DOE/RMOTC - 41010

PERGAM GAS LEAK DETECTION

Final Report for the Period of August 2006 to January 2007

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By

Lyle Johnson, RMOTC, Casper, WY

Aaron Bufton and Oleg Ershov, Pergam Technical Services

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Rocky Mountain Oilfield Testing Center (RMOTC)

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DISCLAIMER

ABSTRACT

Pergam Technical Services (Pergam) conducted a series of pipeline leak tests with an airborne laser-based detection system (ALMA) in September 2006 at the Rocky Mountain Oilfield Testing Center (RMOTC). The pipeline surveillance course is a simulated underground pipeline 7.5 miles (12 km) in length with 15 predetermined leak points. These leak points and leak rates were blinded to the testers and were changed twice a day for the testing period. The leak rates ranged from 1.8 to 5,000 scfh (0.05 to 140 scmh). As part of the testing protocol, data analyses were submitted by Pergam to RMOTC before the actual leak sites and rates were given to the testers. Pergam then compared its results to the actual results and explained any variances.

The Pergam helicopter mounted laser-based system detected methane leak rates between 50 and 5,000 scfh (1.4 and 140 scmh), 86% of the time. The leaks at 14 scfh (0.4 scmh) leak were detected an average of 15% of the time. Leaks rates below 7 scfh (0.2 scmh) were never detected. The system remained operational throughout the three-day test. The Pergam airborne methane detection system produced substantial improvement in gas leak detection for the mid- and higher-range leak rates compared to systems tested in prior years.

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EXECUTIVE SUMMARY

Pergam Technical Services conducted a series of pipeline leak tests with an airborne laser-based detection system (ALMA) in September 2006 at the Rocky Mountain Oilfield Testing Center (RMOTC), located 35 miles (56 km) north of Casper, Wyoming. The pipeline surveillance course is a simulated underground pipeline 7.5 miles (12 km) in length with 15 predetermined leak points. These leak points and leak rates were blinded to the testers and were changed twice a day for the testing period. The leak rates ranged from 1.8 to 5,000 scfh (0.05 to 140 scmh). As part of the testing protocol, data analyses were submitted by Pergam to RMOTC before the actual leak sites and rates were given to the testers. Pergam then compared its results to the actual results and explained any variances.

The simulated pipeline was constructed in 2004 for previous leak detection testing. Previous tests were conducted under the same scientific conditions with gas detection systems utilizing several technologies including Passive Infrared Multi Spectral Scanning, Laser-based Differential Absorption (Lidar), Hyper Spectral Imaging, and Tunable Diode Laser Absorption Spectroscopy. The systems were mounted in an automobile, helicopter, or fixed-wing aircraft. For these tests, the detection of leak rates of 500 scfh (14 scmh) or higher was only 50% with the detection rate rapidly decreasing to 5% for 10-15 scfh (0.3-0.4 scmh) and 0% for 1.8 scfh (0.05 scmh) leaks.

The Pergam helicopter mounted laser-based system detected methane leak rates between 50 and 5,000 scfh (1.4 and 140 scmh) 86% of the time. The leaks at 14 scfh (0.4 scmh) leak were detected an average of 15% of the time. Leaks rates below 7 scfh (0.2 scmh) were never detected. The system remained operational throughout the three-day test. The Pergam airborne methane detection system produced substantial improvement in gas leak detection for the mid- and higher-range leak rates compared to systems tested in prior years.

INTRODUCTION

The Rocky Mountain Oilfield Testing Center (RMOTC) is located at the Teapot Dome oil field, also known as the Naval Petroleum Reserve No. 3 (NPR-3). The field is 35 miles (56 km) north of Casper, Wyoming (Figure 1). RMOTC is operated by the Department of Energy as a test site for new and developing oil and gas and renewable energy related technologies.

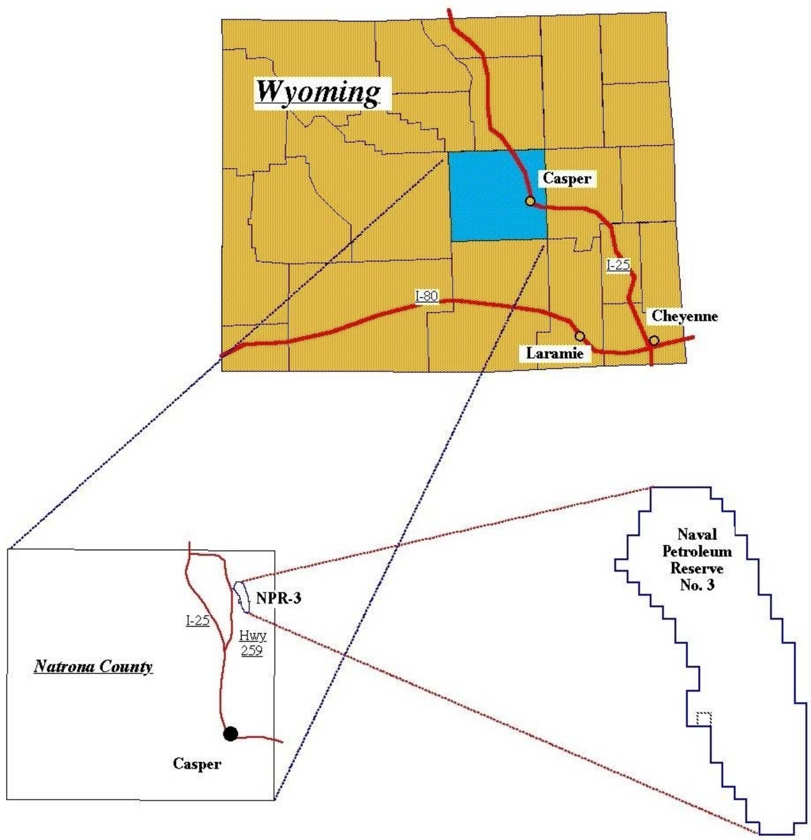


Figure 1. Location map for Rocky Mountain Oilfield Testing Center.

The oil and gas pipeline infrastructure within the United States is aging and deteriorating. The explosions and loss of lives in New Jersey and New Mexico, as well as major supply line closures in Alaska, have confirmed these facts. The industry needs a method to access individual pipelines and find leaks before they create major economic and personal loss.

The pipeline surveillance course at RMOTC is a simulated underground pipeline 7.5 miles (12 km) in length with 15 predetermined leak points (Figure 2). The course and leak points were constructed in 2004 based on the recommendations and design by an advisory panel made up of representatives from the Department of Energy (DOE), trade organizations, gas companies, and Southwest Research Institute. This panel determined all critical issues such as leak rates, leak locations, topography, ambient conditions, and the creation of a "calibration" leak site (Buckingham, J. C., et.al., 2004). To identify the "virtual pipeline," ground markers and GPS waypoint coordinates were provided. The waypoint coordinates were originally provided based on the NAD27 datum; unfortunately, the GPS equipment used by the testers required NAD83 datum. The leak locations and waypoints were re-surveyed based on the NAD83 datum and new coordinates were produced.

For this testing, the majority of the leak points and leak rates were blinded to the testers and were changed twice a day for the three days of testing. Location and rate for one or two of the leak points were given to the testers for calibration purposes. The leak rates range from 1.8 to 5,000 scfh (0.05 to 140 scmh).

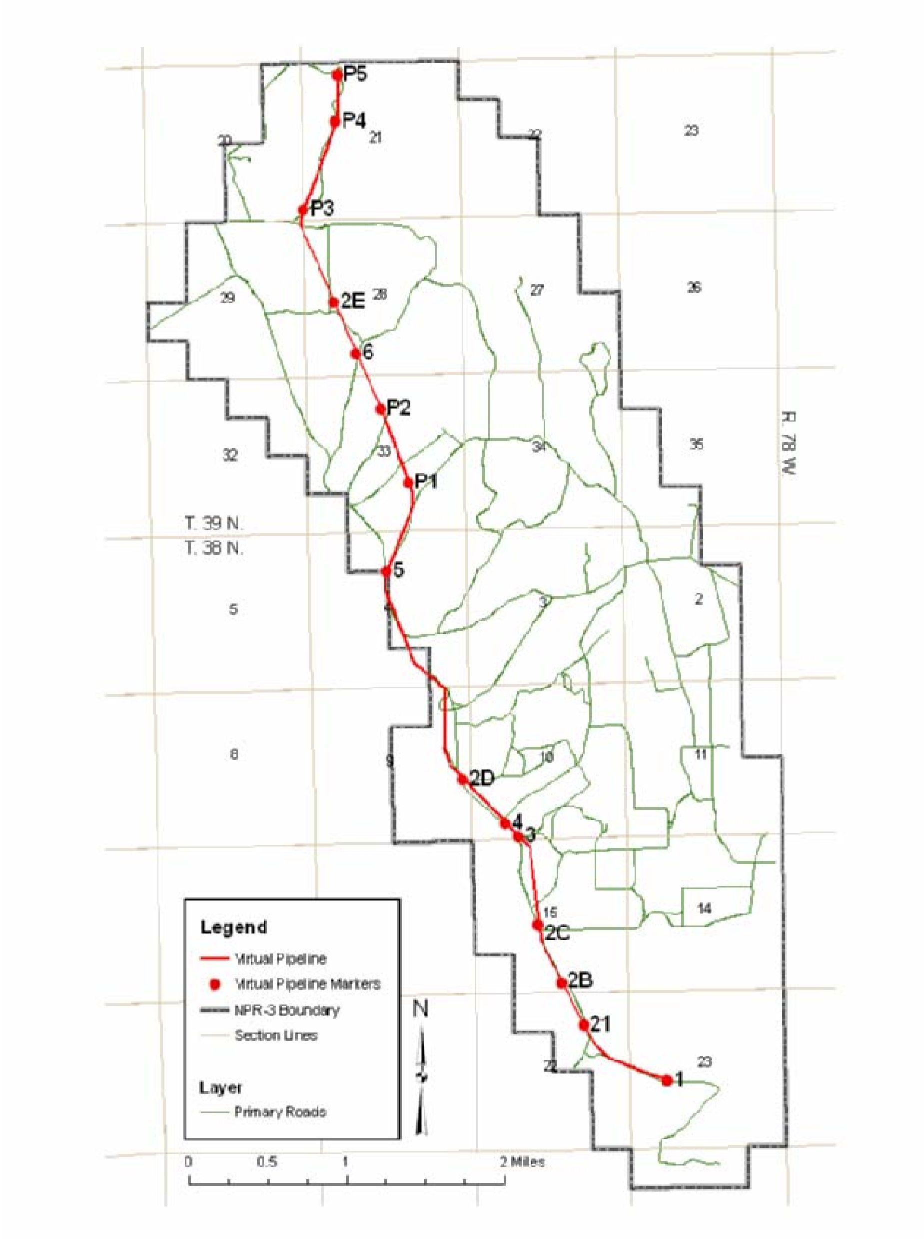


Figure 2. Virtual pipeline with leak points

Pergam Equipment Details

The Pergam-Suisse ALMA system (Figure 3) detects methane gas leaks from airborne platforms (predominately helicopters, Figures 4 and 5) by passing a laser beam through the methane cloud that surrounds the leak source. The infrared laser light emitted includes a wavelength in the region of 1,650 nm that methane absorbs. The system analyzes the laser light backscatter to determine how much, if any, of the laser energy was absorbed by methane. The operator monitors the data provided by the system to confirm leak detections, helps the pilot with navigating along the pipeline, and determines if an area needs further inspection. The system continually records the data including GPS information. The system consists of an optical unit containing the laser, camera, and helicopter mount; an electronic unit with DGPS antenna; a notebook computer; and a pilot monitor. Additional options, including a digital video recorder and IR cameras, are available.

Figure 3. ALMA system optical unit (left); electronic unit, digital video recorder, and pilot monitor (center); and notebook computer (right)

Figure 4. ALMA optical unit attached to Bell JetRanger via the side mount

Figure 5. ALMA optical unit attached to Bell JetRanger via the loadsling mount

The methane leak detection reliability is dependent on aiming the laser beam downwind of the pipeline to intercept the gas cloud. The distance downwind depends on the wind speed. Optimal operation is between 15 and 65 feet (5 and 20 meters) downwind. The optical unit is rigidly fixed to the helicopter enabling the pilot to control the laser beam location with the helicopter position and attitude (roll, pitch, and yaw angles). The camera system, including the pilot monitor, displays the area around the laser beam position. The DGPS, visual references, and camera system are used in combination to aid the pilot and operator in correctly aiming the equipment.

Testing Methodology

For this series of tests, a predetermined schedule of leak sites and leak rates were developed. Each test day had two sets of rates and locations. Not all locations were used during a given period and the leak rates ranged from 1.8 to 5,000 scfh (0.05 to 140 scmh). All testing was planned to start near sunrise to minimize the effects of wind. Each day, the second set of conditions was established after the tester was satisfied with his data collection for the first set of releases. A 30-minute equilibrium period was set between each leak scenario. Leak rates were continually monitored during the testing.

Testing occurred over four days. The first day was for system calibration with the remaining three days (September 12-14, 2006) being for official testing. Each day, two different gas leak sets were provided by changing which of the 15 leaks were active and the size of the leak. Pergam made an average of three inspection runs of the "virtual pipeline" for each gas leak set. The ground speed, altitude, and navigation position was varied during some of the runs to demonstrate system performance. To perform an impartial and controlled evaluation of the ALMA leak detection system, Pergam was required to provide an analysis of its testing results prior to RMOTC providing the actual leak data scenarios. Pergam then re-evaluated its results based on the actual data.

TEST RESULTS

Pergam made three or four flyovers of the "virtual pipeline" for each gas leak set September 12-14, 2006. The setup in Figure 4 was used for this test. The ground speed, altitude, and navigation position was varied during some of the runs to evaluate system performance. The summary of the results of the testing is given in Tables 1-3 and Figure 6. Detailed analysis of missed detections for rates greater than 50 scfh (1.4 scmh) are given in Appendix A. More details of each flyover, including measured values for each leak, are given in Appendix C.

Table 1. Data and results for September 12, 2006, testing

Date		**September 12, 2006**				**September 12, 2006**				
Gas Leak Set		**Set 1**				**Set 2**				
Run		**Leak Size** (scfh)	1	2	3	**Leak Size** (scfh)	1	2	3	4
Altitude			150 ft	150 ft	150 ft		150 ft	200 ft	300 ft	150 ft
Ground Speed			45 mph	45 mph	45 mph		45 mph	45 mph	45 mph	60 mph
Wind Speed	**Ave**		6 mph	7 mph	7 mph		9 mph	8 mph	8 mph	8 mph
	Max		9 mph	12 mph	12 mph		13 mph	11 mph	14 mph	13 mph
Leak Point										
1		500	Yes	Yes	Yes	6				
2A		0				0				
2B		0				14				Yes
2C		0				0				
3		100	Yes	Yes	Yes	1000	Yes	A	Yes	Yes
4		2000	Yes	Yes	Yes	100	Yes	Yes	Nav	Yes
2D		14				0				
5		5000	Yes	Yes	Yes	5000	Yes	Yes	Yes	Yes
P1		740	Yes	Yes	Yes	740	Yes	Yes	Yes	Nav
P2		100	Nav	Yes	Yes	100	Yes	Yes	Yes	Nav
6		1000	Nav	Yes	Yes	500	Yes	Yes	Yes	Yes

2E	14		Yes		0				
P3	14		Yes		14				
P4	0				0				
P5	3.5				3.5				
Detection Reliability for >50 scfh leaks		71%	100%	100%		100%	83%	83%	67%
Detection Reliability for all leaks		45%	82%	64%		60%	50%	50%	50%

A = Miss - Incorrect Analysis
Nav = Miss - Incorrect Navigation

Table 2. Data and results for September 13, 2006, testing

Date		**September 13, 2006**				**September 13, 2006**			
Gas Leak Set		**Set 1**				**Set 2**			
Run		**Leak Size** (scfh)	1	2	3	**Leak Size** (scfh)	1	2	3
Altitude			150 ft	150 ft	200 ft		150 ft	150 ft	150 ft
Ground Speed			45 mph	40 mph	40 mph		45 mph	40 mph	60 mph
Wind Speed	**Ave**		19 mph	17 mph	20 mph		15 mph	16 mph	16 mph
	Max		24 mph	24 mph	25 mph		24 mph	27 mph	24 mph
Leak Point									
1		700	Wind	Wind	Wind	500	Wind	Yes	Wind
2A		14				0			
2B		0				0			
2C		0				14			
3		2000	Yes	Yes	Yes	100	Yes	Yes	Yes
4		50	Yes	Yes	Yes	2000	Yes	Yes	A
2D		14				0			
5		4700	Yes	Yes	Yes	3000	Yes	Yes	Yes
P1		740	Yes	Yes	Yes	740	Yes	Yes	Yes
P2		100	Yes	Yes	Yes	100	Yes	Yes	Yes
6		100	Yes	Yes	Wind	1000	Yes	Yes	Yes
2E		0				0			
P3		250	Yes	Yes	Yes	500	Wind	Yes	Yes
P4		14				14			
P5		1.8				1.8			
Detection Reliability for >50 scfh leaks			88%	88%	75%		75%	100%	75%
Detection Reliability for all leaks			58%	58%	50%		55%	73%	55%

A = Miss - Incorrect Analysis
Wind =Miss - Incorrect Anticipation of Wind Direction

Table 3. Data and results for September 14, 2006, testing

Date		**September 14, 2006**				**September 14, 2006**			
Gas Leak Set		**Set 1**				**Set 2**			
Run		**Leak Size** (scfh)	1	2	3	**Leak Size** (scfh)	1	2	3
Altitude			150 ft	50 ft	400 ft		100 ft	100 ft	100 ft
Ground Speed			55 mph	70 mph	55 mph		55 mph	55 mph	55 mph
Wind Speed	**Ave**		8 mph	12 mph	14 mph		20 mph	20 mph	20 mph
	Max		16 mph	17 mph	22 mph		27 mph	27 mph	28 mph
Leak Point									
1		100	Yes	N/A	Yes	500	Yes	Yes	Yes
2A		0				14	Yes	Yes	Yes
2B		14				0			
2C		0				0			
3		2000	Yes	N/A	Yes	500	Yes	Yes	Yes
4		1000	Nav	N/A	Yes	2000	Yes	Yes	Yes
2D		0				0			
5		5000	Noise	Yes	Yes	3000	Yes	Yes	Yes
P1		740	Noise	N/A	Yes	740	Wind	Yes	Yes
P2		1000	Yes	Yes	Wind	100	Yes	Yes	N/A
6		500	Yes	N/A	Wind	1000	Yes	Yes	Yes
2E		14				0			
P3		250	Yes	Yes	Yes	250	Yes	Yes	Yes
P4		7				7			
P5		1.8				1.8			
Detection Reliability for >50 scfh leaks			63%	38%**	75%		88%	100%	88%†
Detection Reliability for all leaks			42%	25%**	50%		73%	82%	73%†

Nav = Miss - Incorrect Navigation

Wind =Miss - Incorrect Anticipation of Wind Direction

N/A = see below for explanation of run

** Set 1, Run 2 was low level flight to gather more data for system noise investigation

† Set 2, Run 3 wasflown upwind to understand upwind detection capability

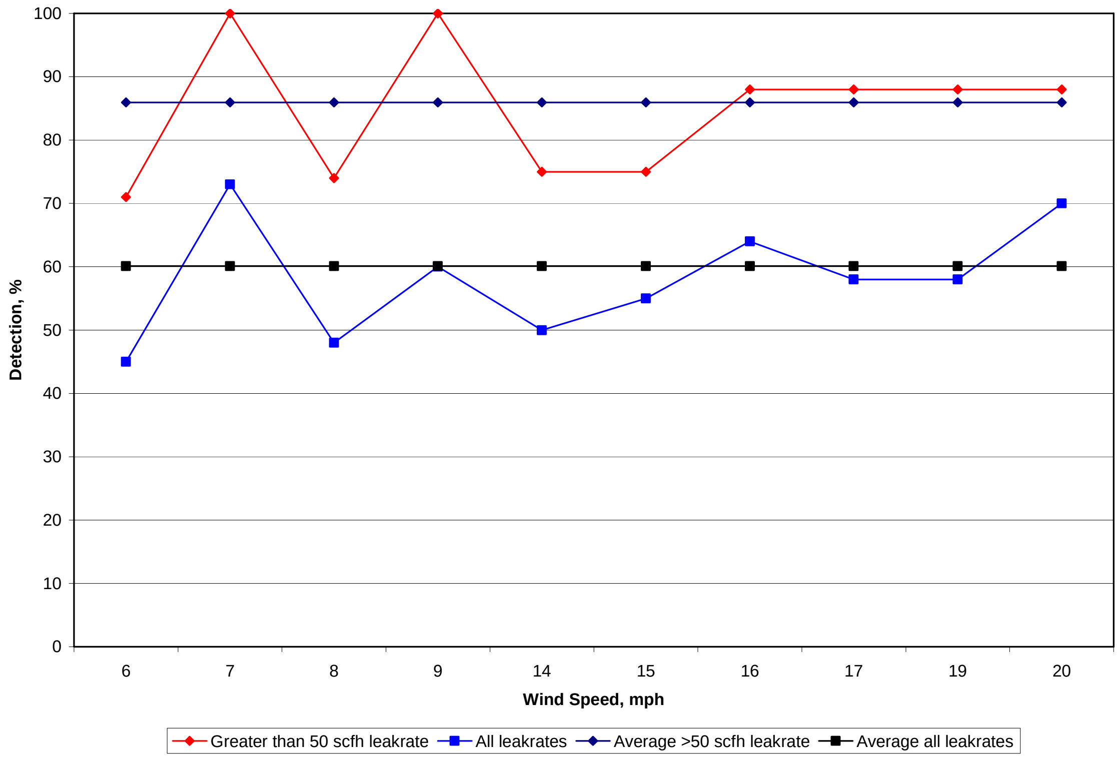


Figure 6. Wind speed versus detection rate for all tests

The ALMA system's average run leak detection reliability was 60% for all leaks presented and 86% for leaks 50 scfh (1.4 scmh) and larger. Fifty percent of these runs encountered what was considered to be strong wind conditions. Five of the 19 runs detected 100% of the leaks 50 scfh (1.4 scmh) and larger. Two of the five runs occurred in strong wind conditions. The combination of strong wind and terrain at the RMOTC testing site made it difficult to aim the laser beam at the optimal position downwind of the leak sources. The ridges and gullies caused inconsistency in the wind direction and speed. The landscape at NPR-3 is generally barren with very few indications of wind direction. The wind data is taken from one weather station on the RMOTC field about 0.75 miles (1.2 km) east of the "virtual pipeline" center. The data provided generic information of the wind speed and direction, but as it would be in the real world, did not describe what was actually happening at each leak source.

The leak size of 50 scfh (1.4 scmh) appeared to be near the end of the system detection range with any significant wind. Depending on conditions, the system can detect smaller leaks. Leak rates of 14 scfh (0.4 scmh) were detected an average of 15% of the time while rates below 7 scfh (0.2 scmh) were never detected

The system had no false detections during the runs and remained operational throughout the three-day test. The main influences on the system leak detection reliability were navigation and prediction of wind conditions.

The system did detect two other methane leak sources while flying over other parts of the RMOTC facility. These leaks were associated with other field operations and are discussed at the end of Appendix A.

CONCLUSIONS & DISCUSSION

The Pergam helicopter mounted laser-based system detected 60% of all methane leaks and 86% of all leaks between 50 and 5,000 scfh (1.4 and 140 scmh). Several runs had 100% detection of leaks between 50 and 5,000 scfh (1.4 and 140 scmh). Lower-level leaks were not routinely detected. The leaks at 14 scfh (0.4 scmh) were detected an average of 15% of the time; leaks rates below 7 scfh (0.2 scmh) were never detected.

The system remained operational throughout the three-day test, had no false detections, and performed well in windy conditions. Compared with previous tests in prior years, the Pergam airborne methane detection system produced substantial improvements in gas leak detection for the mid- and higher-range leak rates.

REFERENCES

Buckingham, J. C., et al.: "Field Testing of Remote Sensor Gas Leak Detection Systems, Final Report," Prepared for Department of Energy and Department of Transportation, SwRI Project No. 18.10485, December, 2004, Southwest Research Institute, Houston, TX.

APPENDIX A

Example of a Methane Leak Source Detection

The methane cloud from Leak Source 5 was detected during three sequential inspection runs. Figure A1 depicts the helicopter flight paths and methane leak detection locations relative to the coordinates of Leak Source 5. The measured distances are from the leak source to the helicopter position. The distances do not take into account how the helicopter attitude affects the laser beam position or the inaccuracy of the leak source coordinates.

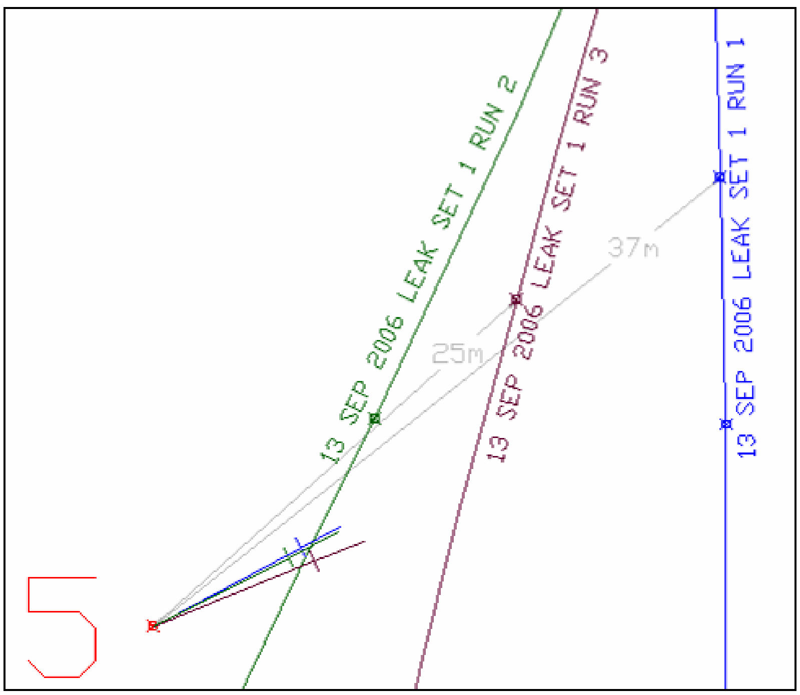


Figure A1. Diagram of flight paths and leak detections for Runs 1-3 on September 13, 2006, with Gas Leak Set 1 at Leak Source 5 (See Appendix B for legend)

Analysis of Misses

The miss on 12 September 2006 with Gas Leak Set 1 during Run 1 at Leak Source P2

Navigation was the cause of the miss. Figure A2 shows the flight path too far right to have detected the gas cloud.

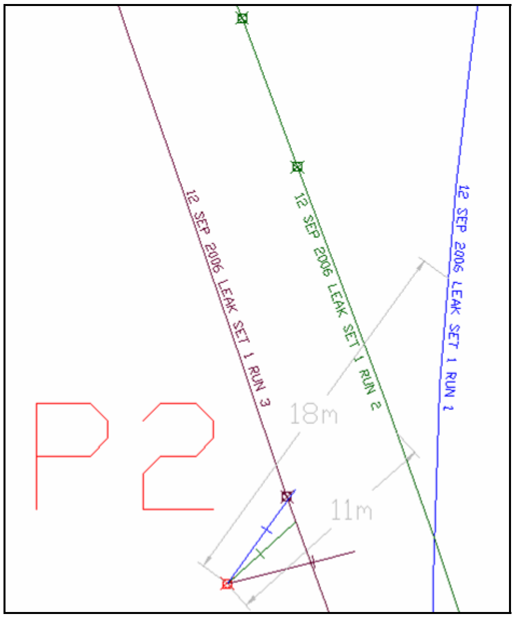


Figure A2. Diagram of flight paths and leak detections for Runs 1-3 on September 12, 2006, with Gas Leak Set 1 at Leak Source P2 (See Appendix B for legend)

Miss on 12 September 2006 with Gas Leak Set 1 during Run 1 at Leak Source 6

Navigation was the cause of the miss. Figure A3 shows that the flight path of Run 1 was within 2 meters of the leak source. Most likely the helicopter attitude was such that the laser passed upwind of the leak source. Figure A3 shows detection on the second and third runs at 13 and 16 feet (4 and 5 meters) downwind of the leak source.

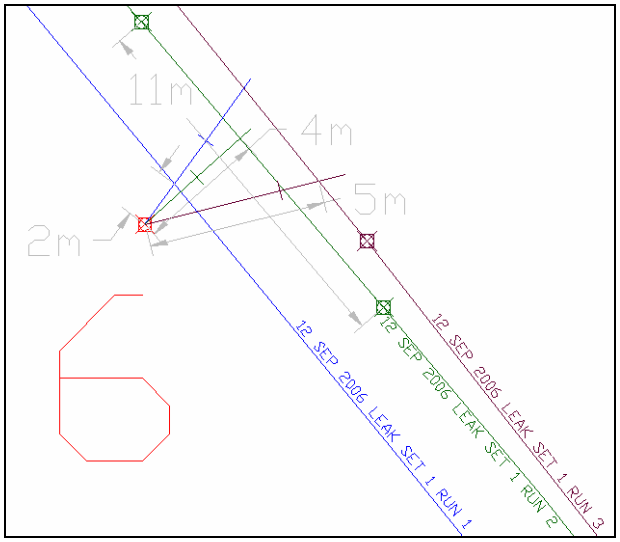


Figure A3. Diagram of flight paths and leak detections for Runs 1-3 on September 12, 2006, with Gas Leak Set 1 at Leak Source 6 (See Appendix B for legend)

Miss on 12 September 2006 with Gas Leak Set 2 during Run 2 at Leak Source 3

Misinterpreting the leak detection signal during the offline analysis was the cause of the miss. Figure A4 shows the leak was detected at 10:30:17.67. It was interpreted as another detection of the upwind leak due to the low concentration of the signal. The gas cloud detection locations displayed in Figure A5 found during the other runs show the inconsistency of the wind measurement for this leak source and the inaccuracy of the coordinates. Figure A5 also displays the location of the missed signal.

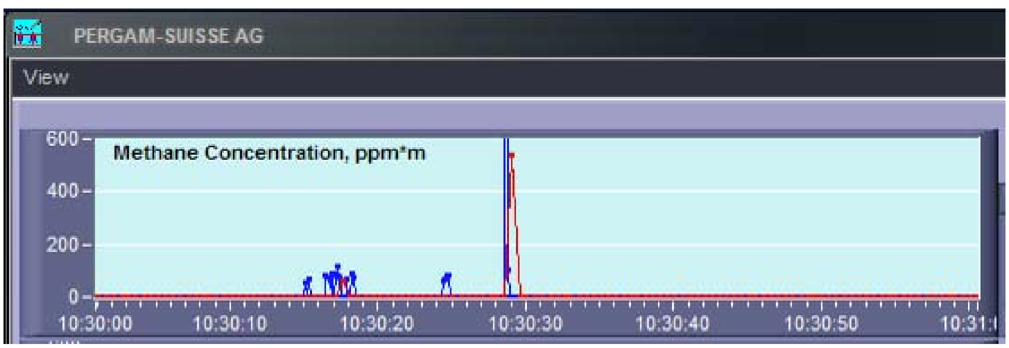


Figure A4. Graph of the gas detections for Run 2 on September 12, 2006, with Gas Leak Set 2 at Leak Source 3 and 4

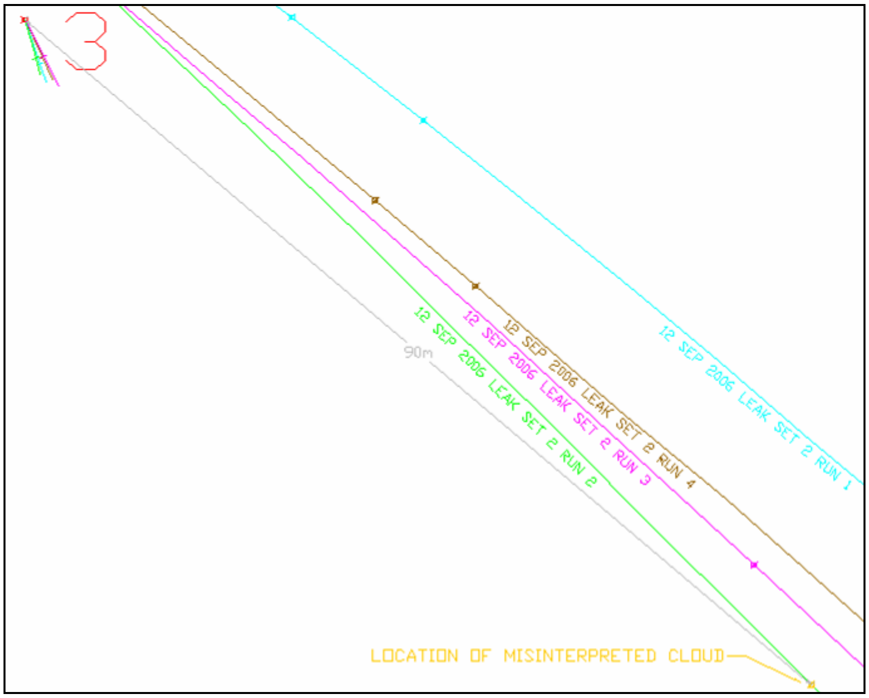


Figure A5. Diagram of flight paths and leak detections for Runs 1-4 on September 12, 2006, with Gas Leak Set 2 at Leak Source 3 (See Appendix B for legend)

Miss on 12 September 2006 with Gas Leak Set 2 during Run 3 at Leak Source 4

> Navigation was the cause of the miss. Figure A6 shows the flight path of Run 3 was upwind of the leak source. Several small gas detections seen in Figure A7 indicate the equipment detected the edge of the gas cloud. Normally this data would prompt the operator to inspect the area again. The gas detection locations in Figure A6 also show that either the measured wind direction or the leak source coordinates relative to the flight paths were inaccurate.

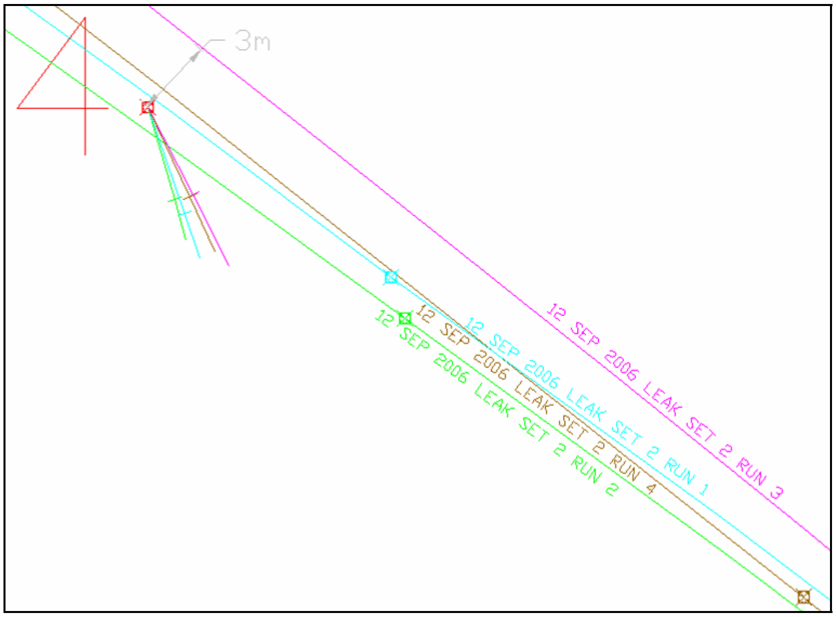


Figure A6. Diagram of flight paths and leak detections for Runs 1-4 on September 12, 2006, with Gas Leak Set 2 at Leak Source 4 (See Appendix B for legend)

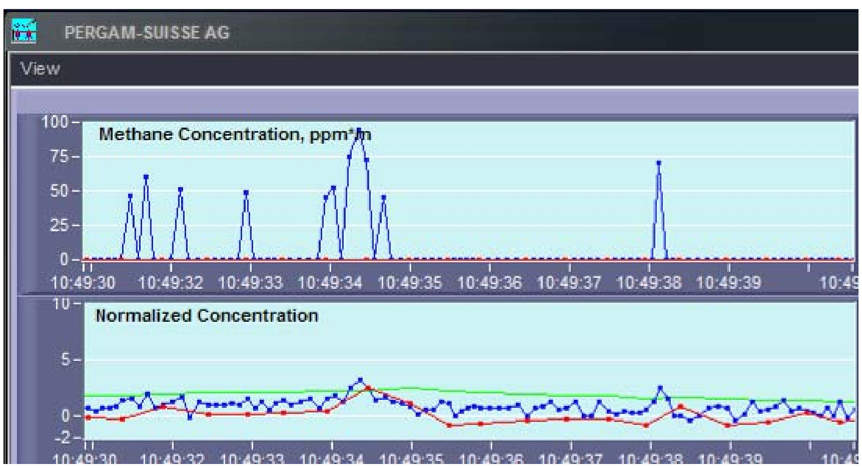


Figure A7. Graph of the gas detections for Run 3 on September 12, 2006, with Gas Leak Set 2 at Leak Source 4

Miss on 12 September 2006 with Gas Leak Set 2 during Run 4 at Leak Source P1

Navigation was the cause of the miss. The equipment was aimed too close to the source to detect the cloud. Figure A8 shows the flight path of Run 4 was upwind of the leak source, but the picture in Figure A9 shows the laser passing within 1 meter of the leak source. The best results are obtained by pointing the equipment at least 16 feet (5 meters) downwind of the leak source. It is known that the P1 leak source was on the west side of the road, but Figure A10 shows the coordinates on the right side of the road. The true position of P1 should be at least 20 meters to the right, which would align the leaks detected with the wind direction in Figure A8. A small cloud was detected south of the leak source (Figure A8 & A11). Normally this data would prompt the operator to inspect the area again.

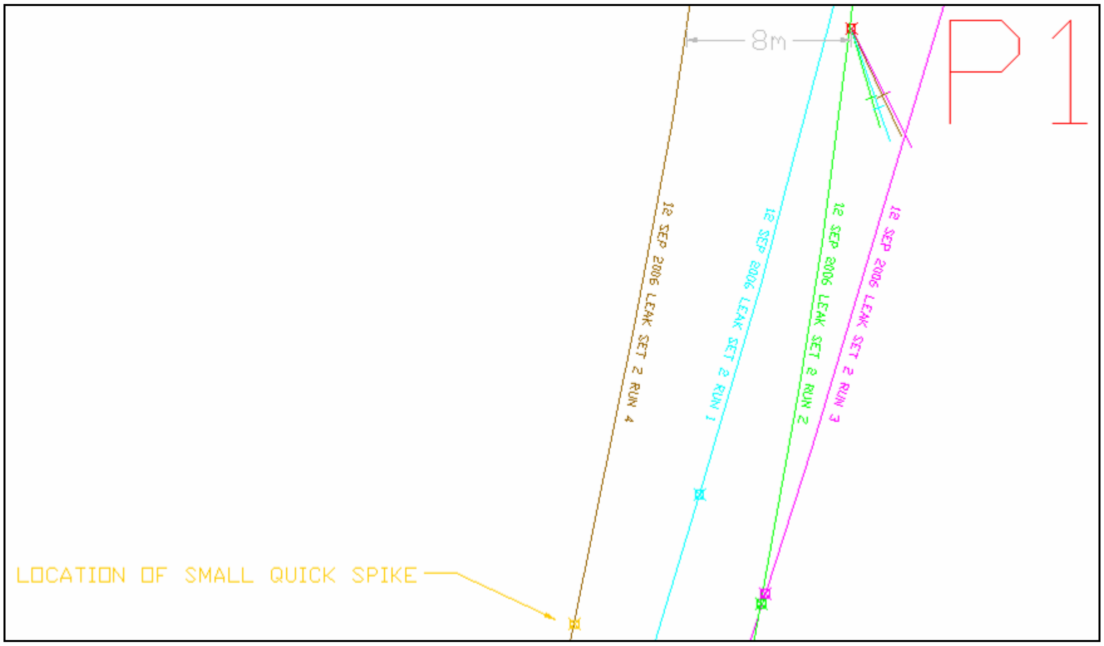


Figure A8. Diagram of flight paths and leak detections for Runs 1-4 on September 12, 2006, with Gas Leak Set 2 at Leak Source P1 (See Appendix B for legend)

Figure A9. Picture from the flight recording of the P1 leak source during Run 4

Figure A10. Google Earth image of Leak Source P1 with coordinates. The coordinates are from the second set. For scale, the white line is 10 meters

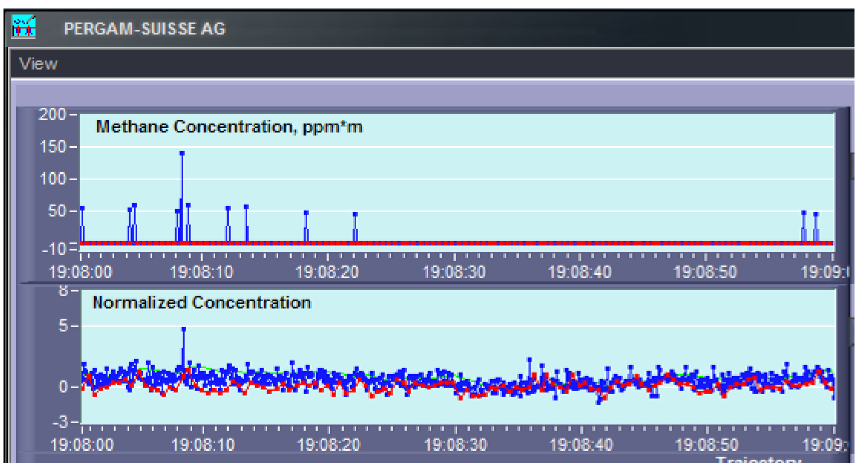


Figure A11. Graph of the gas detections for Run 4 on September 12, 2006, with Gas Leak Set 2 at Leak Source P1

Miss on 12 September 2006 with Gas Leak Set 2 during Run 4 at Leak Source P2

Navigation was the cause of the miss. Figure A12 shows the laser passed upwind of the leak source.

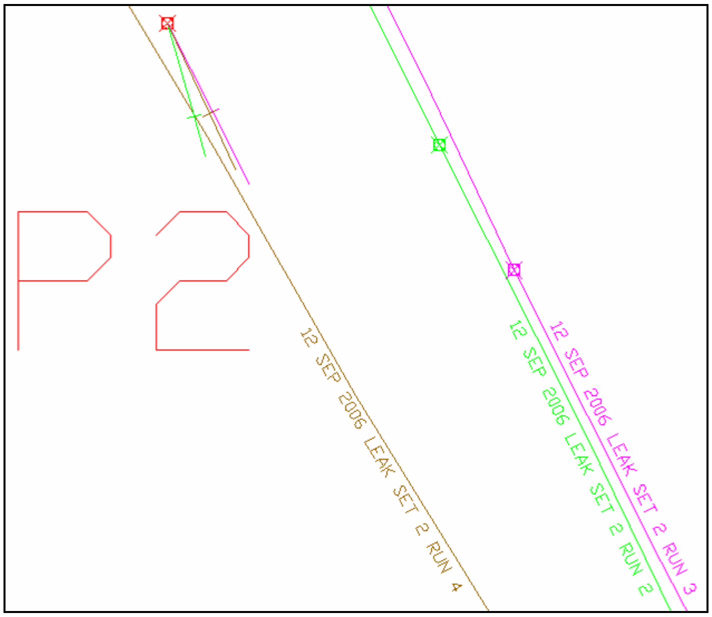


Figure A12. Diagram of flight paths and leak detections for Runs 1-4 on September 12, 2006, with Gas Leak Set 2 at Leak Source P2 (See Appendix B for legend)

Misses on 13 September 2006 with Gas Leak Set 1 during Runs 1-3 and with Gas Leak Set 2 during Runs 1 & 3 at Leak Source 1

The cause of the misses was an unanticipated difference in wind direction at Leak Source 1 compared to ground and airborne indications. The wind was very strong with an average speed of 17 mph (28 kph) and gusts up to 25 mph (40 kph). It is known that Leak Source 1 was south of the rig on the west side of the road, but Figure A13 shows the coordinates on the right side of the road. The true position of Leak Source 1 should be roughly 200 feet (60 meters) to the west. Figure A14 shows that the flight paths were correct for either position for the expected wind direction. Figure A15 confirms that the equipment was aimed in the correct position (about 32 feet [10 meters] from leak source) for the expected wind direction. The one gas detection seen in Figure A16 was a small, quick signal, which means only the low-concentration side of the gas cloud was detected. Figure A17 shows successful detections at the same leak source during runs on the next day in similar wind speed but with a different wind direction.

Figure A13. Google Earth image of Leak Source 1. The coordinates on the right are from the second set. The coordinates on the left are based on field observations of the leak source position

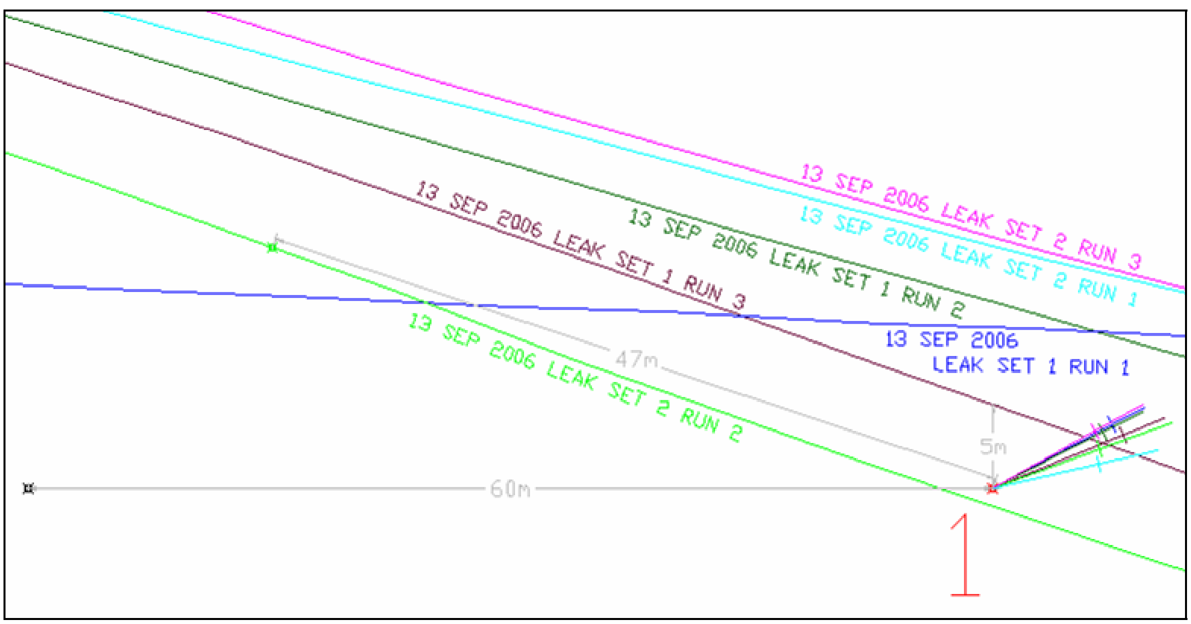


Figure A14. Diagram of flight paths and leak detections on September 13, 2006, with Gas Leak Set 1 during Runs 1-3 and with Gas Leak Set 2 during Runs 1 and 3 at Leak Source 1 (See Appendix B for legend)

Figure A15. Pictures from the flight recording of Leak Source 1 during Run 3

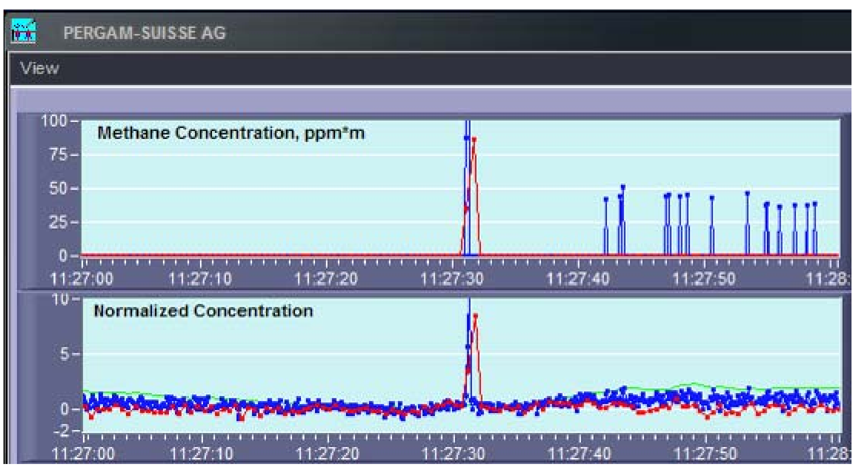


Figure A16. Graph of the gas detections for Run 2 on September 13, 2006, with Gas Leak Set 2 at Leak Source 1

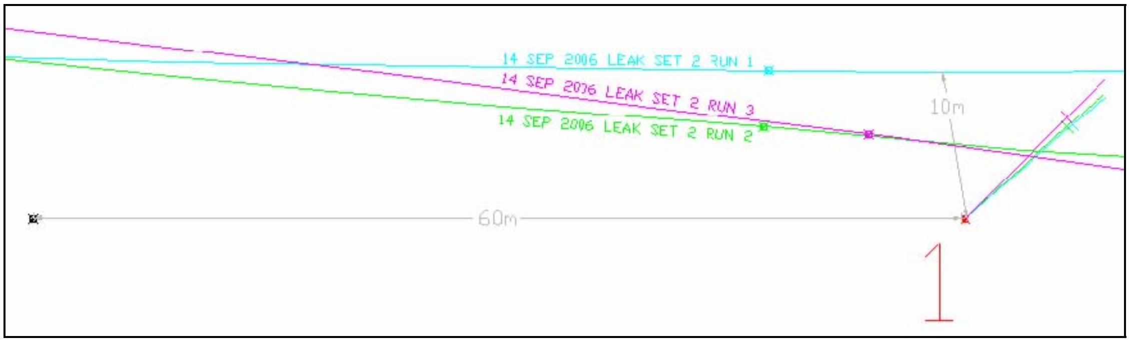


Figure A17. Diagram of flight paths and leak detections on September 14, 2006, with Gas Leak Set 2 during Runs 1-3

Miss on 13 September 2006 with Gas Leak Set 1 during Run 3 at Leak Source 6

The cause of the miss was an erratic wind direction. The different locations of leak detections shown in Figure A18 demonstrate how the wind direction varied during the runs. The picture in Figure A19 shows the flight path within 10 feet (3 meters) of the leak source on what was anticipated to be the downwind side. Offline analysis depicted in Figure A20 shows a quick signal which would correspond to a small, sparse gas cloud. Normally this data would prompt the operator to inspect the area again.

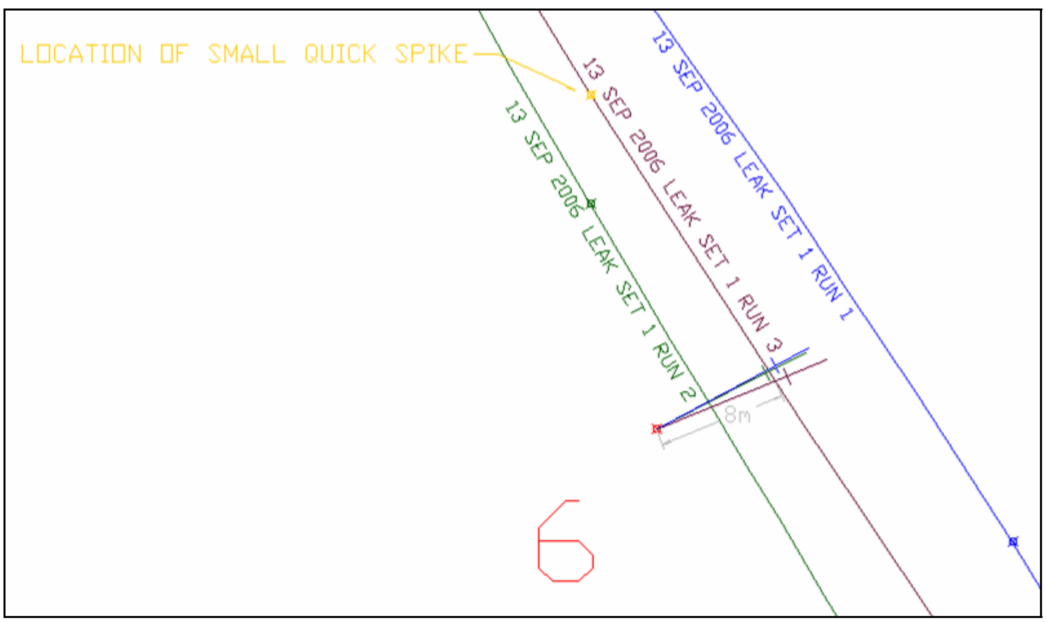


Figure A18. Diagram of flight paths and leak detections for Runs 1-3 on September 13, 2006, with Gas Leak Set 1 at Leak Source 6 (See Appendix B for legend)

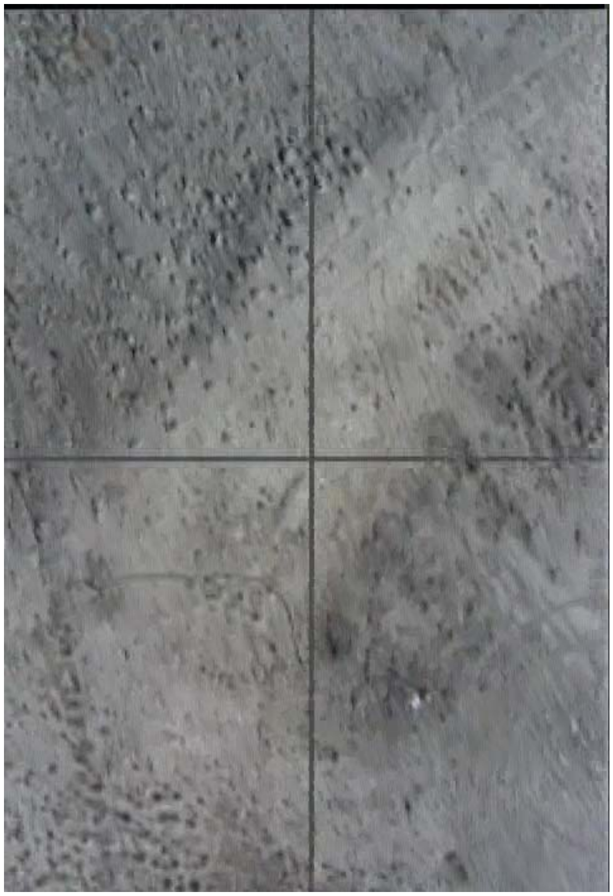


Figure A19. Pictures from the flight recording at Leak Source 6 during Run 3

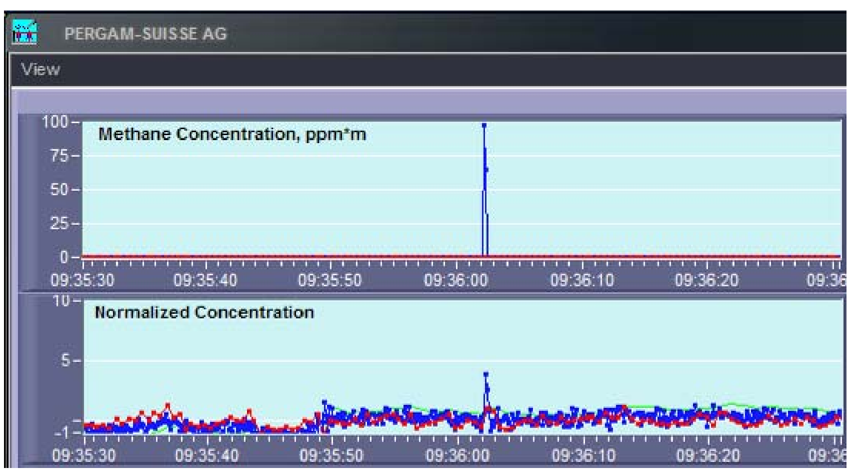


Figure A20. Graph of the gas detections for Run 3 on September 13, 2006, with Gas Leak Set 1 at Leak Source 6

Miss on 13 September 2006 with Gas Leak Set 2 during Run 1 at Leak Source P3

The cause of the miss was an unanticipated difference in wind direction at the leak source compared to ground and airborne indications. Figure A21 shows gas detections during the other runs north of the leak source. The wind indications were from the west.

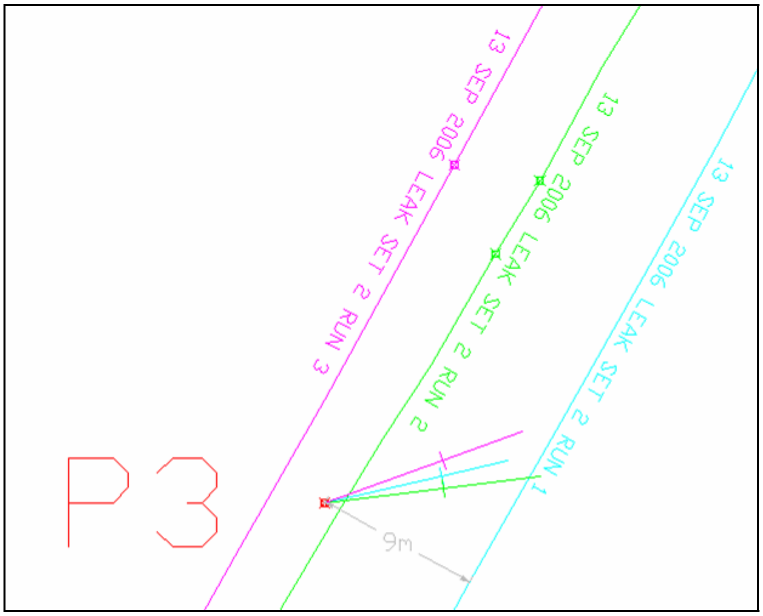


Figure A21. Diagram of flight paths and leak detections for Runs 1-3 on September 13, 2006, with Gas Leak Set 2 at Leak Source P3 (See Appendix B for legend)

Miss on 13 September 2006 with Gas Leak Set 2 during Run 3 at Leak Source 4

Analysis was the cause of the miss. The methane cloud was detected at 11:37:58.48. The low concentration of the signal led to interpreting the cloud as another detection of the upwind leak. The location of the misinterpreted cloud is displayed in Figure A22. The gas detection locations in Figure A22 also show that either the measured wind direction or the leak source coordinates relative to the flight paths were inaccurate. The numerous blue spikes in Figure A23 represent small gas detections signifying the area was full of methane.

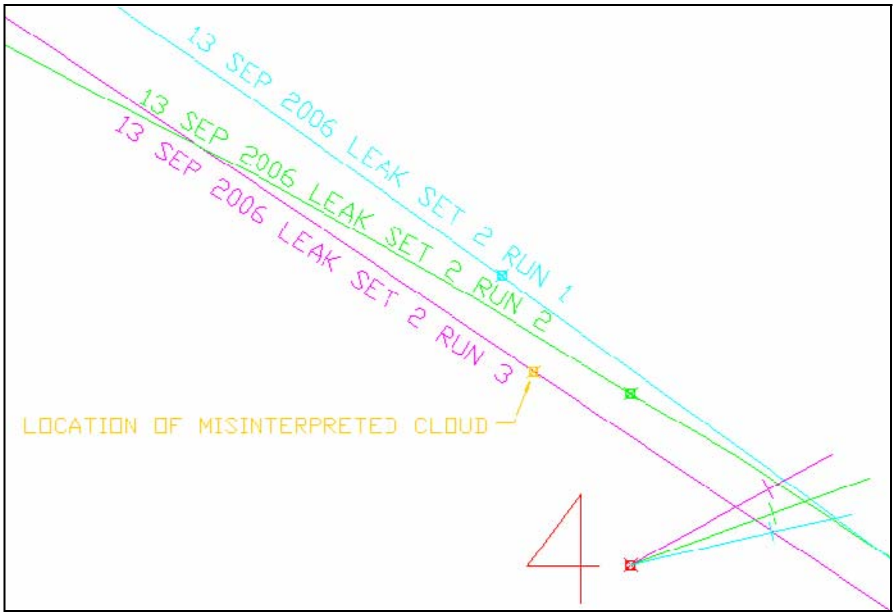


Figure A22. Diagram of flight paths and leak detections for Runs 1-3 on September 13, 2006, with Gas Leak Set 2 at Leak Source 4 (See Appendix B for legend)

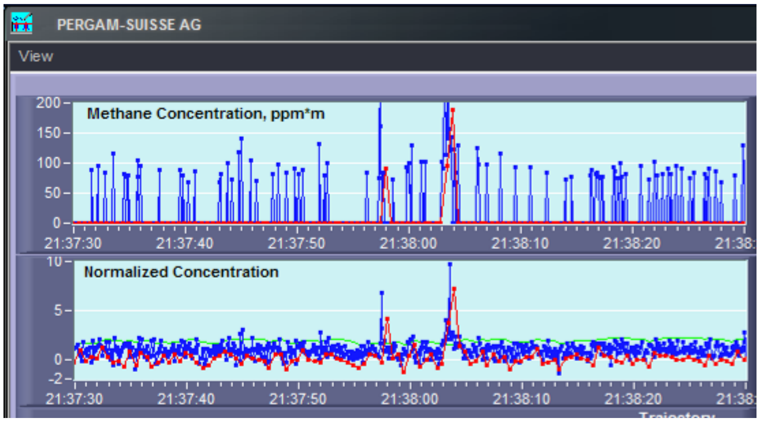


Figure A23. Graph of the gas detections for Run 3 on September 13, 2006, with Gas Leak Set 2 at Leak Source 3 and 4

Miss on 14 September 2006 with Gas Leak Set 1 during Run 1 at Leak Source 4

Navigation was the cause of the miss. Figure A24 shows the flight path upwind of the leak source which indicates the equipment was aimed either too close to or upwind of the leak source depending on the accuracy of the wind direction measurement and leak source coordinates.

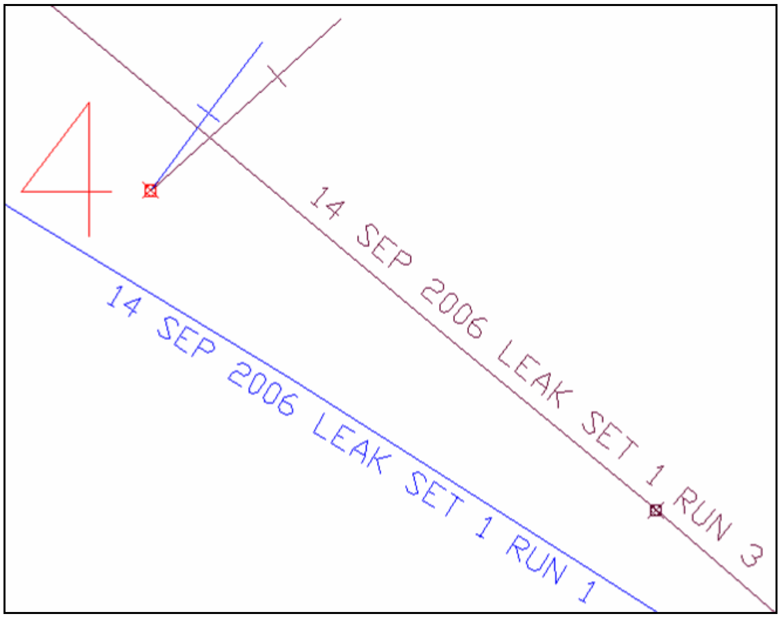


Figure A24. Diagram of flight paths and leak detections for Runs 1 and 3 on September 14, 2006, with Gas Leak Set 1 at Leak Source 4 (See Appendix B for legend)

Misses on 14 September 2006 with Gas Leak Set 1 during Run 1 at Leak Sources 5 and P1

Excessive system noise was the cause of the misses. Figure A25 depicts the noise. This was an unexpected event. The source of the noise was traced back to the quality of certain electronic components and a grounding issue. (The acceptance specs of these components have been tightened and changed how the optical unit is manufactured to reduce the noise to a level where it no longer affects system operation.)

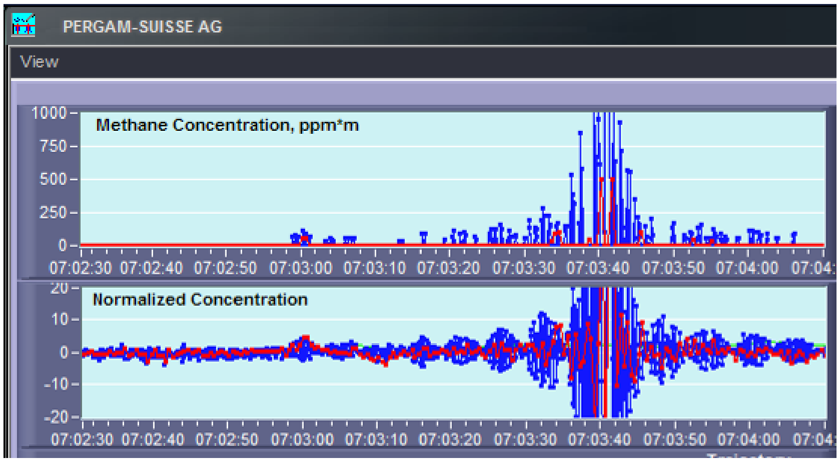


Figure A25. Graph of the gas detections for Run 1 on September 14, 2006, with Gas Leak Set 1 at Leak Source 5 and P1

Misses on 14 September 2006 with Gas Leak Set 1 during Run 2

The run was dedicated to investigating the system noise source and as such was unofficial.

Miss on 14 September 2006 with Gas Leak Set 1 during Run 3 at Leak Source P2

The cause of the miss was unanticipated difference in wind direction at Leak Source P2 compared to ground and airborne indications. Figure A26 shows a leak was detected during the previous official run.

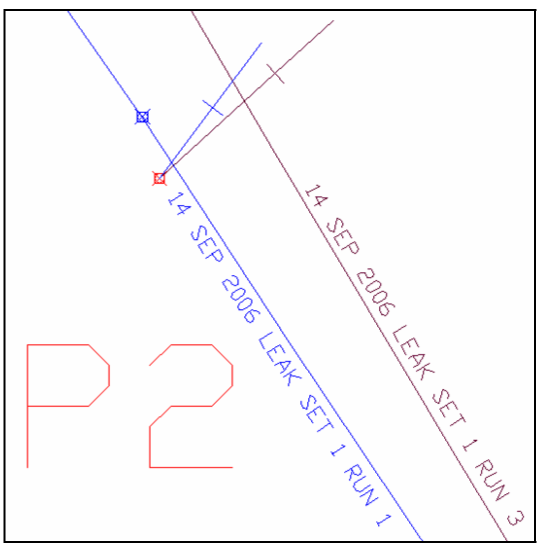


Figure A26. Diagram of flight paths and leak detections for Runs 1 and 3 on September 14, 2006, with Gas Leak Set 1 at Leak Source P2 (See Appendix B for legend)

Miss on 14 September 2006 with Gas Leak Set 1 during Run 3 at Leak Source 6

The cause of the miss was unanticipated difference in wind direction at Leak Source 6 compared to ground and airborne indications. Figure A27 shows leak detection during the previous official run.

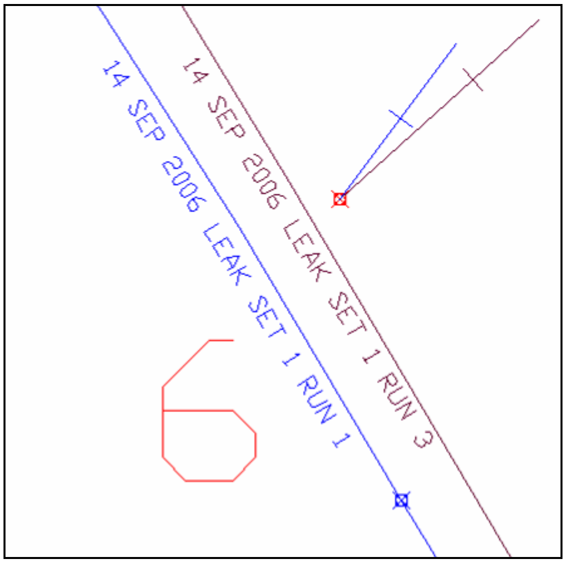


Figure A27. Diagram of flight paths and leak detections for Runs 1 and 3 on September 14, 2006, with Gas Leak Set 1 at Leak Source 6 (See Appendix B for legend)

Miss on 14 September 2006 with Gas Leak Set 2 during Run 1 at Leak Source P1

The cause of the miss was unanticipated difference in wind direction at Leak Source P1 compared to ground and airborne indications. Figure A28 shows gas leak detection during a later run in a different direction than the expected wind direction. The true position of the P1 leak source should be at least 65 feet (20 meters) to the right of the indicated position as discussed previously.

Figure A28. Diagram of the flight paths and leak detections for Runs 1 and 2 on September 14, 2006, with Gas Leak Set 2 at Leak Source P1 (See Appendix B for legend)

Misses on 14 September 2006 with Gas Leak Set 2 during Run 3 at Leak Sources P1, P2, 6, and P3

The last run was dedicated to investigating the ability of the system to detect methane leaks when aimed increasingly upwind of the leak source, and therefore was not an official run.

Other Methane Leak Source Detections

Table A1. Methane leak sources found in other areas of the RMOTC facility

Date	Registration time	Longitude (decimal)	Latitude (decimal)	Comments
13.09.06	11:29:29.03	-106.195400	43.287465	• Found while to the side of the "virtual pipeline" flying back to the starting point. • The location is in the vicinity of a large RMOTC treatment facility that has tanks with vents. • Designate as "Alpha" in Figure A29.
14.09.06	08:19:38.67	-106.188783	43.260868	• Found while to the side of the "virtual pipeline" flying to the starting point. • The location is near a RMOTC main gas line valve. • Designate as "Bravo" in Figure A29.

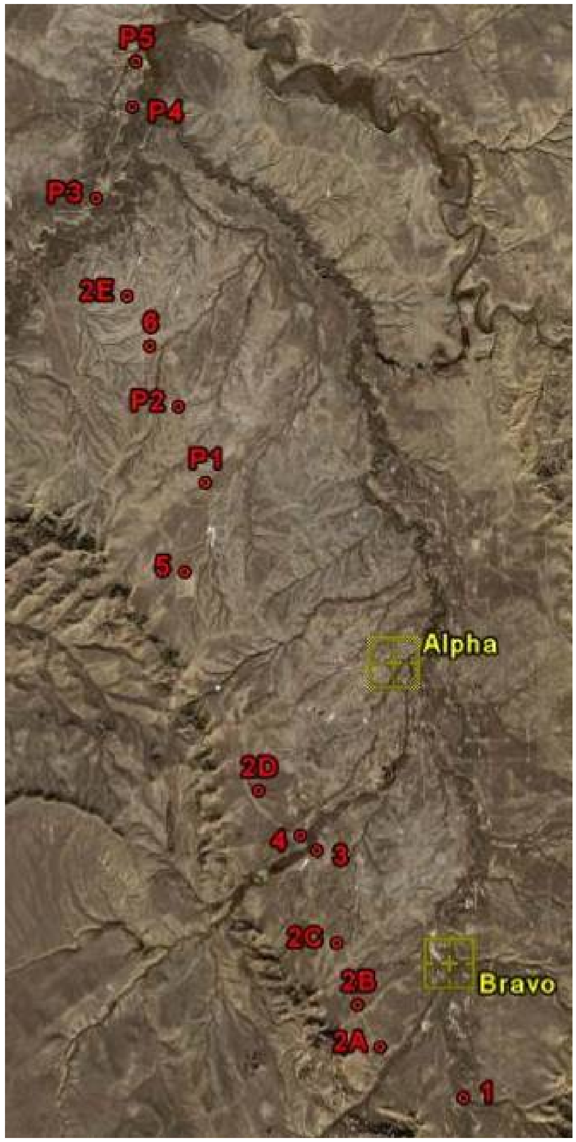
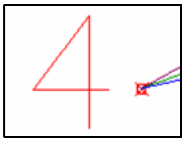


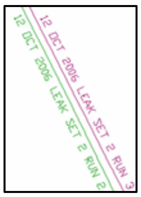
Figure A29. Google Earth image of RMOTC leak sources and other sources detected

APPENDIX B

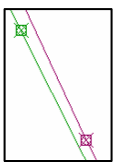
Legend for Diagram of Flight Paths and Leak Detections



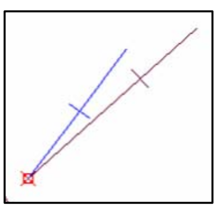
Leak sources are red points with red labels.



The flight paths or "virtual pipeline" inspection runs are colored lines.



Methane detection locations are points in the same color as the corresponding flight path.



The wind measurement data is depicted as a line originating at the leak source in the same color as the corresponding flight path. The line illustrates the approximate direction and distance gas could flow in 1 second. The average wind speed is the line originating at the leak source up to the perpendicular intersecting line. The maximum wind speed is the entire line length. The wind speed units are meters per second. The line uses the same scale for meters as the diagram.

APPENDIX C

List of Methane Gas Detections

12 September 2006; Gas Leak Set 1; Run 1

Leak name	Registration time	Longitude (decimal)	Latitude (decimal)	Methane, ppm*m	Comments
1	07:40:19.42	-106.187260	43.248292	261	
3	07:43:24.81	-106.205763	43.271080	310	
3	07:43:25.33	-106.205820	43.271150	191	
4	07:43:32.23	-106.207075	43.272252	170	
4	07:43:32.75	-106.207157	43.272312	1164	
5	07:45:39.11	-106.221643	43.295457	2543	
P1	07:47:28.58	-106.218983	43.303512	559	
P1	07:47:29.01	-106.219000	43.303595	133	
P1	07:47:29.58	-106.219012	43.303650	128	

12 September 2006; Gas Leak Set 1; Run 2

Leak name	Registration time	Longitude (decimal)	Latitude (decimal)	Methane, ppm*m	Comments
1	08:02:07.61	-106.187188	43.248368	103	
3	08:04:50.51	-106.205742	43.270902	164	
3	08:04:51.05	-106.205785	43.271028	166	
4	08:04:59.01	-106.206817	43.272322	457	
4	08:04:59.53	-106.206925	43.272382	274	
5	08:07:02.89	-106.221623	43.295412	1542	
Cloud P1	08:07:44.34	-106.219747	43.303002	71	
Cloud P1	08:07:45.84	-106.219777	43.303265	240	
Cloud P1	08:07:46.36	-106.219788	43.303330	368	
Cloud P1	08:07:46.86	-106.219807	43.303427	250	
Cloud P1	08:07:47.36	-106.219822	43.303490	94	
P2	08:08:32.80	-106.222217	43.310313	79	
P2	08:08:33.22	-106.222243	43.310383	132	
6	08:09:05.69	-106.225645	43.315592	414	
6	08:09:06.28	-106.225718	43.315678	70	
2E	08:09:33.73	-106.228670	43.319880	338	
2E	08:09:34.16	-106.228712	43.319983	54	
P3	08:10:17.69	-106.231790	43.328913	56	

12 September 2006; Gas Leak Set 1; Run 3

Leak name	Registration time	Longitude (decimal)	Latitude (decimal)	Methane, ppm*m	Comments
1	08:20:52.97	-106.187043	43.248190	74	
1	08:20:53.55	-106.187127	43.248195	277	
1	08:22:28.50	-106.187227	43.248215	129	Small circle near 1.
3	08:25:18.20	-106.205797	43.270972	155	
4	08:25:27.69	-106.207362	43.272195	689	
5	08:27:40.64	-106.221593	43.295463	190	
5	08:27:41.06	-106.221623	43.295532	2181	
Cloud P1	08:28:36.09	-106.218828	43.304505	119	Cloud around P1 leak source was found while performing 360° turn.
Cloud P1	08:28:36.50	-106.218713	43.304502	153	
Cloud P1	08:28:37.09	-106.218637	43.304493	138	
Cloud P1	08:28:39.58	-106.218172	43.304340	67	
Cloud P1	08:28:40.08	-106.218108	43.304302	82	
Cloud P1	08:28:41.50	-106.217887	43.304120	72	
Cloud P1	08:28:42.08	-106.217838	43.304068	84	
Cloud P1	08:28:42.58	-106.217772	43.303985	102	
Cloud P1	08:28:43.09	-106.217730	43.303928	62	
Cloud P1	08:28:43.58	-106.217673	43.303838	53	
Cloud P1	08:28:43.98	-106.217640	43.303777	80	
Cloud P1	08:28:44.58	-106.217608	43.303713	104	
Cloud P1	08:28:45.56	-106.217533	43.303515	59	
Cloud P1	08:28:46.06	-106.217515	43.303447	86	
Cloud P1	08:28:46.48	-106.217493	43.303343	96	
Cloud P1	08:28:47.06	-106.217482	43.303275	120	
Cloud P1	08:28:47.58	-106.217472	43.303168	119	
Cloud P1	08:28:48.08	-106.217468	43.303098	51	
Cloud P1	08:28:49.00	-106.217477	43.302922	54	
P1	08:29:10.05	-106.219022	43.303500	1779	
P1	08:29:10.55	-106.219040	43.303558	744	
P2	08:29:56.00	-106.222222	43.310158	374	
6	08:30:34.00	-106.225650	43.315612	172	
	08:39:35.33	-106.218452	43.294222	119	Detected cloud from Leak Source 5 while on approach for landing at helicopter refueling station.
	08:39:35.92	-106.218483	43.294387	149	
	08:39:36.91	-106.218535	43.294662	138	
	08:39:45.41	-106.219607	43.296757	279	
	08:39:47.81	-106.220275	43.297028	819	
	08:39:48.31	-106.220395	43.297050	1015	

12 September 2006; Gas Leak Set 2; Run 1

Leak name	Registration time	Longitude (decimal)	Latitude (decimal)	Methane, ppm*m	Comments
3	10:14:01.67	-106.205668	43.270862	114	
3	10:14:02.09	-106.205783	43.270952	161	
4	10:14:10.14	-106.207378	43.272155	155	
5	10:16:19.51	-106.221577	43.295297	63	
5	10:16:20.01	-106.221572	43.295412	5854	
P1	10:17:05.00	-106.219107	43.303490	41	
P2	10:17:49.84	-106.222205	43.310050	71	
6	10:18:23.39	-106.225637	43.315417	360	
6	10:18:23.92	-106.225695	43.315515	314	
	10:24:09.55	-106.213638	43.295270	286	Detected cloud from Leak Source 5 while flying to start of "virtual pipeline."

12 September 2006; Gas Leak Set 2; Run 2

Leak name	Registration time	Longitude (decimal)	Latitude (decimal)	Methane, ppm*m	Comments
4	10:30:29.06	-106.207373	43.272140	541	
5	10:32:32.51	-106.221517	43.295253	403	
5	10:32:33.05	-106.221518	43.295332	1585	
P1	10:33:16.98	-106.219077	43.303437	587	
P2	10:33:57.92	-106.222152	43.310073	119	
6	10:34:30.39	-106.225637	43.315543	304	

12 September 2006; Gas Leak Set 2; Run 3

Leak name	Registration time	Longitude (decimal)	Latitude (decimal)	Methane, ppm*m	Comments
Cloud 3	10:49:20.97	-106.204343	43.269498	66	
Cloud 3	10:49:25.98	-106.205122	43.270235	305	
Cloud 3	10:49:27.48	-106.205378	43.270473	152	
5	10:51:33.26	-106.221573	43.295020	575	
5	10:51:33.87	-106.221573	43.295112	4238	
P1	10:52:15.22	-106.219075	43.303442	914	
P1	10:52:34.30	-106.219860	43.30 6365	42	
P2	10:52:56.19	-106.222125	43.310028	84	
6	10:53:28.72	-106.225593	43.315490	262	

12 September 2006; Gas Leak Set 2; Run 4

Leak name	Registration time	Longitude (decimal)	Latitude (decimal)	Methane, ppm*m	Comments
2B	11:04:49.00	-106.200152	43.256875	39	
3	11:05:48.51	-106.205622	43.270717	201	
3	11:05:48.94	-106.205710	43.270792	280	
4	11:05:55.70	-106.207227	43.272038	100	
5	11:07:35.33	-106.221568	43.295382	550	
6	11:09:01.83	-106.225432	43.315223	67	
6	11:09:02.73	-106.225567	43.315432	276	
	11:12:29.70	-106.225567	43.315915	83	Detected cloud from Leak Source 6 while flying back to helicopter refueling station.

13 September 2006; Gas Leak Set 1; Run 1

Leak name	Registration time	Longitude (decimal)	Latitude (decimal)	Methane, ppm*m	Comments
	07:39:33.28	-106.204905	43.271427	295	Detected cloud from Leak Source 3 while flying to starting point.
3	07:44:09.00	-106.205712	43.270938	924	
4	07:44:18.50	-106.207270	43.272058	189	
5	07:46:20.28	-106.221427	43.295635	577	
5	07:46:20.86	-106.221430	43.295760	1340	
P1	07:47:01.23	-106.219035	43.303518	302	
P2	07:47:44.28	-106.222203	43.310138	85	
6	07:48:18.04	-106.225495	43.315547	37	
P3	07:49:33.09	-106.231695	43.328968	203	

13 September 2006; Gas Leak Set 1; Run 2

Leak name	Registration time	Longitude (decimal)	Latitude (decimal)	Methane, ppm*m	Comments
P3	09:15:57.01	-106.231693	43.329088	132	
6	09:17:48.30	-106.225758	43.315757	34	
P2	09:18:34.40	-106.222327	43.310387	36	
P1	09:19:22.33	-106.219053	43.303655	205	
5	09:20:14.69	-106.221605	43.295638	165	
4	09:22:49.00	-106.207605	43.272390	55	
3	09:22:59.51	-106.205965	43.271073	760	

13 September 2006; Gas Leak Set 1; Run 3

Leak name	Registration time	Longitude (decimal)	Latitude (decimal)	Methane, ppm*m	Comments
P3	09:34:28.40	-106.231620	43.329185	60	
P2	09:36:40.19	-106.222268	43.310342	62	
P1	09:37:54.20	-106.218478	43.304665	50	
P1	09:37:55.70	-106.218570	43.304482	62	
P1	09:37:56.11	-106.218608	43.304402	68	
P1	09:37:56.70	-106.218633	43.304350	93	
P1	09:37:59.11	-106.218797	43.304007	141	
P1	09:37:59.61	-106.218823	43.303953	267	
P1	09:38:00.11	-106.218863	43.303873	87	
P1	09:38:01.59	-106.218957	43.303683	246	
P1	09:38:02.12	-106.218982	43.303627	482	
5	09:38:46.14	-106.221533	43.295698	3502	
4	09:40:57.50	-106.207565	43.272413	86	
3	09:41:07.50	-106.205870	43.271150	291	
3	09:41:08.01	-106.205800	43.271073	128	
	09:47:24.12	-106.218363	43.298017	152	Detected cloud from Leak Source 5 while on approach for landing at helicopter refueling station.
	09:47:24.55	-106.218555	43.298080	173	
	09:47:44.08	-106.221678	43.295590	1186	

13 September 2006; Gas Leak Set 2; Run 1

Leak name	Registration time	Longitude (decimal)	Latitude (decimal)	Methane, ppm*m	Comments
6	11:00:54.76	-106.225753	43.315817	156	
P2	11:01:35.73	-106.222238	43.310298	55	
P1	11:02:20.69	-106.218975	43.303662	288	
5	11:03:05.14	-106.221607	43.295657	2155	
4	11:05:11.80	-106.207527	43.272352	35	
3	11:05:21.50	-106.206067	43.271198	511	
3	11:05:22.01	-106.205983	43.271120	161	

13 September 2006; Gas Leak Set 2; Run 2

Leak name	Registration Time	Longitude (decimal)	Latitude (decimal)	Methane, ppm*m	Comments
P3	11:15:04.40	-106.231662	43.329148	151	
P3	11:15:04.97	-106.231687	43.329107	321	
6	11:17:07.30	-106.225745	43.315703	254	
P2	11:17:58.73	-106.222277	43.310273	194	
P1	11:18:57.67	-106.219045	43.303635	368	
Cloud 5	11:19:41.64	-106.220880	43.297553	113	
Cloud 5	11:19:42.14	-106.220902	43.297500	135	
Cloud 5	11:19:42.64	-106.220935	43.297422	107	
Cloud 5	11:19:43.11	-106.220967	43.297342	141	
Cloud 5	11:19:43.53	-106.220987	43.297290	171	
Cloud 5	11:19:44.14	-106.221008	43.297238	58	
5	11:19:53.12	-106.221467	43.296082	496	
5	11:19:53.55	-106.221495	43.296010	1076	
5	11:19:54.14	-106.221513	43.295963	707	
5	11:19:54.62	-106.221540	43.295892	1014	
5	11:19:55.01	-106.221558	43.295845	1422	
5	11:19:55.55	-106.221585	43.295777	1266	
5	11:19:56.12	-106.221602	43.295730	314	
5	11:19:56.51	-106.221628	43.295663	4619	
5	11:19:57.12	-106.221645	43.295620	5828	
4	11:22:40.34	-106.207467	43.272297	66	
3	11:22:54.90	-106.205982	43.271118	276	
3	11:22:55.44	-106.205922	43.271068	234	
1	11:27:31.50	-106.187548	43.248282	86	
	11:29:29.03	-106.195400	43.287465	126	Found while to the side of the “virtual pipeline” flying back to the starting point. The location is in the vicinity of a large RMOTC treatment facility that has tanks with vents.

13 September 2006; Gas Leak Set 2; Run 3

Leak name	Registration time	Longitude (decimal)	Latitude (decimal)	Methane, ppm*m	Comments
P3	11:33:36.25	-106.231710	43.329157	148	
6	11:34:35.11	-106.225840	43.315760	297	
P2	11:35:03.67	-106.222307	43.310320	319	
P1	11:35:37.14	-106.219045	43.303715	124	
5	11:36:17.09	-106.221553	43.295770	1882	
5	11:36:17.61	-106.221613	43.295642	2598	
3	11:38:04.48	-106.205993	43.271242	190	
	11:42:34.20	-106.218047	43.294818	75	Detected cloud from Leak Source 5 while on approach for landing at helicopter refueling station.
	11:42:44.19	-106.220455	43.296492	132	
	11:42:44.72	-106.220600	43.296475	407	
	11:42:45.20	-106.220693	43.296457	222	

14 September 2006; Gas Leak Set 1; Run 1

Leak number	Registration time	Longitude (decimal)	Latitude (decimal)	Methane, ppm*m	Comments
1	06:59:43.37	-106.187240	43.248195	101	
3	07:01:51.25	-106.205878	43.270918	675	
P2	07:04:52.03	-106.222257	43.310142	95	
6	07:05:25:04	-106.225695	43.315510	158	
P3	07:06:34.05	-106.231757	43.328868	1045	

14 September 2006; Gas Leak Set 1; Run 2

5	07:17:25.81	-106.221637	43.295445	1646	Experimental run to gather more data for system noise investigation.
P2	07:18:23.80	-106.222230	43.310038	101	
P3	07:19:38.67	-106.231815	43.328923	419	

14 September 2006; Gas Leak Set 1; Run 3

1	07:26:08.28	-106.187172	43.248208	92	
3	07:28:21.64	-106.205803	43.270848	1155	
4	07:28:29.22	-106.207278	43.272098	183	
5	07:30:15.11	-106.221647	43.295490	5567	
5	07:30:15.55	-106.221633	43.295623	1236	
5	07:30:16.03	-106.221625	43.295712	454	
5	07:30:16.53	-106.221612	43.295845	969	
5	07:30:17.14	-106.221603	43.295933	136	
Cloud 5	07:30:20.51	-106.221453	43.296750	128	
Cloud 5	07:30:21.05	-106.221425	43.296840	212	
Cloud 5	07:30:21.62	-106.221377	43.296975	58	
Cloud 5	07:30:22.12	-106.221342	43.297067	141	
Cloud 5	07:30:22.62	-106.221283	43.297202	74	
Cloud 5	07:30:23.11	-106.221243	43.297293	107	
P1	07:30:49.58	-106.219128	43.303122	100	
P1	07:30:50.00	-106.219110	43.303253	325	
P1	07:30:50.59	-106.219093	43.303383	696	
P1	07:30:51.01	-106.219082	43.303470	2388	
P3	07:32:51.40	-106.231758	43.328900	414	

14 September 2006; Gas Leak Set 2; Run 1

Leak number	Registration time	Longitude (decimal)	Latitude (decimal)	Methane, ppm*m	Comments
	08:19:38.67	-106.188783	43.260868	82	Found while to the side of the “virtual pipeline” flying to the starting point. The location is near a RMOTC main gas line valve.
1	08:20:48.17	-106.187227	43.248228	105	
2A	08:21:37.70	-106.197867	43.253412	29	
3	08:23:05.95	-106.205843	43.270912	118	
4	08:23:14.05	-106.207305	43.272128	640	
5	08:24:48.44	-106.221733	43.295378	1956	
P2	08:25:59.50	-106.222165	43.310032	101	
Cloud 6	08:26:13.86	-106.224045	43.312652	53	
Cloud 6	08:26:17.36	-106.224457	43.313300	67	
Cloud 6	08:26:18.86	-106.224615	43.313563	131	
Cloud 6	08:26:19.28	-106.224678	43.313678	173	
Cloud 6	08:26:19.87	-106.224742	43.313792	110	
Cloud 6	08:26:20.33	-106.224783	43.313867	85	
Cloud 6	08:26:20.86	-106.224825	43.313942	69	
6	08:26:29.34	-106.225695	43.315505	1208	
P3	08:27:31.76	-106.231717	43.328848	51	
P3	08:27:32.28	-106.231767	43.328968	179	
P3	08:27:32.80	-106.231800	43.329048	70	
P3	08:27:33.78	-106.231885	43.329248	62	

14 September 2006; Gas Leak Set 2; Run 2

Leak number	Registration time	Longitude (decimal)	Latitude (decimal)	Methane, ppm*m	Comments
1	08:34:56.33	-106.187230	43.248192	91	
2A	08:35:45.70	-106.197878	43.253433	60	
3	08:37:19.19	-106.205925	43.270885	274	
4	08:37:26.59	-106.207358	43.272192	454	
5	08:39:16.56	-106.221665	43.295465	1945	
P1	08:39:51.51	-106.219102	43.303407	261	
P2	08:40:28.48	-106.222237	43.310097	122	
6	08:40:56.95	-106.225698	43.315558	354	
P3	08:41:58.31	-106.231760	43.328878	359	

14 September 2006; Gas Leak Set 2; Run 3

Leak number	Registration time	Longitude (decimal)	Latitude (decimal)	Methane, ppm*m	Comments
	08:49:27.30	-106.187255	43.248193	43	Detected cloud from Leak Source 1 while circling at start point waiting to begin run.
1	08:51:45.26	-106.187162	43.248187	98	Experimental run to understand upwind detection capability.
2A	08:52:28.20	-106.197830	43.253393	44	
3	08:53:59.16	-106.205838	43.270800	306	
4	08:54:08.06	-106.207295	43.272148	648	
5	08:55:51.53	-106.221678	43.295422	683	
5	08:55:51.98	-106.221640	43.295553	2270	
P3	09:00:14.70	-106.231458	43.329397	30	An amateur pilot flew part of "virtual pipeline" to understand system piloting skill requirements.
6	09:01:27.50	-106.225758	43.315723	342	
P1	09:02:48.50	-106.219030	43.303623	205	