic components, and low-cost DSP electronics with the well-understood principles of Wavelength Modulation Spectroscopy (WMS), to indicate, with a sensitivity of 5 ppm-m and 10 Hz response, the presence of natural gas located between the operator and a topographic target (such as pavement, grass, building walls, etc.).

TDLAS instruments rely on well-known spectroscopic principles and sensitive detection techniques coupled with advanced diode lasers, and often with optical fibers.[1-4] The principles are straightforward: Gas molecules absorb energy at specific wavelengths in the electromagnetic spectrum. At wavelengths slightly different than these absorption lines, there is essentially no absorption. Specifically, when the laser frequency (reciprocal wavelength) is tuned to correspond to a particular absorption transition of the target gas molecule, the transmitted light is attenuated according to the Beer-Lambert relation:

$$I_\nu = I_{\nu,0} \exp\left[-S(T)g(\nu - \nu_0)N\ell\right] \tag{1}$$

where I_ν is the transmitted intensity at frequency ν after propagating through a gas path ℓ, $I_{\nu,0}$ is the initial laser intensity, S(T) is the temperature-dependent absorption line-strength (a fundamental spectroscopic property of the molecule), N is the target species number density, and $g(\nu - \nu_0)$ is the absorption lineshape (describing the spread in frequency of the transition strength). The argument of the exponential function is the fractional change in the laser intensity across the measurement path and is conventionally known as the absorbance. By (1) transmitting a beam of light through a gas mixture sample containing a quantity of the target gas, (2) tuning the beam's wavelength to one of the target gas's absorption lines, and (3) accurately measuring the absorption of that beam, one can deduce the concentration of target gas molecules integrated over the beam's path length. This measurement is often expressed in units of ppm-m.

Practical and robust commercial TDLAS instrumentation came into existence during the 1990's, made possible by the advent of reliable monochromatic near-infrared (NIR, 1.2 to 2.5 μm, or 4000 to 8500 cm^{-1}) diode lasers that operate continuously and unattended near room temperature. These lasers (specifically the distributed feedback, or DFB, variety that include a grating-like optical element which forces each laser to emit light at a specified NIR wavelength) offer linewidths less than 0.003 cm^{-1}, which is considerably narrower than molecular absorption linewidths that are typically 0.1 cm^{-1} at atmospheric pressure. Furthermore, by accurately controlling the laser temperature and the electrical current that powers the laser (the "injection current"), the laser wavelength may be tuned rapidly and precisely over a range of about ± 2 nm around its specified wavelength. *Typically, each TDL system is built using a laser having a specific design wavelength chosen to optimize the sensitivity to a particular target gas. The wavelength is selected to correspond to a specific absorption line of the target analyte gas that is free of interfering absorption from other molecules.*

Fast, sensitive detection of methane is accomplished using the technique of Wavelength Modulation Spectroscopy (WMS), wherein the laser's fast tuning capability is exploited to rapidly and repeatedly scan the wavelength across the selected gas absorption line. While this periodic wavelength modulation occurs, the fraction of emitted laser power that is transmitted through the atmosphere is monitored with a photodetector. When the wavelength is tuned to be off of the methane absorption line, the transmitted power is higher than when it is on the line. Because each cycle of the modulation causes the wavelength to cross the absorption feature twice, the resulting amplitude modulated signal is periodic with a fundamental frequency of twice the wavelength modulation frequency. In the literature, the fundamental component is called the 2f signal. Phase sensitive (lock-in) detection accurately measures the amplitude of the 2f signal, which depends on both the power of the transmitted beam and the path-integrated concentration of methane. 2f signals representing absorption of 1/100,000 of the average received laser power are detected routinely by this technique. The average value of the received laser power, P_{DC}, is measured separately and utilized to normalize the 2f signal. The resulting ratio depends only on path-integrated concentration.

All of the circuitry and processing hardware required to operate the laser and implement WMS is, in the RMLD, contained on a single 6 inch square printed circuit board. All of the laser control, thermal control, signal processing, and data reporting functions are performed on this board, which draws only 1.5 W of power.

The handheld RMLD was designed for a maximum range to the topographic target of 100 ft to accommodate several operational requirements, including weight, size, and power consumption. With this design, laser power collected from targets beyond 100 ft (30 m) is insufficient to provide a signal-to-noise ratio useful for detecting low-grade leaks. Furthermore, because the RMLD is designed to be comparable in sensitivity to FID, it is also sensitive to the natural methane in the ambient atmosphere, which is typically present at concentrations of about 2 ppm. Since the RMLD measures path-integrated concentration, the ambient methane can contribute up to 60 ppm-m (2 ppm x 30 m) of signal, which is comparable to the signal due to a small leak.

With support from the US Department of Energy's National Energy Technology Laboratory, PSI has built and demonstrated an enhanced RMLD intended for surveying streets curb-to-curb from a mobile vehicle. We report here the extension of this technology to the transmission pipeline survey application.

3. SIMULATED TRANSMISSION PIPELINE SURVEY TEST PARTICIPATION

3.1 Sensor System

Physical Sciences Inc. (PSI) and our partner Heath Consultants Incorporated participated in the tests conducted under DoE National Energy Technology Laboratory sponsorship at the Rocky Mountain Oilfield Testing Center (RMOTC) during the week of September 13, 2004. The NETL recognized the potential to extend this technology to mobile detection so as to enable its application to transmission pipeline surveys. RMLD participated as a ground-based instrument during the tests at RMOTC. A photograph of the RMLD unit that participated in the RMOTC tests is shown in Figure 2. The control unit is connected to the optical transceiver via a single umbilical.

Figure 2. Remote methane leak detector alpha prototype unit.

Different surfaces reflect different amounts of light and so the maximum range will depend on the viewed surface. We have found the effective range to be at least 100 feet (30 meters) for most natural terrain and even paved surfaces, although often detection to 150 feet (45 meters) is possible. For walking survey applications, the proven sensitivity is at 10 ppm-m level. If insufficient signal is returned – a not valid indicator prohibits a survey area to be missed by accident. The RMLD is self-contained, operates an entire day on a battery charge. It has had extensive testing by researchers and LDC surveyors. One of the objectives of this test was to determine the effective range for a mobile survey application. Once you turn on RMLD power, all self checks are performed in 5 seconds, and you are ready to begin measurements. Each day we performed a performance verification test by viewing a methane containing enclosure. We performed the survey from the rear seat of a car (Chevy Suburban) rented for occasion. Little special preparation was required. The RMLD technology is well advanced.

3.2 Data Collection And Reduction Scheme

For the development of a unit for mobile testing we transformed the electronics to permit more rapid sample collection and improved the user interface to permit more rapid and sensitive leak detection. In particular, we made use of an audio tone as a column concentration indicator.

Our objective during the RMOTC tests was to determine the effectiveness of these changes in permitting detection at speeds far in excess of walking. However, because this was the first time we had participated in a testing of the mobile version of this unit, we chose to travel slowly in an attempt to optimize the detection of leaks, rather than test the maximum speed where the sensor would work. As a result we traveled at 8 to 10 miles per hour (13 to 16 kilometer per hour), and stopped to investigate and characterize each leak. For these tests we typically averaged 5 mph for the entire 7.4 mile course, but we believe that operating at 35 mph would produce the same level of detection.

We had hoped to investigate the effect of viewing height (on the roof of the vehicle vs. inside), but this was not permitted due to safety constraints. All data were acquired with the surveyor sitting in the rear set of the vehicle looking sideward, viewing the terrain at the limit of RMLD range (about 100 feet) through the open rear windows. We used the audio tone as a rapid indicator of methane cloud detection. We also recorded numerous instrument performance indicators, returned signal levels and the detected concentration on a laptop computer in the front seat of the vehicle. Also operational in the vehicle was a GPS unit (Garmin Etrex, WAAS enabled) connected to a second laptop running a DeLorme topographical mapping software program. The Virtual Pipeline route, markers and road crossings were inserted into this display prior to the RMOTC testing. An example of a map created for the RMOTC tests is shown in Figure 3. These tools permitted the survey vehicle location to be instantaneously displayed with respect to the pipeline and a track of the entire driven route to be shown. When a leak was detected, a compact laser rangefinder (Bushnell Yardage Pro Sport Rangefinder) was used to estimate the range to the leak. The location of the survey vehicle when a leak was observed was entered onto the GPS map. We entered the detected leaks onto the test form provided each day, making note of the relative wind direction, magnitude of leak and other salient characteristics. Each test was a single traverse of the pipeline route.

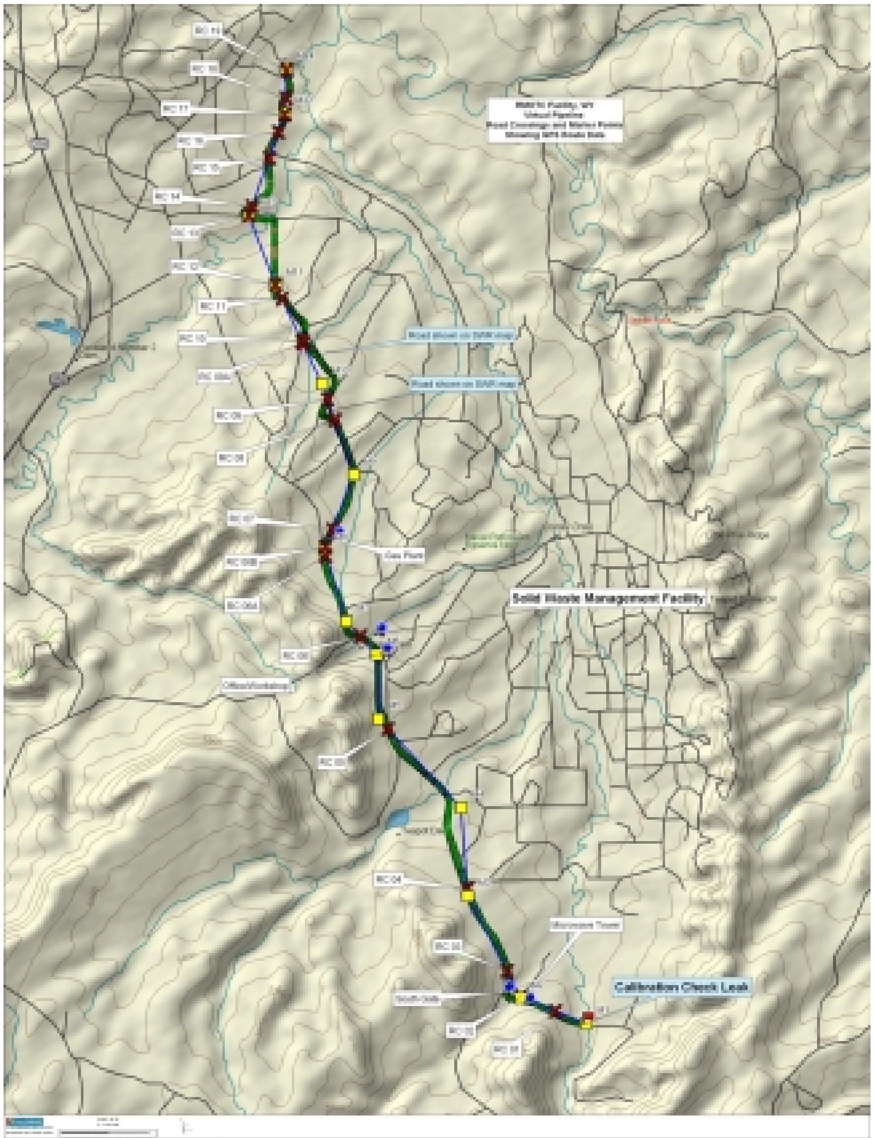

Figure 3. Topographical map with path traveled during testing shown in green. Total distance traveled is 7.4 miles.

3.3 Test Participation

PSI participated in morning and afternoon tests Monday through Thursday, always traveling the same route shown in Figure 3. We measured the low-level calibration leak only on Friday. No modifications were made to the system or software any time. We have detected numerous leaks presented to us during each transit. Shown in Figure 4 is the topo map with Virtual Pipeline and markers indicated along with the detected leaks. The leaks are indicated as on the road, but could be corrected for off road position. Leaks in close proximity were easily resolved in our ground operations.

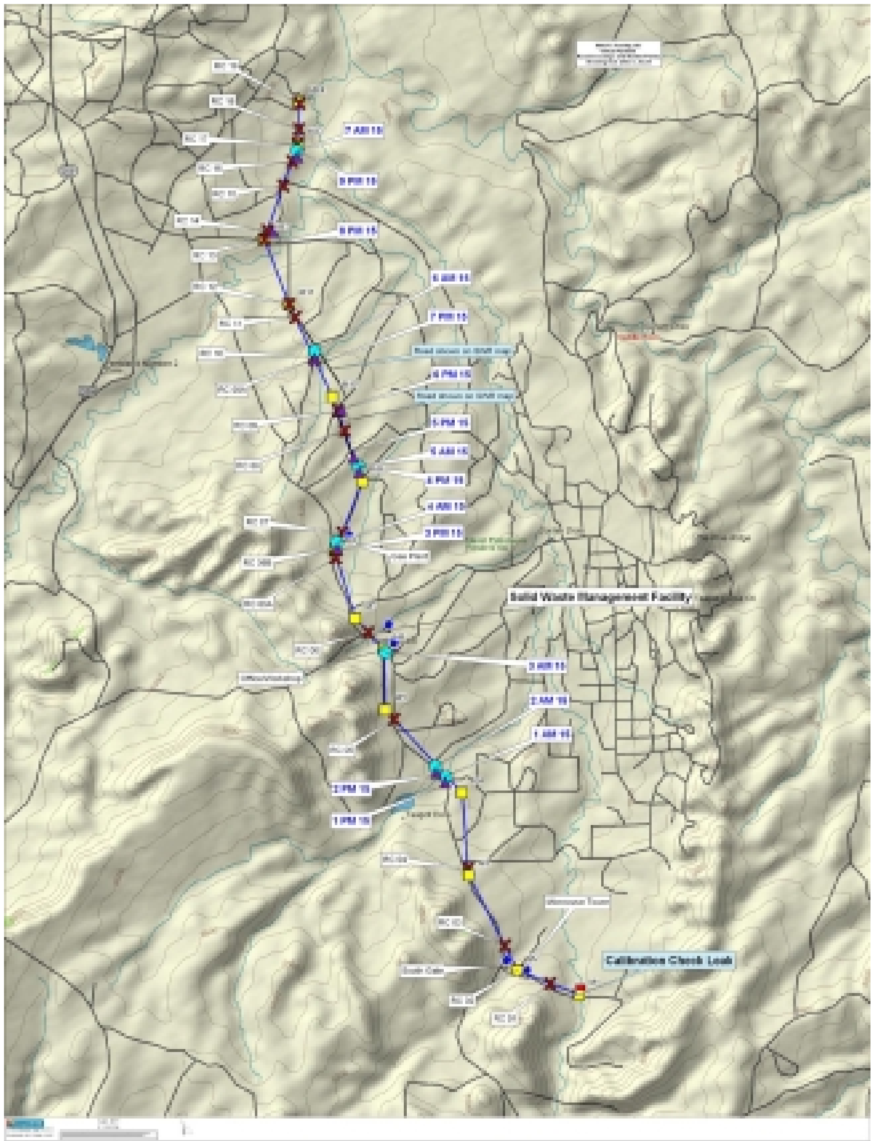

Figure 4. Positions of survey vehicle when enhanced methane was observed on Monday, September 13, ● AM, ▲ PM.

3.4 Test Results

Our findings are summarized in tabular form by Table 1 and its notes. Figure 5 displays the data graphically.

There are 88 leaks identified in Table 1 that were active during our testing period. Nine of the 88 were at the calibration site. Thirty leaks (at Leak Sites 2C, 2D/1F, P2, 6, and P3) were located 100 ft or more from the road, beyond the RMLD's specified detection range. 14 of those 30 were at or just beyond the 100 ft range and had small leak rates, 15 scfh or less. The data plotted in Figure 5 indicate that detection of these smaller leaks becomes increasingly challenging as distance increases beyond 70 ft. Eight leaks (at Leak Site P5) had flow rates of only 1 scfh, yielding gas concentrations of less than 3 ppm at 10 ft from the source. Plumes from

Table 1. Leak Detection Table

Site	Range	9/13			9/14			9/15			9/16			9/17		Fraction Found
		Rate	am	pm	Rate	am	pm	Rate	am	pm	Rate	am	pm	Rate	am	
cal	36	5000	Y	Y	1000	Y	Y	500	Y	Y	100	Y	Y	15	Y	9/9
P5	39	1	N	N	1	N	N	1	N	N	1	N	N	---	---	0/8
3	44	1000	Y	Y	2000	Y	Y	100	Y	?[f]	2000	Y	Y	---	---	7/7
5	59	2900	Y	Y	5000	Y	Y	5000	Y	Y	---	?[f]	---	---	---	6/6
P4	66	500	Y	Y	500	Y	Y	500	Y	Y	500	Y	Y	---	---	8/8
2E	74	---	---	---	---	---	---	---	---	---	15	Y	Y[a]	---	---	2/2
2A	76	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
P1	78	1000	Y	Y	1000	Y	Y	1000	Y	Y	1000	Y	Y	---	---	8/8
2B	78	15	Y[a]	N	---	---	---	---	---	---	---	---	---	---	---	1/2
4	90	100	N[b]	N[b]	500	Y	Y	2000	Y	Y	1000	N[b]	Y	---	---	5/8
1F[c]	100	---	---	---	---	---	---	15	N	N	---	---	---	---	---	0/2
2D[c]	100	---	---	---	15	N	N	---	---	---	---	---	---	---	---	0/2
P3[c]	116	10	N	N	10	N	N	10	N	Y	10	N	Y	---	---	2/8
2C[c]	122	---	---	---	---	---	---	15	N	N	---	---	---	---	---	0/2
6[c,d]	170	500	Y	Y	100	N	Y	1000	Y	Y	500	Y	Y	---	---	7/8
P2[c]	240	100	N	N	100	N	N	100	N	Y	100	N	Y	---	---	2/8

Notes to Table 1:

g) The PSI team recognized and noted brief intermittent very small gas detection signals at Leak Sites 2B and 2E during survey. The surveyors subjectively chose to not report these signals as positively-identified leaks. Subsequent data review shows a distinct rise in signal above the background at these sites. With knowledge that these were actual leaks, we now record them as successfully identified. In actual practice, when a questionable signal of this sort is detected, the surveyor would leave the vehicle and perform a more detailed investigation on foot.

Notes to Table 1 (Continued):

h) Our data show no indication of gas at Leak Site 4 on Monday AM, Monday PM, and Thursday AM. We readily identified Leak Site 4 at other times. On Monday, the combination of relatively small leak rate, location on a ridge above the road limiting opportunities for laser backscatter, and wind blowing from SW (perpendicularly away from the road), may have precluded detection of the leak plume. On Thursday, wind was again SW in the morning by NW, parallel to the road, in the evening. The NW wind facilitated detection.

i) Leak Sites 2C, 2D/1F, P2, 6, and P3 were too far from the road for normal detection with PSI equipment which has a nominal range of 100 ft. It appears that the NW wind Wednesday PM and Thursday PM enabled detection of P2 and P3. Photographs of 2D and P3 suggest that optical access to the leak site may have been obstructed by brush.

j) The very high rate of Leak 6 and favorable winds made its plume generally detectable despite the leak source distance from the road.

k) Photos of P5 appear to place the leak on a ridge above the road surrounded by brush. The very small leak rate and possible obstruction of the laser beam precluded detection of this leak.

l) Although these leak sites are listed as inactive, we detected and our data files recorded small but distinct and momentary signals at or near them.

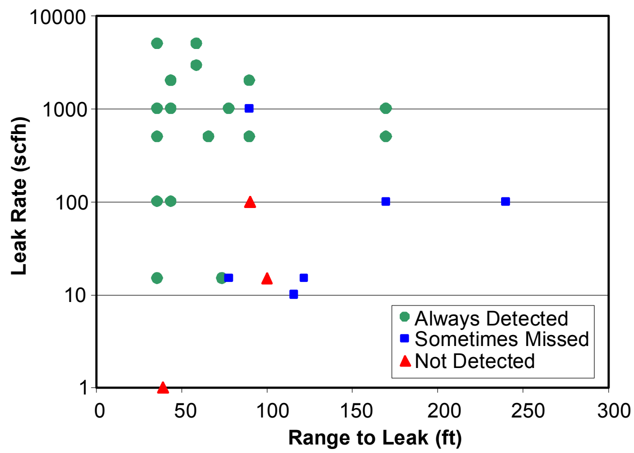

Figure 5. Graphical leak summary.

these leaks are below the 10 ppm-m mobile RMLD detection threshold. Of the remaining 41 leaks, four were not detected by our equipment, including: the 15 scfh leak at site 2B on Monday PM, and three of eight passes at Leak Site 4. Thus we detected 37 of the 41 leaks within our specified performance range, a 90% success rate. Table 1 Note b offers an explanation for missing the leaks at Site 4. Unexpectedly, during favorable wind conditions we were able to detect plumes from Leak Sites 6 and P2, despite the leak sources being located well beyond reach of the RMLD. Although RMLD cannot probe leak sources beyond 100 ft from the sensor, we can detect plumes from leak sources farther away when the natural gas from these sources is transported to within 100 ft.

Some of our reported detection events cannot be correlated with the leak locations. On three occasions we detected methane in the vicinity of N43 17 3, just north of a building. This location was independently tested and determined to be a real (but unplanned) leak source. Other events, noted in our reports as small and momentary, include: 1) a distinct signal, reported in our Equipment Provider Test Report Table 3.3.2 and plotted in the Wednesday PM data record, located at N43 18 18.7, just north of P1 (this may have been a gust associated with P1); and 2) fleeting signals recorded on Wednesday PM at the site of Leak 3 and Thursday AM at Leak 5, despite the leaks (which had previously been quite large) being shut off at the time. During a survey of real pipeline, these events would have warranted a closer walking inspection

3.5 Mobile Test Summary

The RMOTC experience has taught that the RMLD is generally an effective mobile survey tool, but to optimize the detection probability the survey vehicle would preferably drive within a nominal 100 ft of a pipeline and view down at the surface of the ground. Furthermore, leak detection and location can be enhanced by allowing a walking survey at sites of small detection signals. Survey planners and RMLD operators should recognize that the RMLD operates like a flashlight and detects gas in the path between the light source and the surface it illuminates. The absence of a surface behind the leak plume, or an obstruction in front, will preclude detection.

PSI and Heath were delighted to be allowed to participate in these tests at RMOTC. We were impressed with the care and thought that went into creating leak scenarios. A wide range of leak magnitudes and characteristics were presented to test participants. We found the variety stimulating and challenging, and we thank the test conductors. PSI successfully detected the vast majority of the leaks presented with few false positives. We even detected real but unknown, unplanned leaks.

However, as in any simulated test there were artificial constraints that potentially limited the effectiveness of our detection approach. We had no opportunity to optimize the height of viewing. The slant angle to the ground is less well defined at passenger eye level, and thus more sensitive to road vibration moving the viewed volume. As our technique needs a surface to reflect light back to the receiver, we may have missed leaks located at (or just over) a ridge. There were a number of locations where the road passed between embankments, effectively blocking our view and preventing surveying. In a real survey, we would have either traveled the ridge or moved to another position (road) to view the obscured area. We understand that for these structured tests this could not be possible. During real world surveys, the vehicle would travel on the pipeline right-of-way viewing both sides of the pipeline at the maximum uncertain distance and keep the full field in view – stopping and maneuvering to access all areas, walking if necessary.

We feel there are many advantages to ground-based surveys. Leaks can be located and marked immediately. They can be investigated to find obvious sources. They can be assessed in the context of their surrounding (desert vs. grammar school). We did not try to optimize survey speed, but plan to do this in future efforts. We were urged to treat this test as if it were a real survey. We showed up the morning the test began, participated in every test run on schedule, packed up and left moving to the next survey.

4. EXTENSION OF TECHNOLOGY TO AIRBORNE APPLICATION

Physical Sciences Inc. has recently been awarded a program under DoE/NETL sponsorship. Herein, PSI proposes to utilize and extend the technology embedded within the RMLD to build and demonstrate a system for standoff sensing, from high altitudes, of natural gas distribution/transmission pipeline leaks. The solid-state, near-IR lasers within RMLD will be enhanced with scalable, high-power optical fiber amplifiers to provide a compact, power-efficient sensor to be flown in a piloted aircraft. PSI will assemble and flight test a prototype sensor having an operational ceiling of 10,000 ft. This demonstration will prove the concept and lay the foundation for scaling the device to achieve leak detection from altitudes in excess of 50,000 ft.

Operating over longer ranges RMLD must have the ability to discriminate small leaks from ambient methane. *The airborne RMLD will be designed to avoid or overcome these limitations.* The prototype version to be demonstrated will operate at altitudes up to 10,000 ft and sense leak plumes having minimum path-integrated methane concentrations of 1000 ppm-m. *This detection scenario should be sufficient to detect the presence of a leak from a high capacity transmission line.* The system will be designed to provide a signal-to-noise ratio of unity corresponding to about 100 ppm-m, the so-called minimum detection limit.

To adapt the RMLD for high altitude use in the airborne platform, three aspects of it will be modified: 1) The transmitted laser power will be increased by use of an optical fiber amplifier; 2) The size of the optical receiver will be increased; and 3) The laser wavelength will be changed. Equation (1), which relates the received laser power to the transmitted power, optical receiver size, and operating distance, provides the rationale for the first two changes:

$$P_{DC} = \left(\frac{A_{col} R_{dif} \eta_{opt}}{R^2} \right) P_{out} \tag{2}$$

where:

A_{col} = effective area of optical receiver in m^2
R_{dif} = differential reflectance of topographic targets
η_{opt} = optical efficiency
R = distance to topographic target in m
P_{out} = laser output power in W

The RMLD currently achieves a 5 ppm-m detection limit at 30 m using absorption from one of the strongest near-IR transitions of methane, a 4-in. diameter receiver optic, and P_{out} = 10 mW. Equation (1) shows that the collected power scales as the inverse of distance squared, so to achieve a comparable detected photocurrent at 50,000 ft (~ 15,000 m), we would require 2.5 kW of laser power with the same 4-in. receiver, but would need only 125 W with an 18-in. diameter receiver. This laser power and mirror diameter is achievable with scalable fiber amplifier technology and a compact sensor payload consistent with anticipated future flight vehicles. In the current program we will demonstrate the laser power of 5 W and an effective mirror diameter to 10 in., sufficient to demonstrate leak detection from 10,000 ft. The noise-floor of the sensor will correspond to a path-integrated detection limit of 1000 ppm-m. Thus, the sensor will be able to identify leaks of 0.1% methane in a 1 m plume. This is 40 times lower than the explosive limit threshold. A summary of the expected sensor performance specifications is given in Table 2.

Table 2. Summary of Airborne Sensor Target Specifications

	Prototype – This Program	**High-Altitude – Scaled Version**
Operational Ceiling	10,000 ft	50,000 ft
Eye-Safe Laser Power	5 W	125 W
Target Diameter	10 m	50 m
Response Bandwidth	10 Hz	10 Hz
Detection Limit	1000 ppm-m	1000 ppm-m
Ground Survey Speed	50 m/s	50 m/s
Payload Weight	< 100 lbs	< 100 lbs
Power Requirement	< 300 W	< 8 kW

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ACKNOWLEDGEMENTS

The authors acknowledge the support and encouragement of many sponsors in the development and testing of RMLD including Angelo Fabiano of NGA. Dan Driscoll and Rodney Anderson of DoE/NETL sponsored our participation in the RMOTC tests and the development of an airborne version of RMLD. PSI acknowledges the unwavering commitment of our partner Heath Consultant Incorporated in the RMLD development, in particular Jim Rutherford and Steve Chancey. We acknowledge the careful planning and implementation of the pipeline testing by the staff at RMOTC, Chris Buckingham of SwRI and their sponsorship by the DoT OPS.

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