PUBLIC FINAL REPORT

OTD PROJECT NUMBER 7.18.f

GTI PROJECT NUMBER 22438

Evaluation of Handheld Laser Methane Detection Technologies

Reporting Period:

July 1, 2018 through December 31, 2019

Public Report Issued:

September 1, 2020

GTI Project Manager:
Chris Moore, PhD
Sr. Scientist
847-768-0688
cmoore@gti.energy

1700 S. Mount Prospect Rd.

Des Plaines, Illinois 60018

www.gti.energy

Legal Notice

This information was prepared by Gas Technology Institute ("GTI") for Operations Technology Development, NFP (OTD).

Neither GTI, the members of GTI, the Sponsor(s), nor any person acting on behalf of any of them:

a. Makes any warranty or representation, express or implied with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately-owned rights. Inasmuch as this project is experimental in nature, the technical information, results, or conclusions cannot be predicted. Conclusions and analysis of results by GTI represent GTI's opinion based on inferences from measurements and empirical relationships, which inferences and assumptions are not infallible, and with respect to which competent specialists may differ.

b. Assumes any liability with respect to the use of, or for any and all damages resulting from the use of, any information, apparatus, method, or process disclosed in this report; any other use of, or reliance on, this report by any third party is at the third party's sole risk.

c. The results within this report relate only to the items tested.

Table of Contents

Table of Figures

Page

List of Tables

Executive Summary

All participate names have been removed from this public version of a confidential OTD report. The purpose of releasing this report publicly is to highlight that there are some slight differences in handheld laser methane detectors, but overall the sensors perform well for their intended use cases.

The objective of this project was to evaluate the performance of handheld laser-based methane detection sensors against an industry standard sensor as a benchmark. These hand-held sensors use tunable diode laser absorption spectrometry (TDLAS) to measure the concentration of methane within the laser path from the device to a surface behind a methane plume, reporting a "path-integrated" concentration in parts-per-million * meter (ppm*m). These devices allow for methane detection without having to be inside a methane plume or next to the leak source.

The sensors evaluated are not marketed as quantitative instruments capable of precisely determining methane concentrations. This is due to leaks of different sizes having the possibility of having the same reported path integrated concentration. The usefulness lies in the qualitative capabilities to help identify and locate a leak to initiate leak investigation procedures. Five sensors (labeled A through E) were evaluated alongside the industry standard Heath Remote Methane Leak Detector Intrinsically Safe (referred to throughout the report as simply RMLD). In this study the RMLD served as a benchmark for the performance of the other sensors.

The sensors were evaluated using a repeatable test matrix that involved a series of controlled outdoor tests. The tests included two different sized simulated leaks from a meter set to determine differences in concentration measurements and maximum detection distance for leaks on above ground assets. The sensors were also studied in a group of controlled indoor laboratory tests to explore the impact of background material and obstructions on sensor performance and to preliminarily examine effects of single and double pane windows and rain. Additionally, the sensors were evaluated qualitatively in five categories – ease of use, display, portability, field capability, and durability.

A few of the sensors fell short of the RMLD in two key areas – false negatives (not detecting a leak when a leak was present) and detection distance. The RMLD registered fewer false negatives than all sensors except Sensor E as indicated by non-detections in the outdoor step tests. The RMLD was also able to consistently register the presence of a leak from 15 to 50 feet farther away than sensors B, C, and D during the measurement distance limit tests. Sensors A and E, on the other hand, were able to measure concentrations 25 to 160 feet further away than the RMLD.

The controlled laboratory testing revealed that background materials impacted the measurements from each sensor similarly with darker materials causing lower concentration readings. The laboratory testing also determined that the angle of detection through double pane windows optimally should be 67.5 degrees and not 90 degrees, consistent with vendor recommendations for all sensors.

Most importantly the laboratory tests revealed that the narrow measurement beam of Sensor E needs to be considered when scanning complicated asset installations. The narrow beam must precisely scan all areas with the potential for a leak. However, the other sensors, such as the RMLD and Sensor A with larger measurement beams do not have to be as precisely placed on the asset. This trade-off means Sensor E can make measurements from greater distances than the other sensors with wider measurement beams due to the laser measurement beam being in a more focused area.

Qualitatively, all sensors scored higher than the RMLD. Particularly, all the new sensors were easier to use, more portable, and had better displays of the concentration than the RMLD. Sensor D, Sensor E, Sensor B, and Sensor C received high rankings in ease of use, quality of the display, and portability.

In conclusion, the new sensors tested here were user friendly and perform reasonably well depending on the particular use case. Due to preliminary testing on underground leaks and indoor piping conducted in this phase of the project, valuable future work should explore the abilities and limitations of these sensors to identify leaks on indoor piping and on below ground leaks. Future phases should also evaluate how the configuration of the different sensors may contribute to false positives (detection of a leak when none is present).

1 Introduction

1.1 Background

The dominant cost in leak survey and leak identification is the labor required to find the leaks. There is a consistent need to more quickly and efficiently identify system leaks. Handheld laser-based leak detection tools offer the ability to minimize the amount of walking and time needed for leak survey personnel to cover large areas. Additionally, these technologies allow personnel to complete inspections in restricted areas (e.g., fencing, marsh areas, ravines) that would otherwise require several attempts to gain access. The technologies can therefore reduce costs by minimizing the time and expense of re-visits and avoid potential non-compliance inspection issues.

Some but not all utilities are permitted to use handheld laser-based instruments for leak survey or investigation. The primary tool used, and at times specifically mentioned in leak survey procedures is the Heath Remote Methane Leak Detector (RMLD). These instruments can offer faster surveying because the technician can stand in one location and scan above-ground assets up to 100 feet in each direction without moving. These tools also increase safety because the technician is scanning, instead of walking directly over and "touching" the pipe or above-ground asset. This minimizes movement and the need to access areas with unseen hazards. However, these are just one in a suite of tools needed to ultimately pinpoint leaks. The laser-based tools can be used to quickly and efficiently identify that a leak exists but must be paired with other instruments/techniques to further investigate and pinpoint a leak location.

Several new handheld laser-based methane detection instruments have entered the market in the last few years. Therefore, the main objective for this project was to evaluate the performance of the new technologies using the Heath RMLD as a technology benchmark.

1.2 Laser-based instrument background

Laser-based instruments are tuned to specifically measure methane only, whereas a combustible gas indicator will measure all combustible gases, not just methane. The instruments all work on a similar principle, tunable diode laser absorption spectroscopy (TDLAS). For TDLAS, a laser emanates outward from the instrument and is reflected off a surface back to the instrument where a detector measures the amount of the laser that has been absorbed along the path. The laser is tuned to an exact wavelength that corresponds to methane. The measurement made with a handheld laser system represents the concentration of methane along the entire pathlength of the laser, which produces a measurement with units in ppm*m – methane concentration (ppm) multiplied by the length of the detection beam (m). Figure 1 shows an example of how the ppm*m measurement is calculated. In this case the beam travels for 10m, of which one meter has a methane concentration of 500ppm and the other 9 meters of 10ppm. The reading of the TDLAS sensor in this example is (500ppm × 1m) + (10ppm × 9m) = 590ppm * m (Trincavelli et al., 2012).

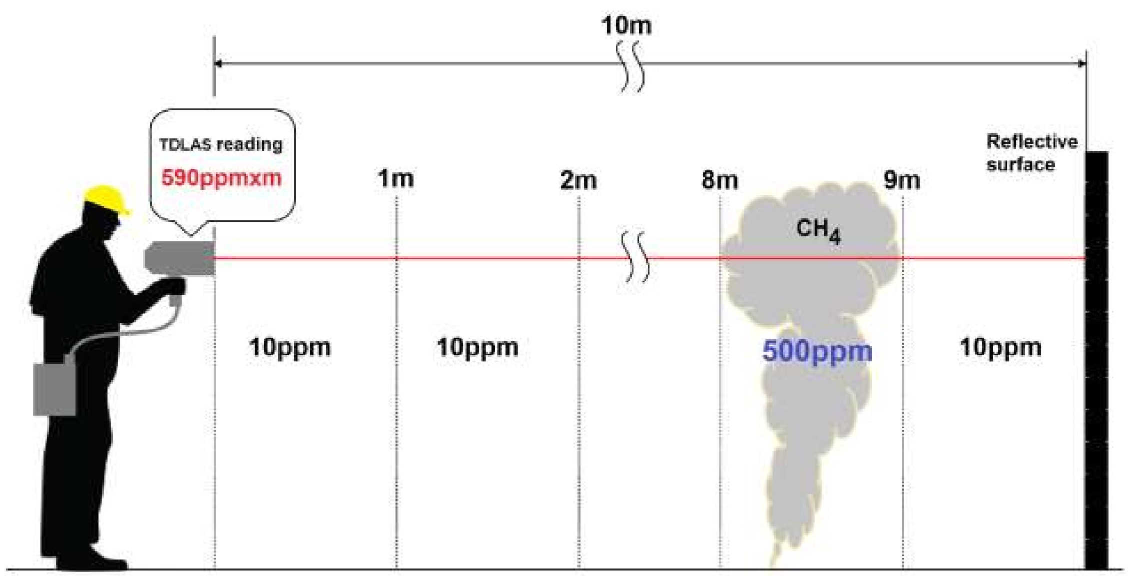

Figure 1. Example measurement with a TDLAS sensor (from Trincavelli et al., 2012).

It is important to qualify these sensors while providing information on methane concentration since these instruments were not designed as quantitative tools for grading or pinpointing methane leaks. This is because leaks of different sizes can report the same path integrated concentration (ppm*m) as shown in Figure 2. Therefore, a positive reading from a handheld laser-based sensor should initiate further leak investigation but currently should not be the sole instrument used in leak grading.

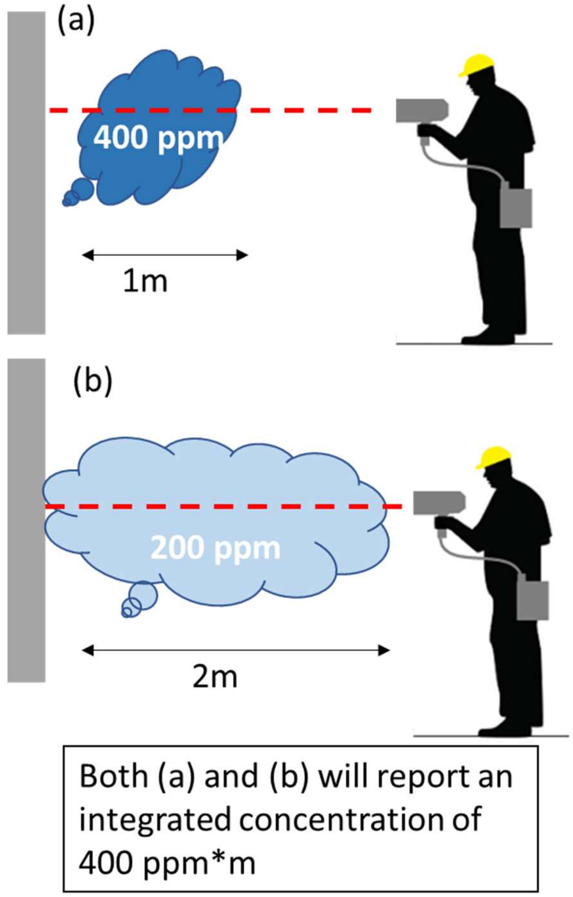

Figure 2: Example of methane plume integrated path measurement (from Trincavelli et al., 2012)

2 Equipment and Methodology

2.1 Instruments Tested

The six TDLAS sensors tested throughout the project include the Heath Remote Methane Leak Detector (RMLD) and five other sensors labeled A through E. The sensor manufacturer and model numbers have been removed from this public report. A summary of sensor capabilities is shown in Table 1.

Table 1: Comparison of Sensor Specifications

	RMLD	Sensor D	Sensor B	Sensor C	Sensor E	Sensor A
Weight	4.0kg	1.5kg	0.6kg	0.3kg	0.76kg	1.36 kg
Battery Life	8 hours	8 hours	6 hours	6 hours	8 hours	8 hours
Connection	BlueTooth	WiFi	BlueTooth, Android App	BlueTooth	BlueTooth	BlueTooth, WiFi, USB Dual Mode
Calibration	Manual	Automatic	Automatic	Manual	Manual	Manual
Display of Beam Intensity	No	Yes	Yes	Yes	Yes	No
Display max concentration	No	Yes	Yes	Yes	Yes	No
Sound Level Control	Yes	Yes	Yes	No	Yes	No
Sound Style Control	Yes	No	No	Yes	No	Yes
Concentration Display Automatic Adjustment (ppm-m, vol%, %lel)	No	No	Yes	Yes	Yes	No
Alarm Level Control	Yes	Yes	Yes	Yes	Yes	Yes
Self-Test	Yes	Yes	Yes	No	Yes	Yes
Data Storage	No	Yes	No	No	Yes	Yes
Error Message Display	Yes	Yes	Yes	No	Yes	Yes

2.2 Controlled Outdoor Field and Leak Training Facility Testing

Controlled field testing was performed in the fall of 2018 and the spring of 2019 at GTI and a utility leak training facility. There were two types of outdoor testing conducted at GTI - step testing and measurement distance limit testing which will be discussed in detail in the next sections. Due to limitations on sensor availability, not all sensors were tested in the fall. Sensors tested under each scenario are shown in Table 2. All tests included the currently used RMLD as a benchmark to compare new instruments with industry standard equipment and to compare performance during testing when some sensors were not available. The test matrix was developed to comprehensibly and simultaneously test the instruments in a defined and controlled manner at prescribed locations around the leak that would simulate approaching the leak during leak survey. Leak rates were chosen to be larger than typical leaks seen on above ground assets based on existing GTI knowledge of leak rates on assets such as industrial meters from OTD project 7.16.h Distribution System Characterization. Larger leaks were chosen to assure that the size of the leak was not limiting and the other parameters such as measurement distance could be tested.

Table 2. Sensors tested during fall and spring testing indicated by an X

Company	Device Name	GTI Step Tests: Fall 2018	Leak Training Facility: Fall 2018	GTI Step Tests: Spring 2019	GTI Distance Limit: Spring 2019
4	Sensor D	X	X		X
2	Sensor B	X	X		X
3	Sensor C	X	X		X
Heath	RMLD	X	X	X	X
5	Sensor E			X	X
1	Sensor A			X	X

Testing at GTI included simulated above-ground leaks from customer meters at different sizes to determine technology performance. Simulated leaks were controlled using a needle valve and monitored with a pressure gauge with leak flow rates determined with a Hi Flow sampler (discussed later). This allowed GTI to test technologies under different concentrations and leak flow rates.

2.2.1 GTI Step Test Protocol

Aboveground leaks were generated at two leak rates from a gas meter at GTI shown in Figure 3. Simulated leaks were controlled using a needle valve and pressure gauge. Leak flow rates were quantified with the Hi Flow sampler coupled with a Sensit Gold G2 in the same fashion as used in several other projects. To quantify the flow rate, the cone attachment of the Hi Flow sampler is placed over the pin hole leak to pull the sample through the instrument a known flow rate. The Sensit Gold G2 is placed in line with the measured flow through the sampler.

Figure 3. GTI simulated meter leak set up

The leak rate is quantified with the equation:

$$Q\ (scfh) = c_{Sensit} * Flow\ Rate_{Hi\ Flow} * 0.000001 * 60$$

where Q is the calculated leak flow rate in scfh, c_{Sensit} is the concentration displayed on the Sensit Gold G2 in ppm, and the Flow $Rate_{Hi\ Flow}$ is the flow rate measured by the Hi Flow sampler in scfm.

The five sensors undergoing performance testing were used to measure concentrations of controlled meter leaks simultaneously with the Heath RMLD. Four, 100 foot transects were charted around the leaking gas meter in front of the shed. Each transect was evenly dispersed, like the spokes on a wheel (Figure 4).

- All test sensors were placed in a cart and moved along the transect together.
- Measurements occurred every five feet providing 20 measurement locations per transect.
- All sensors were held at chest height during the scan.
- Measurements were taken by pointing the laser at the leak source and moving in a "Z" shape then recording the highest concentration.
- Duplicate measurements were taken from each device at each step.
- One device was used immediately after another, providing measurements that were nearly simultaneous.

- The entire experiment was run with a larger leak rate (~19 scfh) and a smaller leak rate (~9 scfh)
- Wind speed, direction, temperature, humidity, barometric pressure, date and time were collected and recorded at the beginning of each transect.

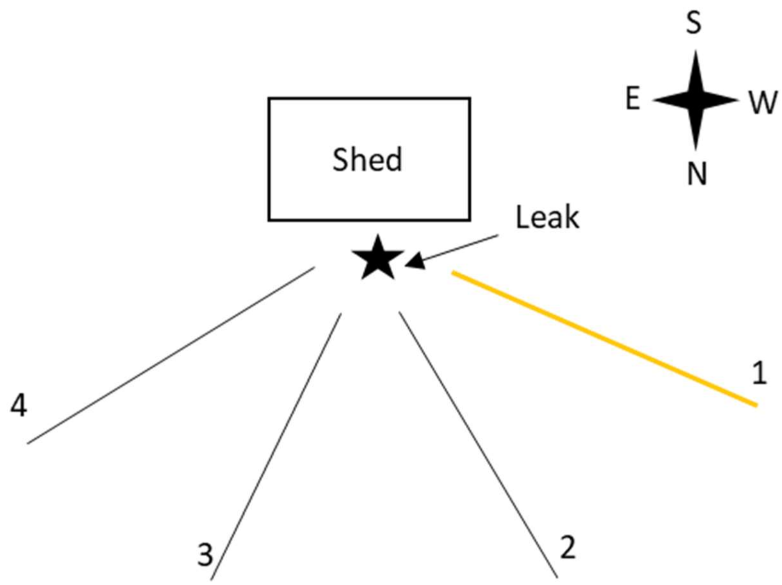

Figure 4. Controlled leak test with spokes.

2.2.2 Measurement Distance Limit Test

The measure distance limit test was used to measure the maximum distance sensors could detect a simulated outdoor gas leak at GTI shed (Figure 5). Measurements were taken every 25 feet along a single 300 foot transect, roughly situated along spoke 2. Sensors were aimed at the leak source and operators used a Z pattern for about 30 seconds and recorded the maximum concentration measured. Each measurement was taken in duplicate.

Figure 5: Measurement Distance Limit Test with the simulated leak circled in orange

2.2.3 Leak Facility Testing

Leak facility testing was conducted at a utility leak training facility located close to the GTI main offices. Due to scheduling, the leak facility testing was conducted in fall of 2018 only, with the RMLD, Sensor D, Sensor B, and Sensor C. Leaks were generated from a meter and ground valve within a 160 ft x 160 ft field. Each leak rate was quantified using the Hi Flow sampler coupled with a Sensit Gold G2.

To conduct the testing, a leak of unknown size was initiated at an unknown location. An operator stood at a centralized location (approximately 50 feet from every potential leak) and surveyed the surrounding area to locate the leak (Figure 6). Surveying for a leak occurred by tracing a “Z” shape across all assets in the field to locate the leak source location. Sensors were evaluated on whether they could locate the simulated leaks.

Figure 6: Operator holding RMLD sensor and a test sensor during utility Leak Training Facility Testing

After completing the leak facility testing, GTI determined that this type of testing was more properly conducted at the GTI pipe farm where testing could occur for long hours over multiple days. After communications with sponsors, it was decided to conduct a thorough controlled laboratory testing instead of a second leak facility testing.

This change in scope was approved by sponsors and reflected in the Quarterly Reporting.

2.3 Indoor Laboratory Testing

The purpose of the indoor laboratory testing was to evaluate factors that may affect the capabilities of the sensors in a controlled laboratory setting. The highly controlled nature of indoor laboratory testing provided a solution for testing a wide range of scenarios and reproducibility of conditions that was just not possible to replicate with outdoor testing.

Indoor laboratory testing evaluated sensor performance with various backgrounds, through glass, around obstructions, and through rain. For these tests, methane was contained in a clear plastic bag (referred to as the methane source) and the devices were held stationary by clamps. All sensors were clamped and held via the set up shown in Figure 7 at predetermined distances. The methane source was enclosed in a Tedlar® bag at a value of 1750 ppm*m across the width of the bag. Since Tedlar® has been shown to filter some radiation, it is important to note that the Tedlar® decreased the measurable concentration by all systems below the actual concentration of 1750 ppm*m. The background material behind the methane source was a light blue cinder block wall unless otherwise noted (i.e., during the background material test).

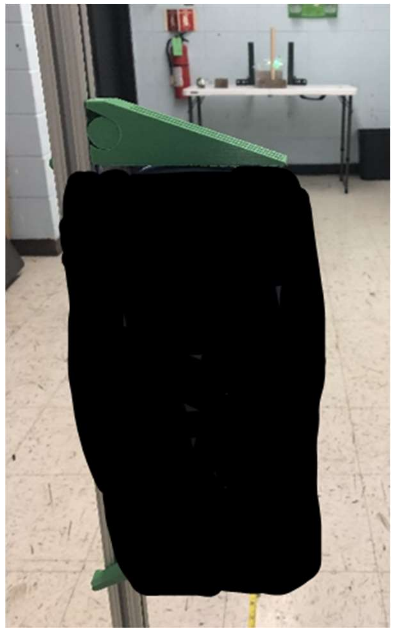

Figure 7. Stationary clamps

2.3.1 Background Material Testing

The background material test was established to evaluate the effect of different backgrounds on signal intensity and the resulting effect on reported methane concentration. The devices were held stationary at 30 feet from the contained methane source for all tests. Background materials are shown in Figure 8 and Figure 9.

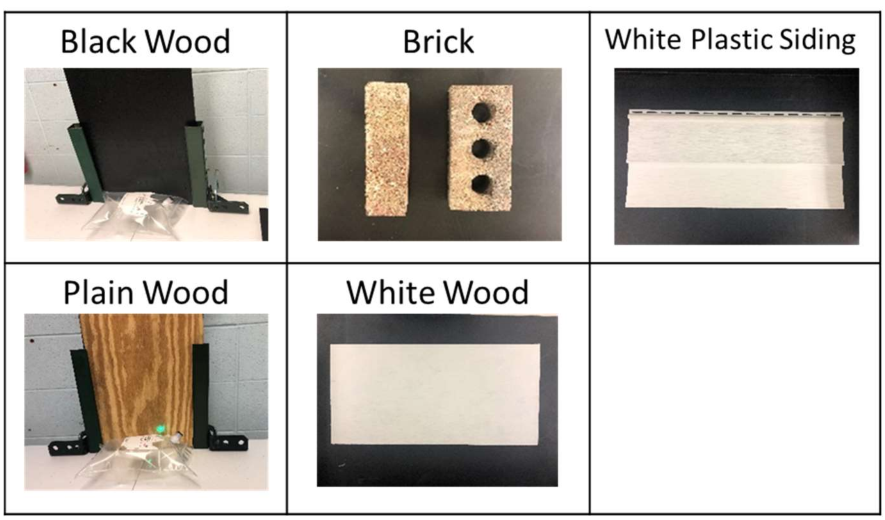

Figure 8. Siding background material used for laboratory testing

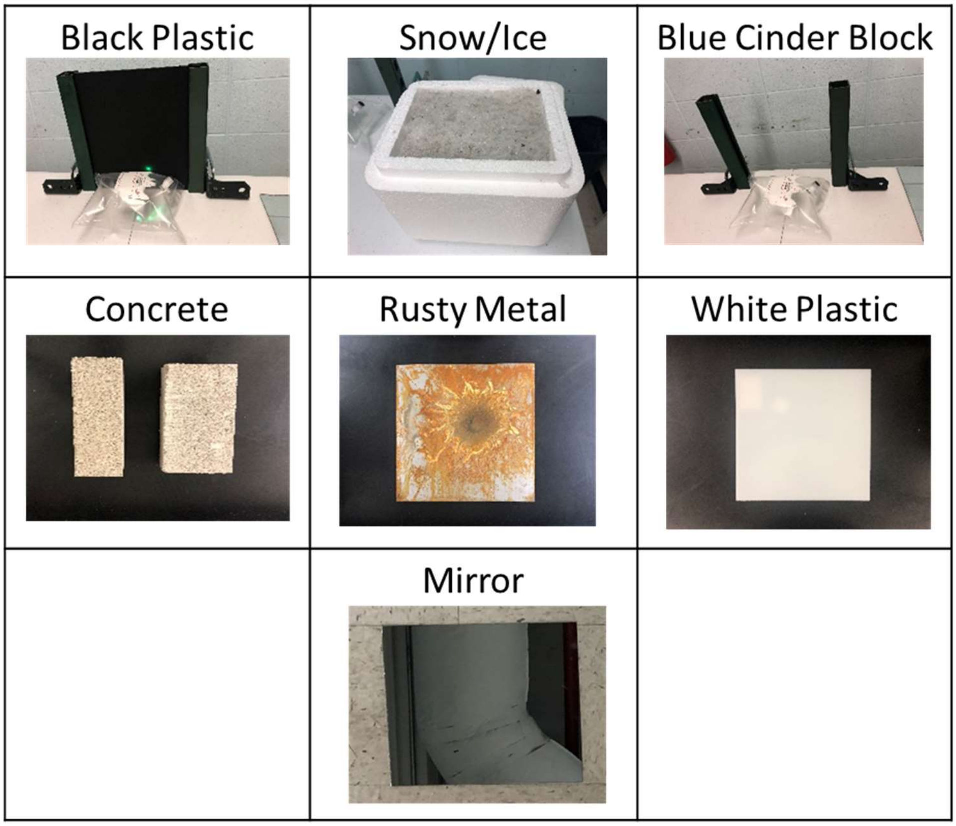

Figure 9. Other background material used for laboratory testing

2.3.2 Glass Pane Testing

The glass test was established to determine whether the instruments operate the same through glass as they do through an open path. Two types of glass were tested (Figure 10): single pane (simulated by using a glass table top with ¼ inch thickness) and double pane glass windows (Park Ridge VBS13214PR Vinyl Basement Slider Window). “No Glass” control measurements were taken at 30 feet, and the measurements with glass were taken at 0, 6.5, 15, 18, 25 and 30 feet for both types of glass.

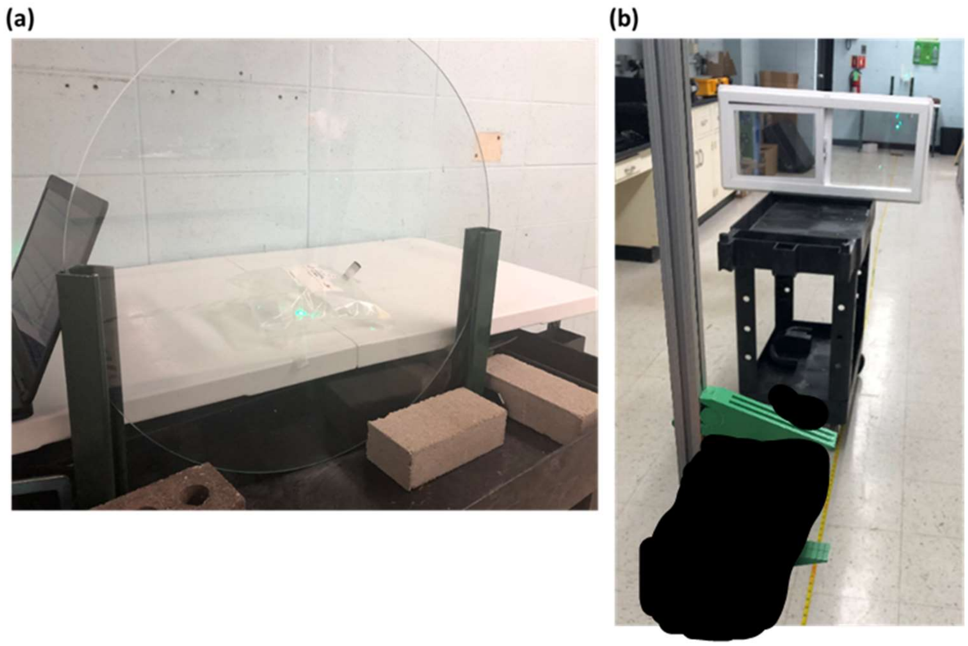

Figure 10: Glass for window tests (a) single pane window (b) double pane window

For multiple distance window testing, sensors were positioned 30 feet from the methane source, with the glass pane positioned at various intervals between the laser and methane source (Figure 11).

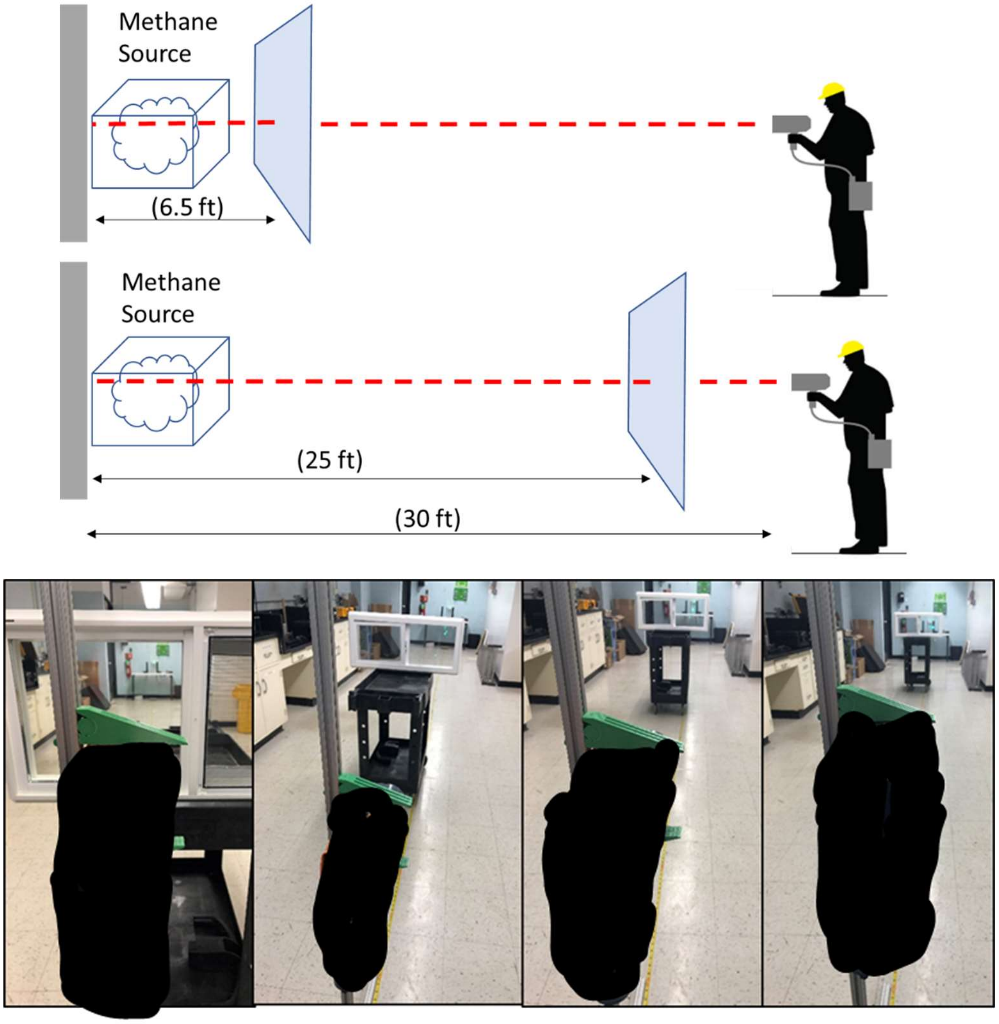

Figure 11: (a) Schematic of window distance test. (b) photos of double pane glass window test

During glass angle testing, the glass pane was placed near the methane source and a large radius was drawn on the floor 15 feet from the source. The sensors were used to make measurements from 90°, 67.5°, 45°, and 22.5 ° along the arc to determine whether the angle of measurement effected the measured concentration and beam intensity through single pane and double pane windows (Figure 12).

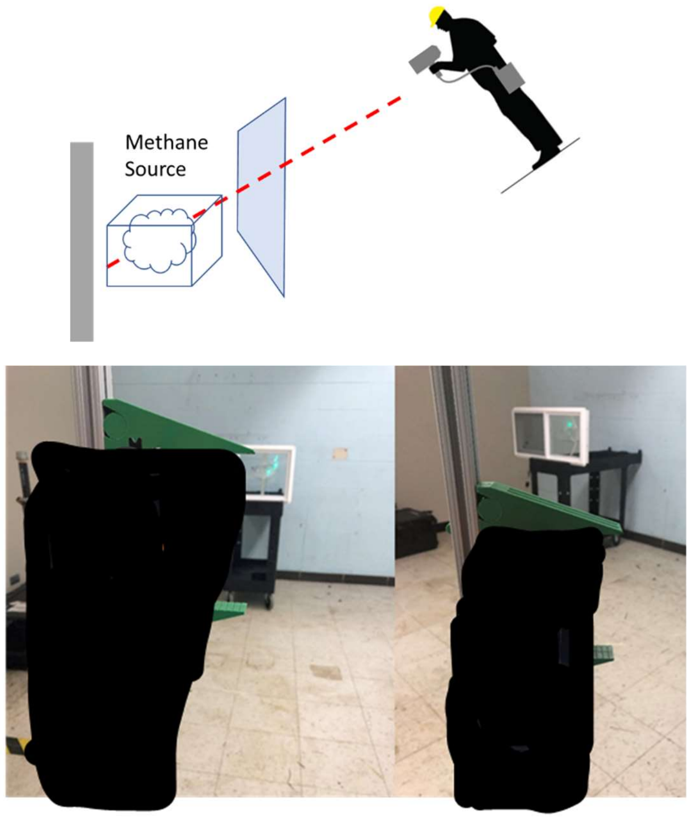

Figure 12: (a) Schematic for window angle test, (b) pictures from double pane window angle testing

2.3.3 Obstruction and Opening Tests

The obstruction and opening tests explored how the width of the measurement beam or "cone" impacted leak detection and measurement around obstacles. During the obstruction test, a 1-inch obstacle (wood dowel) was placed directly in front of the methane source. For the opening test, a piece of wood with a 1-inch opening was placed in front of the methane source. The sensors were held stationary and configured in-line with the obstruction and opening during testing. Measurements were taken every 6.5 feet as the sensor was moved away from the methane source (during both obstruction and opening tests) to a final distance of 30 feet (Figure 13). The measurements for the "No Barrier" control were taken at 15 feet.

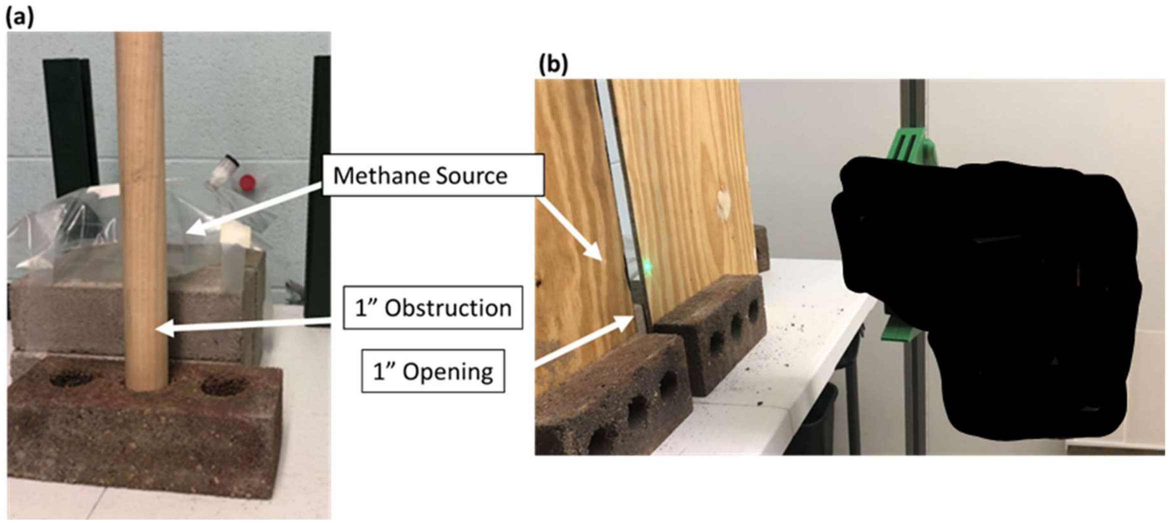

Figure 13: Images from obstruction and opening tests

2.3.4 Rain Test

The rain test was designed to demonstrate the impact of environmental factors on the measurements. For this test, a rain-shower head was used to simulate rain conditions in the lab. The methane source was placed directly behind the rain with a light brown metal cabinet for a background. The sensor was held by the clamps and moved in 6.5 ft increments away from the methane source to a final distance of 30 feet (Figure 14).

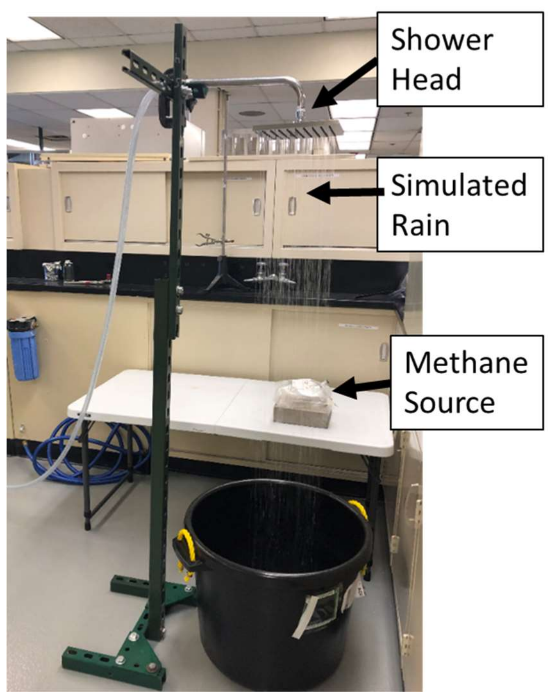

Figure 14: Simulated rain testing

2.4 Statistics

All descriptive statistics to include quantiles, medians, means, maximums, minimums, and standard deviations were calculated in R Project or in Excel and are described in detail below. Comparisons of two sample means were performed using an independent samples t-test and comparisons of multiple sample means were conducted using a one-way analysis of variance (ANOVA) followed by a Tukey's Honestly Significant Difference test (HSD) to determine differences between specific pairs of data. Graphs of data, correlation coefficients (r), coefficients of variation (standard deviation/mean), and coefficients of determination (R^2) were determined in Excel.

2.5 Qualitative Assessment

Each sensor, including the RMLD, was evaluated in five categories by four team members based on their experience using the sensors in the field. The categories for evaluation are in Table 3. Users were asked to score each sensor for the five categories as one through five. One being poor, and five being excellent.

Table 3: Categories for Qualitative Assessment

Category	Description
Ease of Use	How the unit performed in the field, intuitiveness and ease of operation
Display	Clarity of user interface, information provided to user
Portability	How easily the device traveled, size, weight
Field Capability	How appropriate is the device for the use case
Durability	Protection surrounding the instrument and experience with malfunctions

3 Results and Discussions

3.1 Outdoor Testing Results and Discussion

3.1.1 Step Test

The sensors were all tested on a larger leak (fall test mean = 16.7 scfh, spring test mean = 18.5 scfh) and a smaller leak (fall test mean = 8.0 scfh, spring test mean = 9.2 scfh). The leak rates were higher than a typical leak in the distribution system. The larger overall leak rates were set to not limit the performance of the sensors, only to gather a clear picture of the change in performance due to a change in leak rate.

A total of 336 measurements were made with each sensor. Leak rates and weather conditions during all outdoor testing are provided in Table 4. In the fall, all spokes were started and completed on the same day. For the spring, spoke 3 for the larger leak was finished on another day due to time constraints at the site. Also, in the spring, spoke 1 for the low leak was repeated due to inclement weather conditions at the site.

Table 4: Weather and Leak Rates for Outdoor Testing

Leak	Spoke	Leak Rate (scfh)	Temp (F)	Dew Point (F)	Hum (%)	Wind Dir.	Wind Speed	Max Wind Gust	Pres. (in)	Weather
Fall Spoke Testing										
Larger	1	16.79	55	34	45	SW	11	24	29.3	Fair
	2	19.30	50	23	35	WNW	12	21	29.6	Fair
	3	15.31	41	27	58	SW	7	21	29.3	Fair
	4	15.31	46	36	70	SW	8	0	29.3	Fair
Smaller	1	5.90	44	34	68	NE	6	0	29.2	Mostly Cloudy
	2	9.08	38	26	62	W	16	30	29.4	Mostly Cloudy
	3	8.70	34	24	67	VAR	6	0	29.6	Cloudy
	4	8.13	29	16	58	WNW	14	28	29.9	Mostly Cloudy
Spring Spoke Testing										
Larger	1	16.10	71	51	49	SW	5	0	29.2	Mostly Cloudy
	2	18.09	56	45	67	NNE	16	0	29.2	Cloudy / Windy
	3	18.09	69	53	56	NNE	15	0	29.3	Cloudy
	3 (cont)	20.57	73	54	50	SSE	13	0	29.3	Mostly Cloudy
	4	19.41	74	51	45	S	15	31	28.9	Mostly Cloudy
Smaller	1	9.16	50	46	88	NW	11	0	28.9	Light Rain
	1.1 (dup)	7.73	50	32	52	NNE	28	36	29.1	Fair / Windy
	2	9.08	59	44	57	VAR	6	36	29.3	Mostly Cloudy
	3	9.50	57	41	56	SE	10	0	29.3	Mostly Cloudy
	4	8.93	61	36	40	E	7	0	29.2	Cloudy
Spring Measurement Distance Limit Test										
Larger	2	19.41	73	50	45	SSW	18	26	28.9	Cloudy
Smaller	2	9.49	52	41	65	SE	9	0	29.3	Mostly Cloudy

3.1.1.1 Fall step tests – all spokes

Several interesting conclusions can be drawn from investigating all the fall concentration measurements (larger and smaller leaks combined) as shown in Table 5. First, the concentrations measured with the RMLD were significantly lower than those measured with Sensor D ($p=0.001$) and Sensor B ($p=0.002$) and higher than those measured with Sensor C ($p=0.002$) across all data. The Sensor C concentrations were also significantly lower than Sensor D ($p<0.0001$) and Sensor B ($p<0.00001$).

Under certain circumstances, each of the instruments was unable to detect one of the leaks as indicated by the “Normalized Non-Detection” category. This is an important area of distinction and has been normalized to the number of non-detections that were also recorded by the RMLD. This parameter will be discussed in the sections below that are focused on the individual high and low leaks. Interestingly, the lowest coefficient of variation (CV, standard deviation normalized to the mean) was for the traditional RMLD, indicating the RMLD may have had a smaller overall “spread” in the measured concentrations. A CV larger than 1 indicates that the standard deviation is larger than the mean, thus indicating that the data was highly variable. A high CV was expected for the combined data given that large and small leaks at highly varying distances were being investigated, so highly variable concentrations make practical sense.

Table 5. Descriptive statistics for the fall outdoor step testing for all measurements

	Fall Sensors – All Data			
	RMLD	Sensor D	Sensor B	Sensor C
Minimum	0	0	0	0
1st Quartile	405	499	190.5	154.8
Median	730.5	1007	710.5	424.5
Mean	843.6	1108.7	1095.1	589.1
3rd Quartile	1100.0	1495.3	1469.8	800.0
Maximum	3607	4780	10917	3548
Normalized Non-Detections	-	5	20	24
Standard Deviation	579.2	818.1	1338.0	597.9
Coefficient of Variation	0.69	0.74	1.22	1.02

In general, methane concentrations measured with the individual sensors did not vary significantly among the spokes when all measurements were combined. There were four exceptions: methane concentrations measured with the RMLD along spoke 4 were higher than spoke 1 ($p=0.006$) and spoke 2 ($p=0.002$). Spoke 4 was also higher than spoke 1 when measured with Sensor B ($p=0.01$). The wind speed and direction were variable across the measurements. For the larger fall leak, the wind direction was from the southwest. This could have caused the concentrations to be higher on spoke 4 as the southwest wind would have been blowing the leak plume along the spoke.

Many of the patterns found in the overall data also applied to the larger leak (16.7 scfh) concentration measurements as seen in Table 6. Concentrations measured with the RMLD for the larger leak (collected in the Fall) were significantly higher than Sensor C ($p=0.0003$) and significantly lower than Sensor B ($p=0.005$). The Sensor C concentrations were significantly lower than Sensor D ($p<0.00001$) and Sensor B ($p<0.00001$) concentrations. There was no significant difference between the RMLD and Sensor D or between Sensor B and Sensor D. The CV for all sensors was very similar to the combined data with the RMLD having the lowest CV. Sensor B and Sensor C consistently had more highly variable reported methane concentration measurements.

Table 6. Descriptive statistics for the fall outdoor step testing for the larger leak

	Fall Sensors – Larger Leak Data			
	RMLD	**Sensor D**	**Sensor B**	**Sensor C**
Minimum	132	0	0	12
1st Quartile	575	536.3	183	135.8
Median	900	1142	1102	304
Mean	1015.2	1256.2	1370.5	575.7
3rd Quartile	1340.5	1848.3	1931.8	766.8
Maximum	3607	3931	10917	3548
Normalized Non-Detection	-	5	12	0
Standard Deviation	657.4	894.1	1478.4	674.2
Coefficient of Variation	0.65	0.71	1.08	1.17

The most important performance metric for examining differences in performance among the sensors was the normalized non-detection statistic. This was an estimate of the additional false negatives, where a sensor indicated no leak when a leak existed, that occurred beyond the false negatives measured with the RMLD. For example, if the RMLD had one false negative or non-detection and another instrument had six non-detections, then the calculated normalized non-detection was 5.

Even though the larger leak was on the higher end of what would be encountered on above-ground assets, there were instances when Sensor D and Sensor B did not detect the leak (e.g., register a measurable concentration). The RMLD and Sensor C, on the other hand, were able to record a measurable concentration for all spokes and all measurements. These non-detections all occurred at 75 feet away from the leak or farther. The non-detections occurred at a single step or distance and did not indicate that the instrument could not find the leak at all, instead they indicated that at that particular distance the sensor did not report a measurable concentration therefore may be affected by the environmental conditions more heavily than the other sensors.

The differences in concentrations by sensor were less clear for the smaller leak as shown in Table 7. For instance, the concentrations measured with the RMLD were only significantly lower than Sensor D ($p=0.002$) and not significantly different from Sensor C and Sensor B. The only other relevant difference was that the Sensor D concentrations were significantly higher than the Sensor C concentrations ($p=0.0005$). This indicated that at the smaller leak rate the instruments performed more similarly. The CV for Sensor B was the higher for the smaller leak than the larger leak, whereas the CV for the RMLD and Sensor C decreased. The CV for Sensor D was similar between the two leak scenarios.

Table 7. Descriptive statistics for the fall outdoor step testing for the smaller leak

	Fall Sensors – Smaller Leak Data			
	RMLD	Sensor D	Sensor B	Sensor C
Minimum	0	0	0	0
1st Quartile	334	464.3	197.5	204
Median	592	888	502	529
Mean	653.8	945.5	773.1	606.6
3rd Quartile	924	1257.8	1062	839.8
Maximum	2400	4780	10770	2563
Normalized Non-Detection	-	0	8	24
Standard Deviation	401.9	691.9	1070.8	481.4
Coefficient of Variation	0.61	0.73	1.39	0.79

The non-detections were quite different for the smaller leak scenario. The RMLD and Sensor D both had 18 steps/distances for at least one spoke where the sensor did not have a measurable concentration all of which were beyond 75 feet from the leak resulting in a normalized non-detection of 0 for Sensor D. Sensor B had 8 more non-detections than the RMLD beginning at 75 feet. On the other hand, Sensor C had 24 more non-detections, the first of which occurred at 45 feet. Clearly, all sensors had more trouble measuring the concentrations associated with the smaller leak, even though the smaller leak was still quite large in relation to most leaks encountered in the distribution system.

3.1.1.2 <u>Spring step tests – all spokes</u>

As with the fall measurements, several interesting patterns emerged when looking at all data for the sensors tested in the spring as shown in Table 8. In particular, the concentrations measured with the RMLD were significantly lower than the concentrations measured with Sensor E ($p<0.00001$) but not significantly different from Sensor A. The lack of difference between the RMLD and Sensor A makes sense since the two sensors use similar technologies and settings. The concentrations measured with Sensor E were also significantly higher than Sensor A ($p<0.00001$).

Table 8. Descriptive statistics for the spring outdoor step testing for all measurements

	Spring Sensors – All Data		
	RMLD	**Sensor E**	**Sensor A**
Minimum	0	430	0
1st Quartile	380.75	1521	337.25
Median	870.5	2474	747
Mean	1311.7	2687.4	1074.6
3rd Quartile	1771.5	3494	1432.3
Maximum	13720	11659	7098
Normalized Non-Detection	-	-1	8
Standard Deviation	1476.2	1524.5	1054.7
Coefficient of Variation	1.13	0.57	0.98

Sensor E had 0 non-detections for the entire data set, and the RMLD had only one, therefore the normalized non-detection is -1 for Sensor E. This is despite similar winds speeds to the fall. At first glance, this appears to indicate that Sensor E had superior performance to the sensors tested in the fall, however the use of the RMLD as a benchmark brings the results into perspective. The RMLD had only 1 non-detection in the entire dataset in the spring, indicating that conditions were better in the spring for measuring concentrations with the handheld laser sensors. Therefore, interpretation of the results becomes more nuanced.

In this case, the CV becomes an important indication of the performance of the instruments. Unlike the instruments tested in the fall, both Sensor E and Sensor A had CVs that were lower than the RMLD. Sensor A was only slightly lower, whereas Sensor E was substantially lower. This indicated Sensor E consistently reported higher concentrations for the leak with a lower standard deviation compared to the other sensors. As will be shown later, this likely originates from the tendency of Sensor E to report a more consistent concentration as the sensor is moved farther away from the leak.

Like the fall measurements, the concentrations were not significantly different among the spokes, with one exception. Spoke 1 was significantly higher than spoke 4 for Sensor E ($p=0.0002$). Concentrations measured with the RMLD and Sensor A were higher on spoke 1 than spoke 4 as well, but the difference was not enough to be significant.

Unlike in the fall, all sensors in the spring reported significantly higher concentrations for the larger leak. Descriptive statistics are shown in Table 9. For the larger leak, the concentrations measured by Sensor E were significantly higher than the concentrations measured with the RMLD ($p<0.00001$) and Sensor A ($p<0.00001$). The concentrations measured with the RMLD and Sensor A were not significantly different. None of the sensors reported non-detections for the larger leak in spring. The CV for the concentrations measured by Sensor E at the larger leak was even lower than for the full data set.

Table 9. Descriptive statistics for the spring outdoor step testing for the larger leak

	Spring Sensors – Larger Leak Data		
	RMLD	Sensor E	Sensor A
Minimum	90	1018	125
1st Quartile	619.3	2630	537
Median	1398.5	3274	1092
Mean	1780.9	3518.0	1449.0
3rd Quartile	2253.25	4220	2045.25
Maximum	13720	11659	7098
Non-Detection	-	0	0
Standard Deviation	1729.4	1438.3	1217.2
Coefficient of Variation	0.97	0.41	0.84

Like the larger spring leak, Sensor E measured significantly higher concentrations than the RMLD ($p<0.00001$) and Sensor A ($p<0.00001$) for the smaller leak. As shown in Table 10, the smaller leak produced one non-detection for the RMLD at 100 feet from the leak, 0 for Sensor E, and 9 from Sensor A resulting in a normalized non-detection of -1 for Sensor E and 8 for Sensor A. All non-detections for Sensor A occurred beyond 80 feet. The CV also continued to be low for Sensor E for the smaller spring leak.

Table 10. Descriptive statistics for the spring outdoor step testing for the smaller leak

	Spring Sensors – Smaller Leak Data		
	RMLD	Sensor E	Sensor A
Minimum	10	430	0
1st Quartile	254	1004	210.25
Median	458.5	1509	388
Mean	715.0	1601.9	610.2
3rd Quartile	919.5	2039	1010.8
Maximum	4479	4299	2371
Non-Detection	-	-1	8
Standard Deviation	720.3	761.5	518.2
Coefficient of Variation	1.01	0.48	0.85

3.1.1.3 Step Tests out to 100 feet

The concentrations measured with the sensors all followed the same general pattern of slowly decreasing as the sensor was moved away from the leak. For simplicity, the smaller leaks will be used to show this pattern. All measurements (i.e., all spokes) for each sensor are presented with shaded areas representing the maximum and minimum concentrations and a line showing the mean of eight measurements (two replicates at each distance on each of four spokes) as shown in Figure 15 and Figure 16.

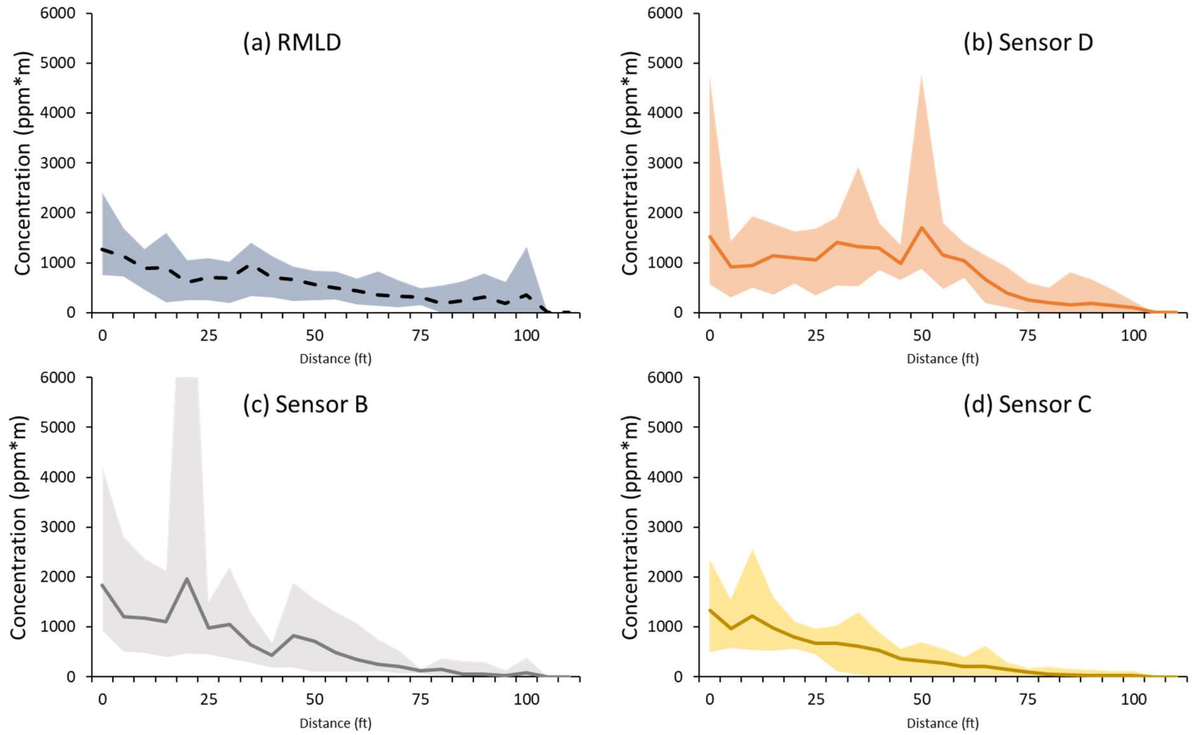

Figure 15. Measured concentrations at distances out to 100 feet for the smaller fall leak. The shaded area indicates the maximum and minimum concentration and the line indicates the mean of eight measurements.

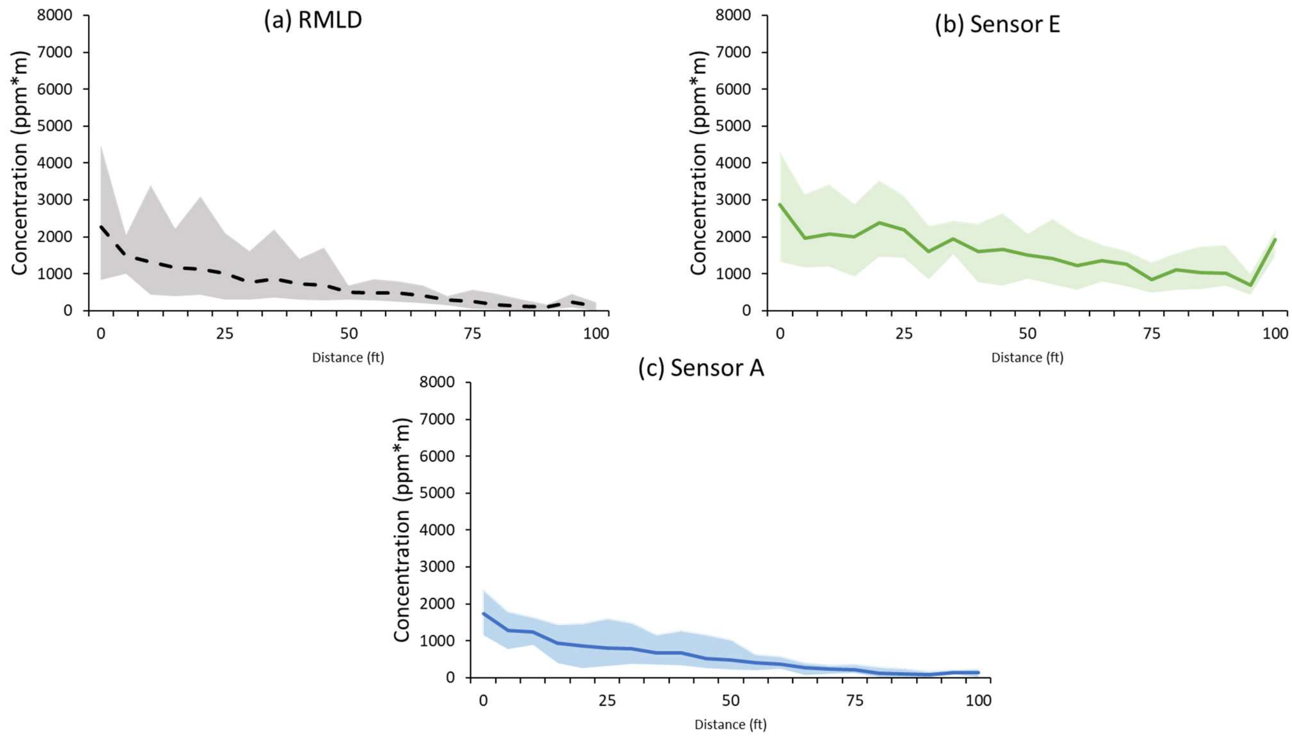

Figure 16. Measured concentrations at distances out to 100 feet for the smaller spring leak. The shaded area indicates the maximum and minimum concentration and the line indicates the mean of eight measurements.

The decrease in concentration with distance drove some of the variation in concentrations discussed in the previous section. However, as can be seen in Figure 15, Sensor D and Sensor B would display large swings in reported concentration at some distances. Although not verified with the vendors, this may be an indication of shorter signal averaging times used by these sensors. The operators reported the maximum concentration seen at each step and the shorter averaging time may have resulted in reporting of concentrations that varied more widely.

Another interesting observation was that at around 100 feet, when the other sensors were approaching a concentration of 0 ppm*m, Sensor E reported a slight increase in concentration. This was consistent with conversations with manufacturer of Sensor E, that indicated they were pushing the technology to achieve a measurement distance approaching 300 feet, instead of the 100 feet that was the focus of the other sensors. The reasoning behind this distance, was they believed 300 feet to be the ideal safe distance from a hazardous/potentially explosive building. Although many scenarios do not allow the first responder to remain 300 feet from the building, they wanted the operator of the sensor to have this option. The potential to reach out to 300 feet was the motivation behind the distance test shown in the next section.

3.1.1.4 Measurement distance limit test

The measurement distance limit test was used to determine the limits of detection based on distance for each sensor at a larger and smaller simulated gas leak. Weather conditions for the measurement distance limit test are provided in Table 11.

Table 11: Weather conditions and leak rate during the measurement distance limit test

Leak	Leak Rate (scfh)	Temp (F)	Dew Point (F)	Humidity (%)	Wind	Wind Speed (mph)	Wind Gust (mph)	Pressure (in)	Weather
High	19.41	73	50	45	SSW	18	26	28.9	Cloudy
Low	9.49	52	41	65	SE	9	0	29.3	Mostly Cloudy

All sensors performed at or better than the distance specifications provided by the vendor for the larger leak as shown in Table 12. Sensor E, designed to detect methane up to 300 feet, was able to detect the larger methane leak out to 300 feet. Sensor E reported higher concentrations of methane than the other sensors once the distance was greater than 50 feet from the leak source. Sensor A reported methane concentrations out to 225 feet. The original RMLD detected the leak out to 100 feet. Sensor D was able to measure methane from the leak 125 feet from the source. Sensor B and Sensor C reported methane concentrations out to 100 feet from the leak source.

Table 12: Maximum detection distance for the larger and smaller leaks during the measurement distance limit test

	Maximum Distance (ft)	
	Larger Leak	Smaller Leak
RMLD	140	125
Sensor D	125	100
Sensor B	100	75
Sensor C	100	75
Sensor E	300	200
Sensor A	225	150

As mentioned in the previous section, Sensor E reported a nearly constant concentration between 75 and 300 feet. Figure 17 shows the mean methane concentration reported by each sensor at each distance for the larger leak. Concentrations reported by all sensors dropped drastically between 0 and 25 feet, then for all sensors other than Sensor E continued to steadily decrease to 0 ppm*m.

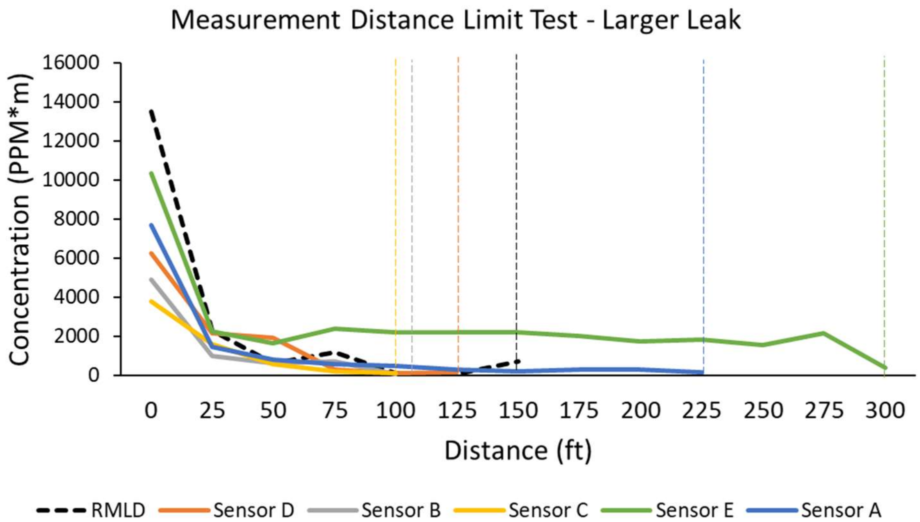

Figure 17. Mean methane concentrations recorded at each distance during the larger leak measurement distance limit test.

The measurement distance limit test performed on the smaller leak only tested the sensors to 200 feet due the unavailability of a platform needed to elevate the operators above a small hill to scan the leak. The sensors still performed well as shown in Figure 18. Sensor E was able to detect the methane out to the maximum scanned distance of 200 feet. Sensor A detected methane out to 150 feet, the RMLD out to 125 feet, and Sensor D out to 100 feet away from the leak. Sensor B and Sensor C were able to detect methane out to 75 feet which is slightly lower than the reported maximum measurement distance of 100 feet.

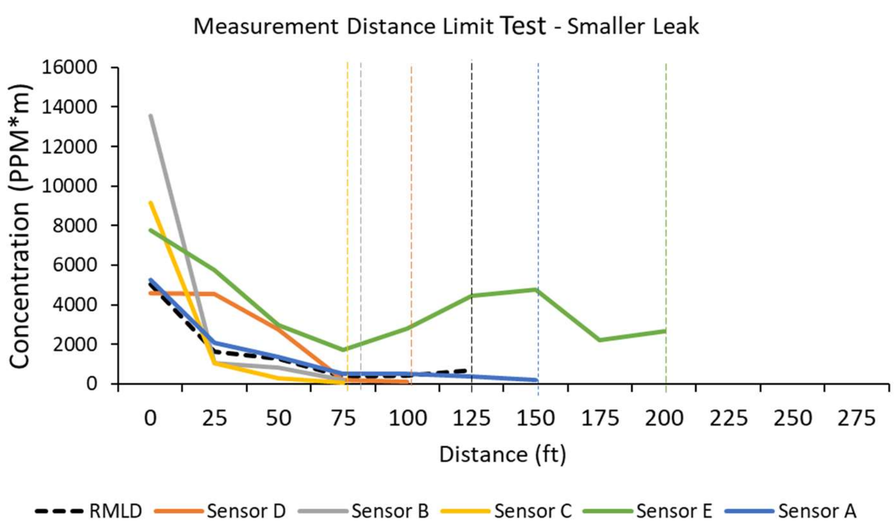

Figure 18. Mean methane concentrations recorded at each distance during the smaller leak measurement distance limit test.

One area that was not explored during this phase of the project was the possibility that configuration of the sensors may cause false positives, or identification of a leak where there no leak was present. False positives can cause wasted time by triggering leak investigations for leaks that do not exist. It would be useful to determine whether the configuration of Sensor E that is particularly focused on detection from long distances, increases the occurrence of false positives.

3.1.2 Leak Facility Testing

At the utility facility, each sensor was used to locate two different unmarked leaks as a “blind” test. The sensors were used to scan all assets in the field and to locate an unknown leak source. All sensors were able to locate the leaks at 50 feet in the field and Table 13 gives the highest concentration read by each sensor.

*Table 13. Concentrations (ppm*m) reported by each sensor during the utility leak training facility testing*

	Leak Rate (scfh)	Asset	RMLD	Sensor D	Sensor B	Sensor C
1	17.5	Meter	101,86	16,291	2,809	390
2	10.8	Ground Valve	717	1,700	1,531	311

Testing at a utility owned leak facility presented several challenges. First, the facilities are usually constructed to train leak crews, therefore offer limited ability to reliably control leak rates. Second, the facilities are often being used presenting logistical challenges that were not able to be solved to get all sensors to such a facility. Finally, the time needed to conduct thorough testing of all sensors did not transfer to the busy schedules of utility owned leak training facilities. Due to these challenges, GTI chose to evaluate the portability, durability, and ease of use of the equipment at the GTI Pipe Farm not at a utility leak facility. Further, after discussions with sponsors it was deemed more important to conduct controlled laboratory testing of the sensors.

3.2 Laboratory Testing Results and Discussion

The laboratory testing presented the opportunity to test the response of the sensors in a highly controlled setting. The testing was conducted on all sensors.

3.2.1 Background Material Test

The background material test was established to evaluate the effect that different materials may have on the measurements reported by the sensors. There were two measurements that could be affected by background material, reported concentration and measurement intensity. Several of the sensors (Sensor D, Sensor B, Sensor C, Sensor E) reported a signal intensity percentage while the other sensors did not. The intensity measurement represented the percentage of the measurement signal that was returning to the detector.

The reported concentration had the potential to be impacted by the orientation of the methane source and the exact path that the measurement beam traveled through the methane source. Identical placement of the measurement beam through the exact spot was impossible between sensors since the relationship between the location of visible lasers used to locate the measurement beam and the actual location of the measurement beam varied from sensor to sensor. The analysis below will focus on the percent difference from the mean concentration to normalize for potential differences in the measurement beam path through the methane source. The normalized percent difference (NPD) was calculated by

$$NPD = \frac{conc_{bkg} - \overline{conc_{sensor}}}{\overline{conc_{sensor}}} \times 100\%$$

where $conc_{bkg}$ is the measured concentration by the sensor for a specific background and $\overline{conc_{sensor}}$ is the mean concentration measured by the sensor for all backgrounds.

The background materials were divided into two groups 1) sidings and 2) other types of materials. Figure 19 and Figure 20 show the NPDs for all sensors for all background materials. The two figures reveal that some material types have clear impacts on the concentration measurements reported by all instruments. The consistently negative NPD indicated that the darker materials, such as black wood siding (Figure 19) and black plastic (Figure 20) consistently caused the reported concentrations by the sensors to be lower than concentrations reported with white wood siding, white plastic siding, white plastic, rusty metal and plain wood as a background, which consistently had a positive NPD. The impact of brick, snow/ice, and blue cinder block was not as clear since the NPD varied between positive and negative depending on instrument.

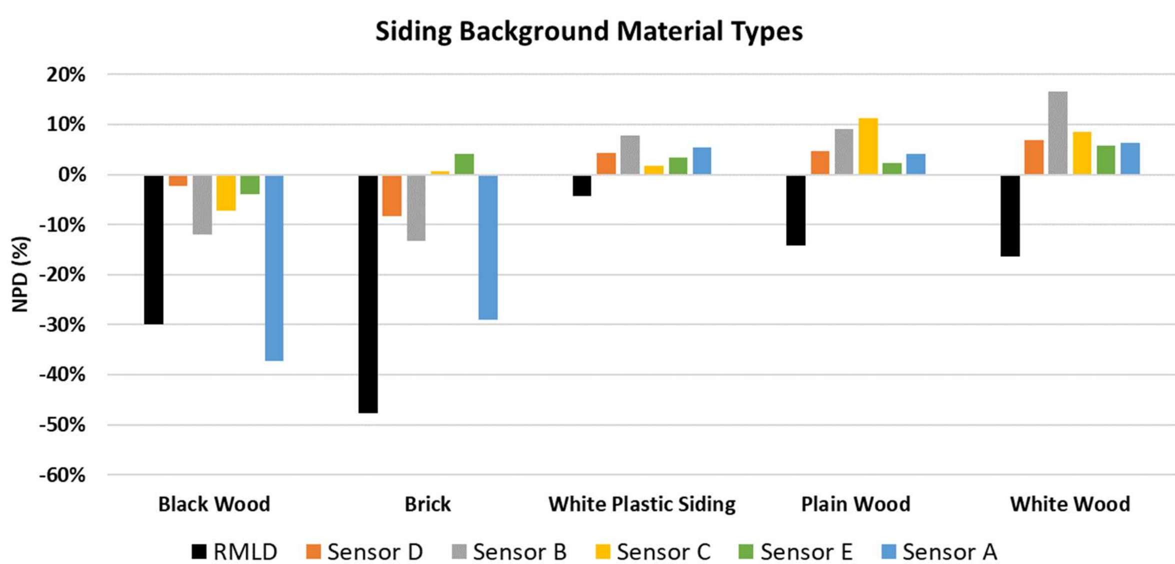

Figure 19. The normalized percent difference for siding background material types

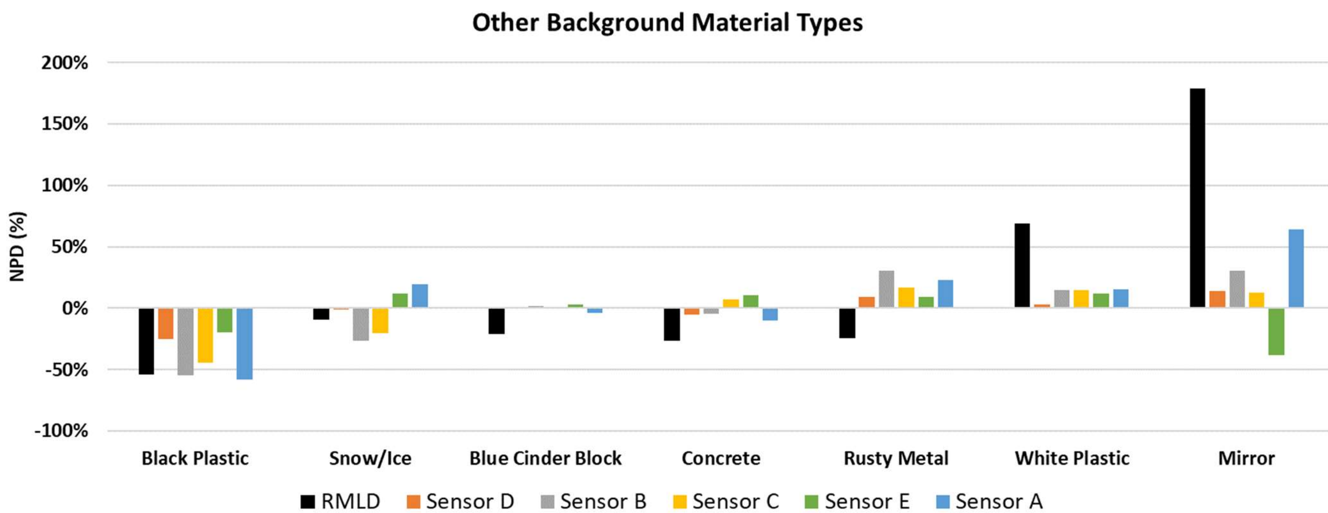

Figure 20. The normalized percent difference for the other background material types

The darker material was likely absorbing more of the measurement beam than the lighter or more reflective material causing these measurements to be biased lower. This was confirmed by examining the signal intensity for the sensors that report this parameter (Figure 21 and Figure 22). In general, the sensors reported a lower signal intensity for black siding and black plastic compared to the other background materials. This has the potential to impact leak identification in the field if the background absorbs too much of the signal and the leak is generating low concentrations, the operator/technician may miss identifying the leak.

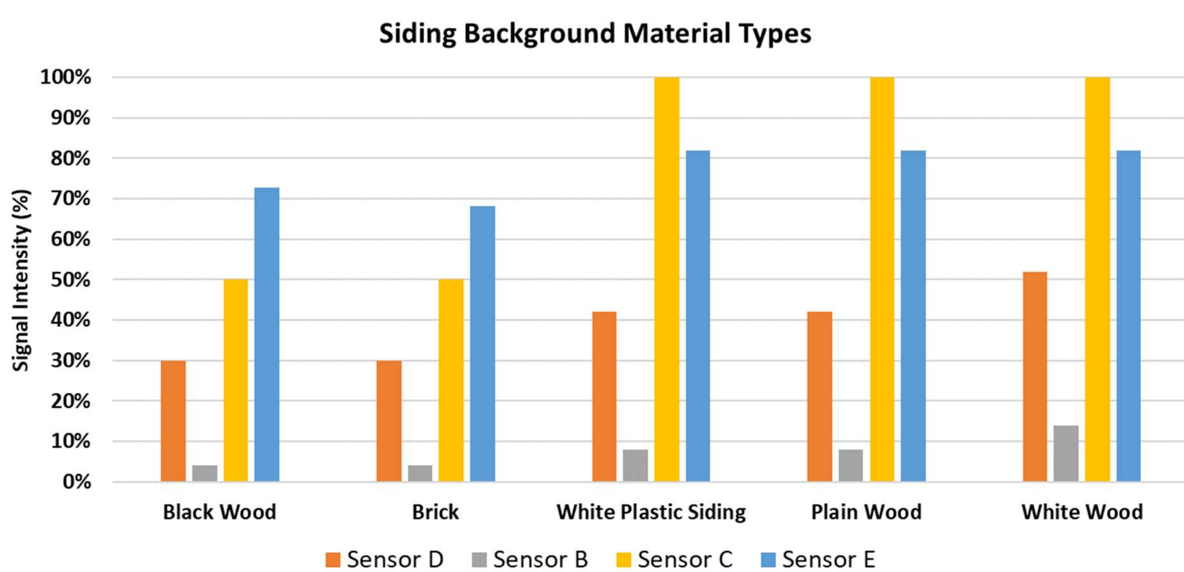

Figure 21. Percentage of measurement beam returning to the sensor for each siding background (signal intensity) for the sensors that report intensity

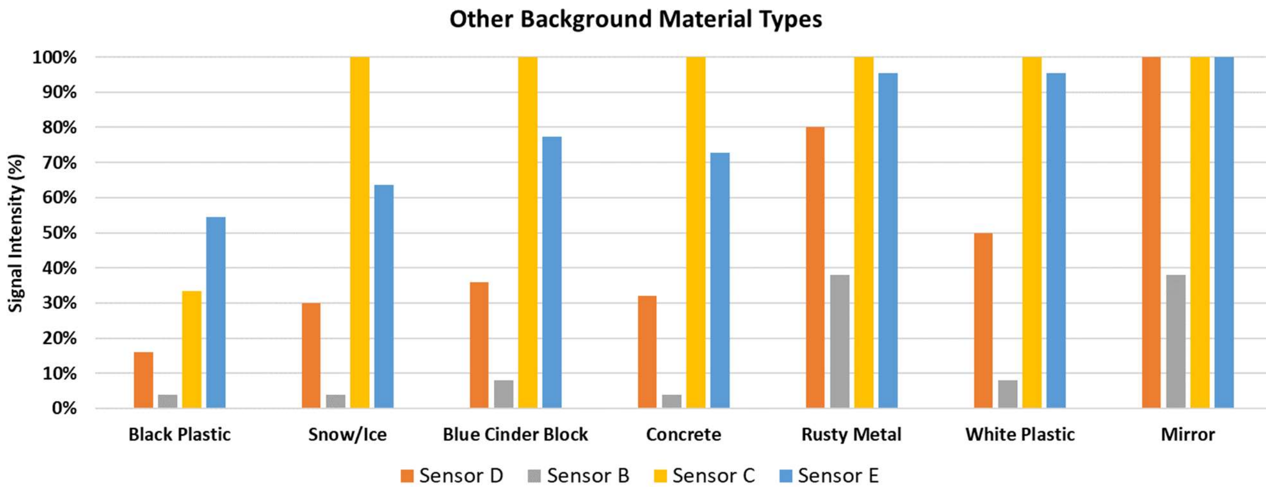

Figure 22. Percentage of measurement beam returning to the sensor for the other background materials (signal intensity) for the sensors that report intensity

Two materials caused the concentrations reported by the sensors to be more variable. First, snow/Ice effected each instrument differently with some sensors reporting positive NPDs and some reporting negative NPDs. The tested snow had been stored in a freezer for several months and had been collected from a pile that also included gravel. This may have caused the reading to be more variable depending on where the measurement beam was placed on the background material sample. This could indicate that in the field, snow/ice may cause the measurements to also be more variable, making leak identification more difficult. Second, the mirror measurements produced highly erratic raw concentrations with large fluctuations, making it difficult to settle on an exact concentration (data not shown). This could also make leak identification more difficult.

3.2.2 Single Pane Window Tests

The single pane windows had little or no effect on the methane concentrations reported by the sensors. The raw concentrations reported by the sensors can best be used to demonstrate this lack of effect as shown in Figure 23. Although there was variation in concentrations measured by the window placed at each distance for each sensor, there were still methane concentration reported. The importance of this reported measurement will become clearer in the double pane window test.

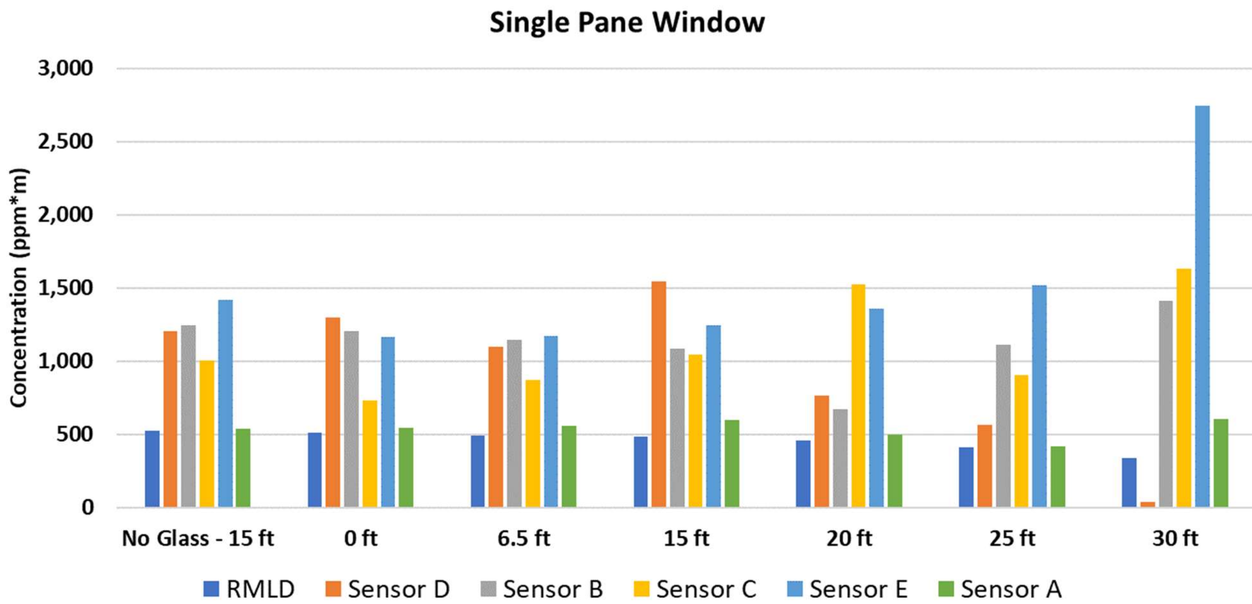

Figure 23. Measured concentrations with all sensors through a single pane window at different distances

The angle of measurement also had little or no effect on the measured methane concentrations for single pane windows as shown in Figure 24. The concentrations measured at 22.5 degrees appeared to be slightly lower for each sensor however, all sensors were still capable of registering a concentration reading at all angles.

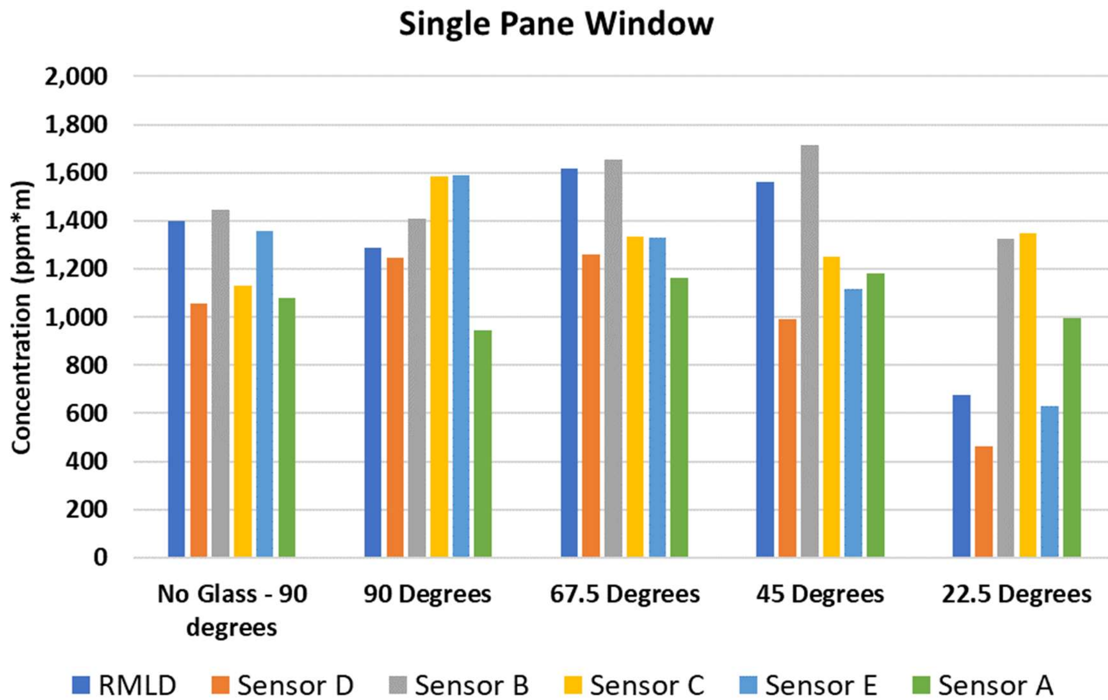

Figure 24. Measured concentrations with all sensors through a single pane window at different angles

3.2.3 Double pane window tests

The double pane window test revealed the importance of not measuring directly perpendicular to the glass. The double pane window distance test was conducted with all sensors oriented exactly 90 degrees to the window. This caused issues with several of the sensors to be able register a concentration reading at several distances, causing the methane concentration readings to be highly variable among the instruments as shown in Figure 25. Specifically, only two sensors produced a measurable concentration at all distances, the RMLD and Sensor B.

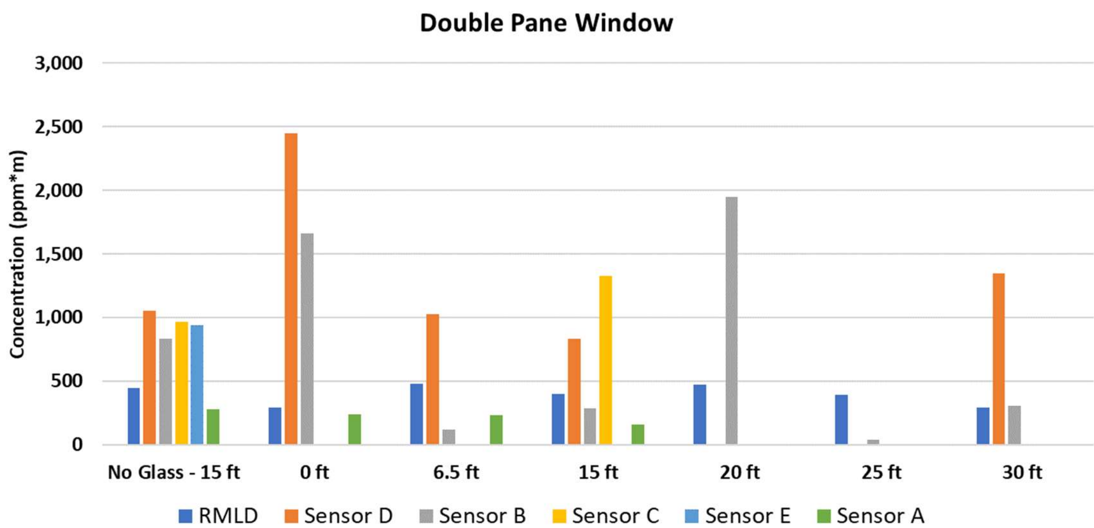

Figure 25. Measured concentrations with all sensors through a double pane window at different distances

The most effective angle for measurement with the sensors was 67.5 degrees as shown in Figure 26. At 67.5 degrees, all sensors performed similarly to the no glass scenario. This was consistent with the specifications provided by the instrument vendors.

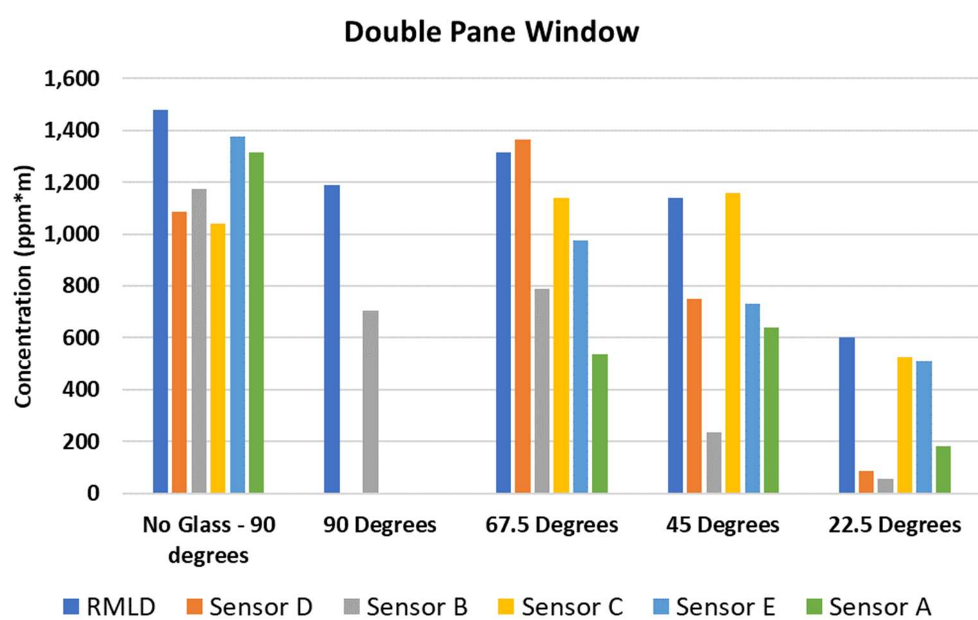

Figure 26. Measured concentrations with all sensors through a double pane window at different angles

3.2.4 Obstruction and Opening Test

The results of the obstruction tests indicated how the size of the "cone" or the width of the measurement beam impacted the ability of the sensor to identify leaks. The measurements demonstrated the pros and cons of both wide and narrow measurement cones or beams. In particular, when the 1-inch obstruction was placed in front of the sensor, it blocked all or a portion of the measurement beam, impacting the measured concentrations as shown in Figure 27. At 0 feet, the 1-inch obstruction blocked all the measurement beam for all sensors except Sensor B which registered a concentration of 7.5 ppm*m. As the sensors were moved away from the obstruction less of the beam became blocked and the sensors with wider beams like the RMLD and Sensor A more quickly recovered to begin identifying the methane in the methane source. The Sensor C measurement beam was able to begin measuring the methane, registering a concentration of 1 ppm*m at 20 feet. Sensor E was never able to register a concentration around the obstruction. This indicated that for Sensor E to have increased measurement distance the measurement beam was the smallest of all sensors.

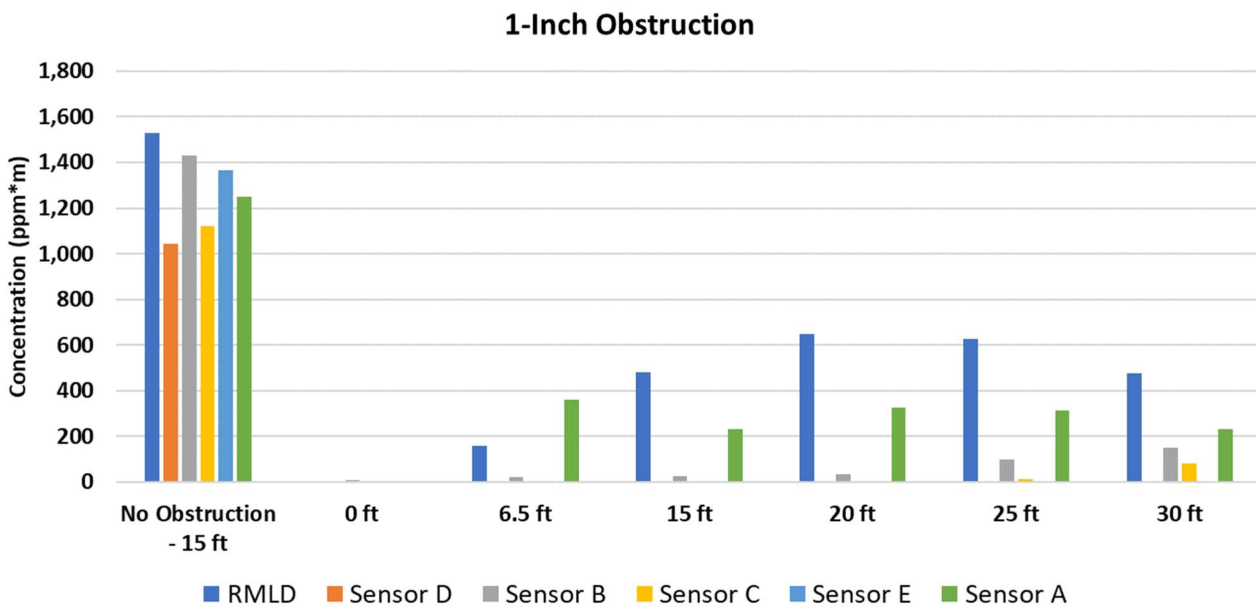

Figure 27. Measured concentrations with a 1-inch obstruction placed in front of the sensors at different distances

The differences in measurement beam size were further demonstrated by the 1-inch opening test as shown in Figure 28 where Sensor E was affected the least by the measurement through the opening. On the other hand, the RMLD and Sensor A measured continuously lower and lower concentrations as the sensors were moved away from the methane source and opening. This indicated that less of the wider beam of the RMLD and Sensor A passed through the methane source.

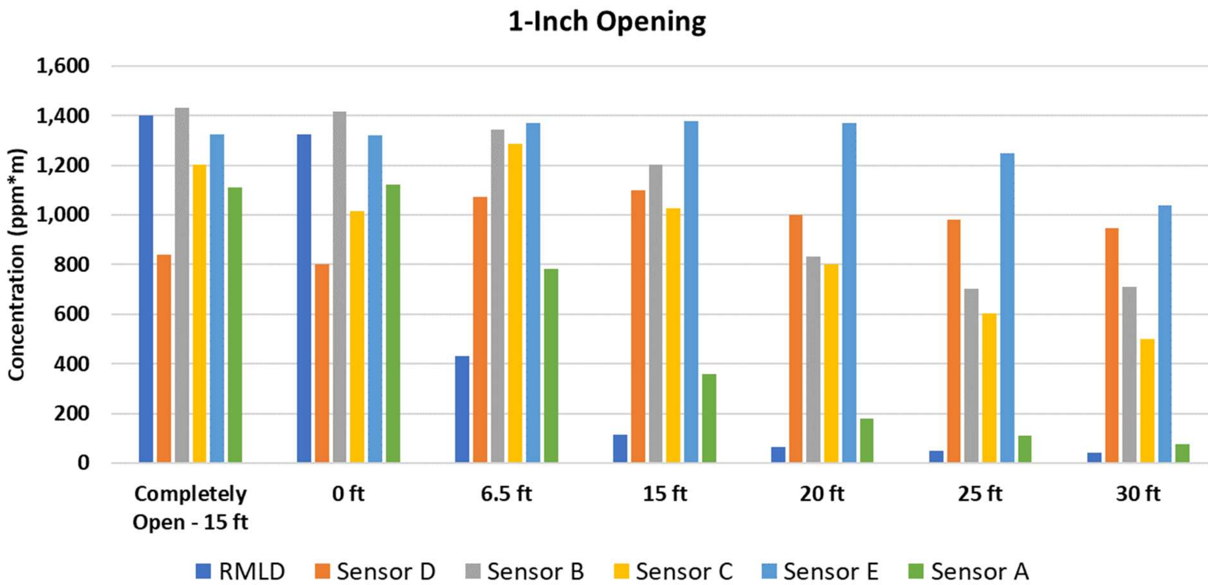

Figure 28. Measured concentrations through a 1-inch opening placed in front of the sensors at different distances

The measurement beam width, therefore, plays an important role in understanding how each sensor can be used for leak identification. For example, Sensor E may have more difficulty identifying leaks in complex asset installations with many components if those assets are between the sensor/operator and the leak. The operator will have to take additional care to ensure the narrower measurement beam precisely scans every component possible, in order to identify the leak. On the other hand, with the RMLD, Sensor A, and somewhat with Sensor B, the wider measurement beam will allow the operator to more broadly scan a complex asset installation to identify leaks.

3.2.5 Rain Test

All detectors performed similarly in the simulated rain test, with little or no impact from the precipitation as shown in Figure 29. Some variation was found in measured concentrations at the longer distances, however all sensors were still able to measure a concentration/identify a leak through the rain. The possibility of false positives (detection of a leak when one does not exist) was not evaluated during this test.

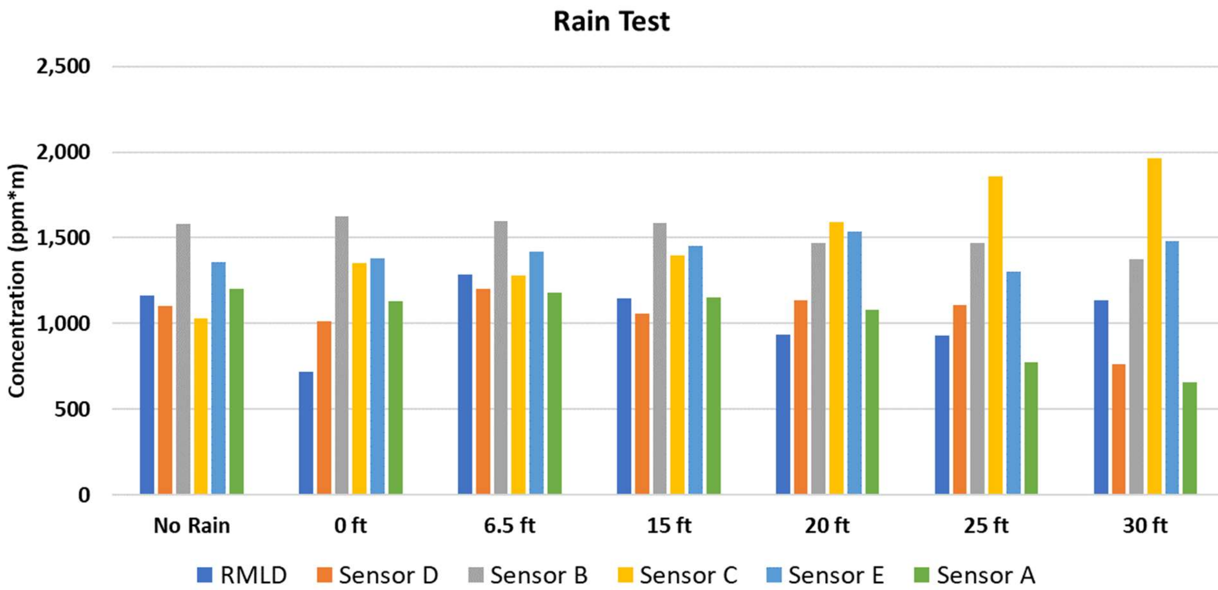

Figure 29. Measured concentrations through simulated rain from different distances

3.3 Other use case test scenarios

3.3.1 Preliminary underground testing

During the fall testing, a preliminary test was performed on an underground leak in sand. The leak generated was a larger, roughly 20 scfh leak. The sensors tested during fall were used to scan the surface above the leak. All sensors registered a measurable methane concentration as shown in Table 14. Future testing of these sensors could focus on the factors that may influence the ability of the sensors to detect underground leaks, given the influence of background material on the reported concentration identified in the controlled laboratory testing.

*Table 14: Results from Underground Leak Survey (ppm*m)*

RMLD	Sensor D	Sensor B	Sensor C
118	303	185	14

3.3.2 Preliminary Indoor Piping Testing

One sensor, Sensor D, was used to survey an area along the ceiling in a commercial/industrial building setting at GTI. This scan would have otherwise required a lift or ladder. Sensor D was chosen for this test only because it was the last remaining handheld laser-based sensor on the GTI campus. All other sensors had been returned to vendors. While scanning the area, concentrations were found to be higher around one of the heaters mounted on the ceiling. After obtaining a lift, GTI facilities personnel confirmed the leak was coming from the heater using a hand-held combustible gas indicator. Using the handheld laser-based sensor in this fashion allowed personnel to quickly and efficiently identify the leak without having to manually scan all piping from an aerial lift. The leak was subsequently repaired more quickly.

This was an unplanned yet highly useful scenario to showcase the ability of the handheld laser-based sensors for locating a leak in an otherwise hard to reach area. Future phases of this project should focus on the capabilities of the sensors to identify indoor piping leaks.

3.4 Qualitative Assessment

Qualitatively, each of the sensors scored similarly, and higher than the RMLD. Each sensor, including the RMLD, was evaluated in five categories by six team members based on their experience using the sensors during the outdoor testing. The evaluations were completed by GTI personnel and only pertains to the use of the systems during the extensive testing for this project. It does not include information from utility personnel. Descriptions of the evaluation categories are above in Table 3. Users were asked to score each sensor for the five categories as one through five. One being poor, and five being excellent, the results are given in Table 15. The RMLD scored lowest, followed by Sensor A. The average score for these two sensors was impacted by low scores for portability and display when compared to the other sensors. The other four sensors all scored similarly, between 22.2 and 22.9.

Table 15: Results from Qualitative Survey

	RMLD	D	B	C	Sensor E	Sensor A
Ease of Use	3.3	4.8	4.5	4.5	4.8	3.8
Display	2.5	5.0	4.8	4.5	4.6	3.3
Portability	2.0	4.1	4.8	5.0	4.8	3.1
Field Capability	4.3	4.5	4.3	4.0	4.7	4.3
Durability	4.0	3.8	4.5	4.5	4.0	4.5
Total	16.1	22.2	22.9	22.5	22.9	19

4 Conclusions

Several of the new sensors fell short of the RMLD in two key areas: false negatives and detection distance. The RMLD registered fewer false negatives (not detecting a leak when a leak was present) than all sensors except Sensor E as indicated by non-detections in the outdoor step tests. Some of these differences were larger for some sensors than others. The RMLD was also able to consistently measure leaks from 15 to 50 feet farther away than Sensor D, Sensor B, and Sensor C during the measurement distance limit tests. Sensor E and Sensor A, on the other hand, were able to measure concentrations 25 to 160 feet further away than the RMLD. A summary of the key findings of the project is presented in Table 16.

Table 16. Summary of Sensor Performance

	RMLD	Sensor D	Sensor B	Sensor C	Sensor E	Sensor A
Quantitative Categories						
Maximum Distance –Larger leak (ft)	140	125	100	100	300	225
Maximum Distance – Smaller leak (ft)	125	100	75	75	200+	150
Normalized Non-Detections	-	5	20	24	-1	8
Mean Concentration – Outdoor testing (ppm-m)	843.6 (fall); 1311.7 (spring)	1007	710.5	424.5	2474	747
Measure through uncoated single pane window	Yes	Yes	Yes	Yes	Yes	Yes
Measure through uncoated double pane window	Yes	Mixed	Yes	Mixed	Mixed	Mixed
Measure around small obstruction at 20 feet	Yes	No	Yes	No	No	Yes
Measure through small opening at 20 feet	Yes	Yes	Yes	Yes	Yes	Yes
Measure through rain	Yes	Yes	Yes	Yes	Yes	Yes
Qualitative Categories						
Ease of Use	3.3	4.8	4.5	4.5	4.8	3.8
Display	2.5	5.0	4.8	4.5	4.6	3.3
Portability	2.0	4.1	4.8	5.0	4.8	3.1
Field Capability	4.3	4.5	4.3	4.0	4.7	4.3
Durability	4.0	3.8	4.5	4.5	4.0	4.5
Total	16.1	22.2	22.9	22.5	22.9	19

The controlled laboratory testing revealed that background materials impact the measurements from each sensor similarly with darker materials causing lower concentration readings. The angle of detection through double pane windows optimally should be 67.5 degrees and not 90 degrees, consistent with vendor recommendations for all sensors.

Most importantly the laboratory tests revealed that the narrow measurement beam of Sensor E needs to be considered when scanning complicated asset installations. The narrow beam must precisely scan all areas with the potential for a leak. However, the other sensors, such as the RMLD and Sensor A with larger measurement beams do not have to be as precisely placed on the asset. This trade off means Sensor E can make measurements from much greater distances than the other sensors with wider measurement beams.

Qualitatively all sensors were scored higher than the RMLD. Particularly, all the new sensors were easier to use, more portable, and had better displays of the concentration than the RMLD. Sensor D, Sensor E, Sensor B, and Sensor C received high rankings in ease of use, quality of the display, and portability.

In conclusion, the new sensors are user friendly and perform reasonably well depending on the particular use case. Due to preliminary testing on underground leaks and indoor piping conducted in this phase of the project, valuable future work should explore the abilities and limitations of these sensors to identify leaks on indoor piping and on below ground leaks. Future phases should also evaluate how the configuration of the different sensors may contribute to false positives (detection of a leak when none is present).

5 List of Acronyms

Acronym	Description
GTI	**Gas Technology Institute**
RMLD	**Remote Methane Leak Detector (Intrinsically Safe; “original”)**

6 References

Trincavelli M, Bennetts VH, Lilienthal AJ. A least squares approach for learning gas distribution maps from a set of integral gas concentration measurements obtained with a TDLAS sensor. https://ieeexplore.ieee.org/document/6411118. Sensors 2012.

END OF REPORT