Refrigerant Concentration Mapping Using Real-Time Gas Monitoring; Phase I- Data Collection System Verification

Jethro Medina
The Chemours Company, United States of America

Mary Koban
The Chemours Company, United States of America, mary.e.koban@chemours.com

Refrigerant Concentration Mapping Using Real-Time Gas Monitoring; Phase I- Data Collection System Verification

Jethro Medina[1]*, Mary Koban

[1]The Chemours Company,
Newark, DE, 19713, USA, jethro.medina@chemours.com

[2]The Chemours Company,
Newark, DE, 19713, USA, mary.e.koban@chemours.com

* Corresponding Author

ABSTRACT

Environmental regulations are increasingly restricting the use of traditional high global warming potential (GWP) fluorinated refrigerants (1). Hydrofluorocarbons or HFCs are fluorinated refrigerants with zero ozone depletion potential (ODP). They are typified by having good shelf and use stability, material compatibility, adequate capacity and generally good performance across a range of operating conditions all while being non-flammable. However, due to the high GWP (>1000-5000), they are losing favor in the marketplace. Many international equipment standards (IEC 60335-2-24, IEC 60335-2-40, IEC 60335-2-89, etc.) and installation standards (ISO 5149) are being revised to further enable use of lower GWP, 0 ODP refrigerants which are flammable (2,3,4,5) Therefore, understanding how different classes of flammable refrigerants leak and pool is a key input to equipment safety standard design. While there have been many recent studies focusing on ASHRAE class 2L (low) flammability refrigerants not much work has been done reviewing ASHRAE class 3 (high) flammable refrigerants, such as propane (6). Therefore, this work was to review how a hydrocarbon, namely propane, could leak from refrigerant A/C equipment and the size and potential concentration pattern from such a leak. Due to the size and scope of this project, it was divided into three parts. The first part of this project was to construct a typical room with an installed packaged heating/air-conditioning unit (PTAC, frequently used in motels) and set-up data collection equipment to reliably collect point concentration and area (room) concentration data. The next part of the project will focus on reviewing leak patterns from equipment using thermal imaging. The third and final part of the project will connect the leak concentrations and patterns together to provide an overview of real-time leakage of propane from an installed PTAC.

1. INTRODUCTION

The objective of part one of this project was to document the leaked refrigerant concentration using real time gas monitoring. Hydrocarbons or ASHRAE class 3 (high flammability) refrigerants have lower flammability concentration thresholds which are typically below 2 volume percent in air. Therefore, setting up gas sensors and a real-time data collection system to accurately collect low concentration levels was a major challenge. Propane was chosen as the target A3 refrigerant for this study. Propane has a lower flammability limit (LFL) of 2.1 vol% or 21,000 ppm. (6) Even though propane was the target refrigerant, a surrogate refrigerant was used for the study for safety reasons.

Carbon dioxide (CO_2 or R-744) was used as substitute for propane in the performed refrigerant leak experiments. Using carbon dioxide allowed for flexibility in testing location and setup. The molecular weight and density of carbon dioxide to closely match propane (44.1 g/mol, 1.98 kg/m3 for propane; 44.01 g/mol, 2.01 kg/m3 for CO_2) (7,8). Therefore, carbon dioxide can be used under choked flow conditions to mimic the potential leak performance of propane. Choke flow will be discussed in greater details in the next paper.

The goal for this project was to set-up a CO_2 concentration data acquisition system. Various gas sensors were reviewed for this work. This information is given in Table 1 below.

Table 1: Comparison of potential gas detectors

Sensor	Sensor Type	Concentration Range	Pros	Cons
Bacharach MGS 550	Infrared	5000 - 50000 ppm	IR detection; continuous gas monitoring; 2 detectors per unit	Lower accuracy than the HGM-SZ and HGM-MZ
Bacharach MGS 250	Infrared	0 - 3500 ppm	IR detection; continuous monitoring	5-minute response time; accuracy limited to 3500 ppm
Bacharch HGM-SZ	Infrared	300 - 8000 ppm	Continuous monitoring; 10 ppm sensitivity	Pumps air around detection point; limited to one detector per unit; 8000 ppm limit
Bacharach HGM-MZ	Infrared	300 - 8000 ppm	10 ppm sensitivity; can connect up to 16 detection points	Pumps air around detection point; non-continuous monitoring (rotates between detection points); 8000 ppm limit
MSA IR400	Infrared	0-100% LEL	IR detection; detector life > 5 years; Drift < 2% per year	Accuracy of3-5% of LEL; primarily a combustible gas detector
Inficon Irwin Methane Leak Detector	Infrared	0-100% gas volume	IR detection, Bluetooth data recording; > 8 hr operating time	Unspecified accuracy; cannot integrate with NI SignalExpress

Six different potential gas detectors were reviewed. Four infrared (IR) gas detectors were explored: Bacharach MGS 550 and 250, MSA IR400, and the Inficon Irwin Methane Leak Detector., The MGS 550 was selected due to acceptable accuracy, ease of output recording, and wide range of detection limits. These detectors were setup to monitor gas concentration from a packaged terminal air conditioner (PTAC).

2. Experimental Setup

2.1 Chosen Sensor Type

The gas detectors used were the Bacharach MGS 550 series. There were 16 total sensors used for testing. A combination of high (50000 ppm) and low (5000 ppm) concentration sensors were used. The sensors have a detection range of 5% of max concentration, with recording accuracy of 0.5% of max concentration. Concentration ranges and measurement for both sensors are listed in Table 2 below.

Table 2: MGS 550 sensor detection ranges and data acquisition accuracies

	Lower Limit (ppm)	Upper limit (ppm)	Data Acquisition Accuracy
High Concentration	2500	50000	± 250 ppm
Low Concentration	250	5000	± 25 ppm

The Bacharach MGS 550 can utilize various sensor technologies including the following: electrochemical, semiconductor, and infrared. The MGS 550, as mentioned prior, is the central enclosure, with up to two sensors connected. The types used were infrared remote sensors. Infrared (IR) sensors are designed to detect a target gas by absorption of infrared radiation, which is concentration dependent. Ambient air diffuses through a metal piece. Light from an IR source passes through the gas, which is reflected to a dual-element detector. One element acts as a reference for the second, which is responsible for measuring gas-dependent light transmission. This light transmission is then converted into a concentration and corresponding output signal. This process is described in Figure 1 below.

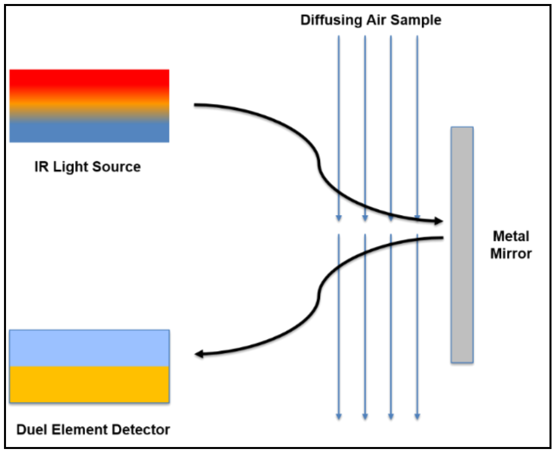

Figure 1: Infrared sensing technology diagram

IR sensors were chosen due to their minimal air disturbance with accurate gas concentration measurements. When measuring refrigerant in air concentration, limiting causes for air flow is important. IR sensors allow air flow to only be caused by the PTAC fan. Incorporation of IR detectors with the MGS 550 was a user-friendly process. Functionality of the MGS 550 was above adequate. Each required 24 Vdc input and provided 4-20 mA output signals. These current signals were then sent to the data acquisition hardware and software for processing into usable refrigerant concentration data. Figure 2 below shows the chosen MGS 550 sensor.

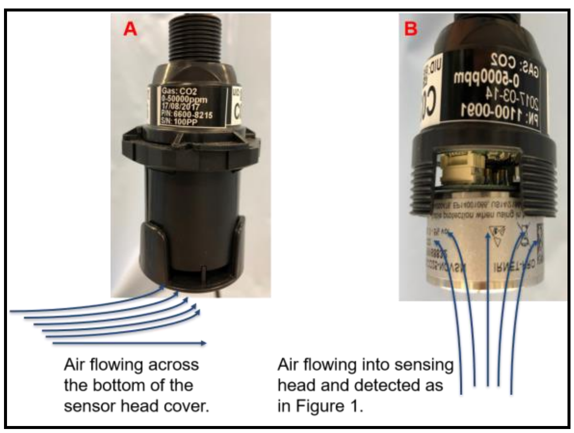

Figure 2: Air flowing around the bottom of the sensor head and case (A). Air flowing through the case and into the detector for measurement per Figure 1 (B).

2.1 Data Acquisition and Additional Equipment

Signals from each sensor were converted into gas concentration data using National Instruments (NI) SignalExpress 2015 (15). A 4-slot chassis, NI cDAQ-9174 housed the following modules: NI 9208 for current input and NI 9211 for temperature. Current signals from the MGS 550 detectors were sent to theNI 9208 current input module. Data acquisition hub is shown below in Figure 3.

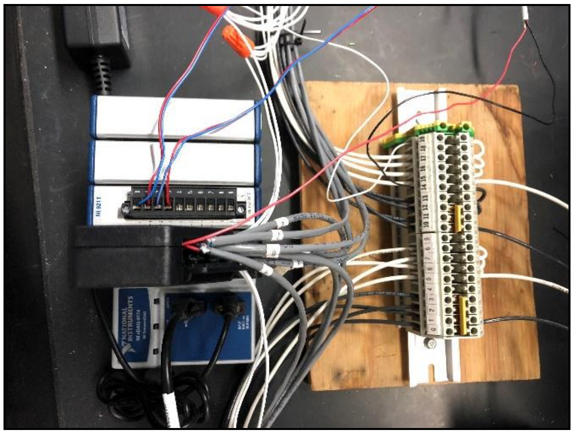

Figure 3: Data acquisition chassis, modules, and terminal block used in measurement system

Signals were converted to gas concentration using linear equations in SignalExpress. The conversion equations for both high and low concentrations are given below in Equations 1 and 2. Equations below were determined by converting detector current output (4-20 mA) to gas detection range (2500– 50,000 ppm).

$$[CO_2] = 3{,}125{,}000\ A - 12{,}500 \quad (1)$$

$$[CO_2] = 312{,}500\ A - 1250 \quad (2)$$

In the above equations, A is current input measured in amps. Concentration for CO_2 is output in ppm (v/v in air). Of the 16 channels in the current input module, 15 were for reading concentration data (8 high concentration, 7 low concentration). The remaining channel was for leak discharge pressure measurement via pressure transducer (Omega PX429-1.0KSG) (16). This pressure transducer has a 1000 psig limit and measures with a 0.08% accuracy. The temperature in module was for measuring discharge temperature at the leak outlet. A T-type thermocouple was surface mounted near the leak point. This is shown in Figure 4 below.

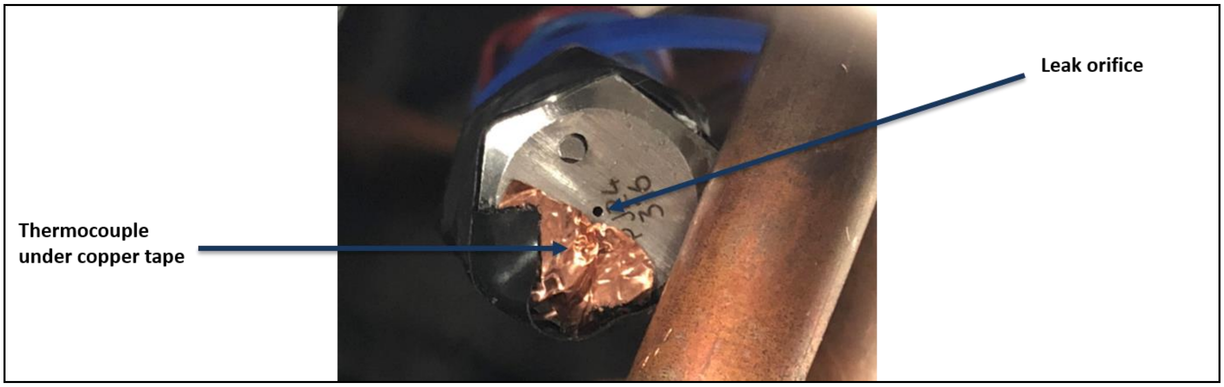

Figure 4: Refrigerant hose cap with thermocouple (under copper tape) on cap surface, near leak orifice

Example SignalExpress live data monitoring can be seen in Figure 5. The full signal path from sensor to SignalExpress is depicted in Figure 6.

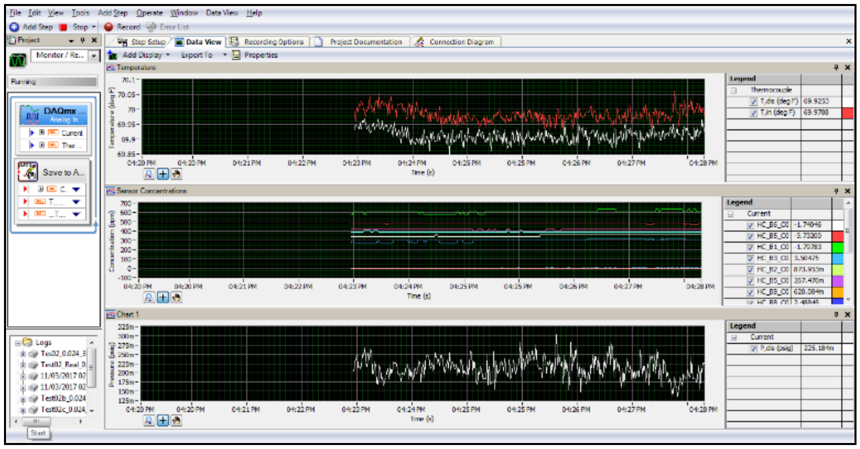

Figure 5: NI SignalExpress sample output display. Temperatures displayed in the upper graph. The middle graph displayed live CO_2 concentration data. The bottom graph displayed leak discharge pressure. A spike in discharge pressure indicates the starting time of the refrigerant leak.

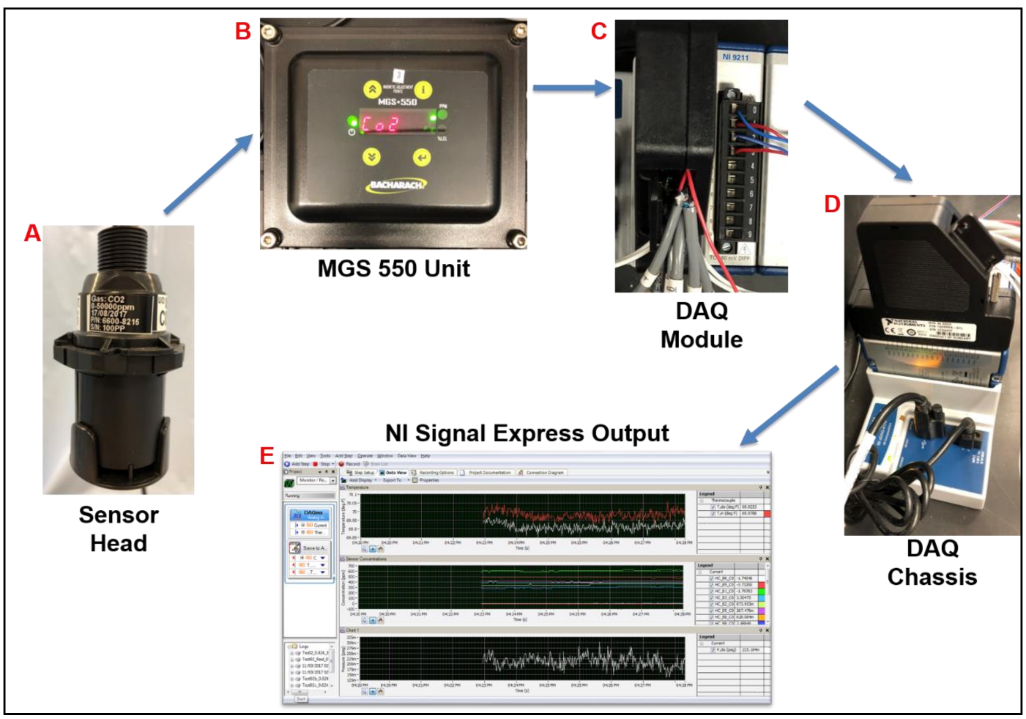

Figure 6: Signal travel path. Concentration is measured in the sensor head (A) which is connected to the MGS 550 unit (B). A current output signal is sent to the relevant modules (C), which is connected to the chassis (D). The chassis transmits information to NI SignaExpress (E)

The diagram in Figure 6 above depicts signal travel path for real time CO_2 concentration monitoring. Data was collected for a 4-minute leak (100g/min – 0.4 kg) across various sample points. Of the 16 total sensors, 8 high concentration sensors were used for sensor analysis due to upper detection range of 50000 ppm.

2.2 Sensor Validation

The 8 high concentration sensors were subject to Gage R&R statistical analysis for testing measurement system validation. A Gage R&R determines the measurement variation from various parts (gas sensors) and operators. This information indicates whether a measurement system can adequately assess target measurement (concentration) despite system variation. Six sensors were placed 1.4 m in front of the PTAC fans and 0.75 m above the PTAC floor level. Two sensors were place 0.9 m across the top of the PTAC and 0.1m above the PTAC blowers. These two sensor groups were subject to separate Gage R&R analysis. Sensor arrangement is shown in Figure 7 below.

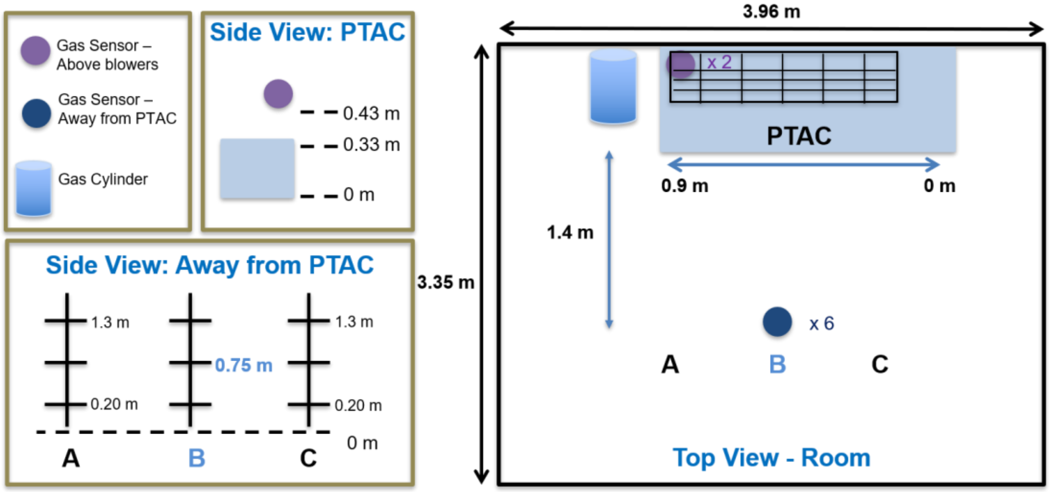

Figure 7: Measurement system validation details. 6 sensors were placed 1.4 m in front of the PTAC and 0.75 m above the PTAC grade. 2 sensors were 0.9 m across the top and 0.1 m above the PTAC fan blowers.

3. Results and Discussion

3.1 Sensor Response Time and Sensitivity

Validating the gas detectors required two analyses: sensor sensitivity repeatability and detector concentration verification. Sensitivity was determined through response time data analysis. The data was obtained by repeated exposure of one sensor to CO_2. Gas flow rate was constant across all testing via CO_2 pressure regulator (set to 75 psig). Regulator outlet was piped to detector outlet for consistent leak scenarios Concentration data was monitored until the first increase in concentration was observed, corresponding to sensor response time. Concentration was recorded in 1-second intervals, as demonstrated in Figure 8 below. Between runs, CO_2 gas flow was shut off, allowing the sensor to return to standard CO_2 in air concentration levels (525 ppm).

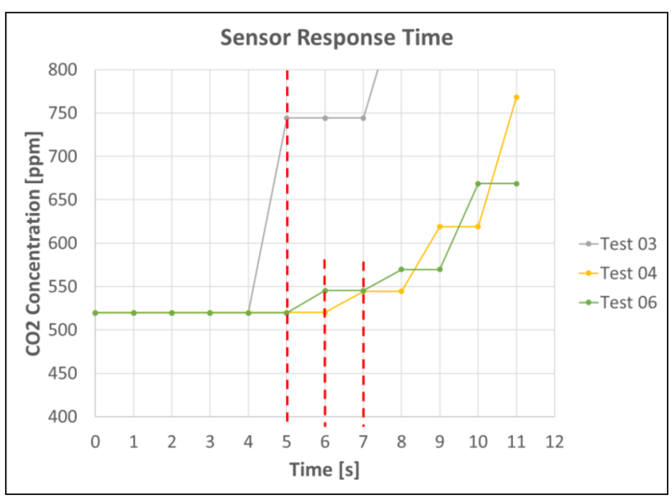

Figure 8: Response time data snapshot. Monitoring shows 3 test runs, with 5, 6, and 7 s response times.

For the distribution analysis, one gas detector was subject to 20 test runs of CO_2 exposure. The resulting average response time was 7.15 s. with a standard deviation of 1.31 s (5 s minimum and 9 s maximum). A histogram of response time data is shown below in Figure 9. There were no apparent outliers nor skewness in the distribution. These data resemble a normal distribution; more test runs would likely adjust response time frequency to further resemble normality. Sensor response time is repeatable within several seconds, which is adequate considering peak concentration data (see Figure 10) is observed several hundreds of seconds after leak begins.

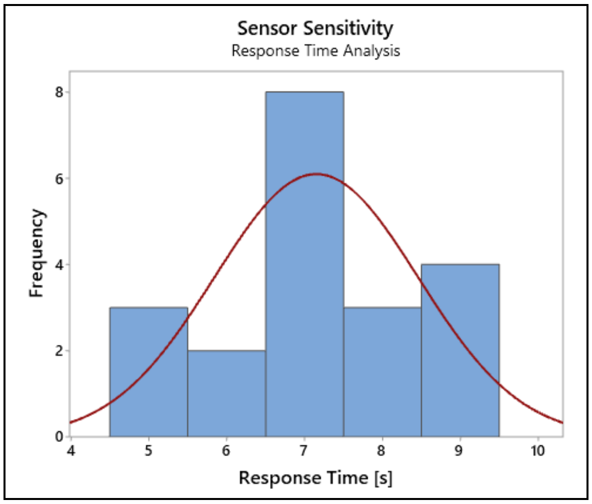

Figure 9: Histogram distribution of sensor response time (7.15 s average). Normal distribution curve overlaps data as a red line.

3.2 Detector Monitoring Validation

For validating the gas detector concentration monitoring, leak orifice and leak rate were maintained at 0.6 mm and 100 g/m respectively. Two Gage R&Rs were run, separated into two and six sensors. Three leaks were performed using the above conditions for measurement validation. Peak refrigerant concentrations were used for the analysis.

Total gage is the combined effect of repeatability and reproducibility on measurement variation. Repeatability is variation in the same part (sensor) with a consistent operator. Reproducibility accounts for variation from different operators. Because only one operator will use the system, only one operator was used for system verification. This results in zero reproducibility and identical total gage and repeatability. Part-to-part represents variation across the different sensors and typically represents the largest source of variation.

The results of the six sensors Gage R&R are shown in Table 3 below.

Table 3: Gage R&R results for 3 leaks, 6 sensors in front of PTAC using peak CO_2 concentrations

Sensor	Leak 1 (ppm)	Leak 2 (ppm)	Leak 3 (ppm)
1	3825	3825	3821
2	3752	3753	3753
3	3614	3615	3615
4	3666	3665	3666
5	3702	3702	3702
6	3665	3664	3664

Source	Std. Dev.	% Study Variation	% Tolerance
Total Gage	0.908	1.22	2.18
Repeatability	0.908	1.22	2.18
Part-to-Part	74.3	100.0	178.2
Study variation	74.4	100.0	178.4

Refrigerant concentrations in Table 3 are reported in ppm (v/v of CO_2 in air). After observing the first peak concentration, the final sensor recorded a peak concentration within 10 seconds A tolerance of 250 ppm was specified because of sensor accuracy specifications from Table 2 (5% of 50,000 ppm). For percent of study variation and percent tolerance, the process variation (6 times standard deviation) is divided by total study variation. Values of 1.22% and 2.18% for study and tolerance percentages respectively are below the 10% threshold, indicating the system can adequately assess performance and differentiate between working sensors. Furthermore, the gage R&R analysis was repeated, lowering the tolerance until the tolerance percentage was above 10%. At a tolerance of 55 ppm, the % tolerance was > 10% indicating adequate measurement system performance beyond the specified 250 ppm.

Regarding concentration data, the range in measurements was 210 ppm, which is less than the tolerance. The time from beginning of leak to reach the minimum 2500 ppm detection range at the sensor location was about 145 seconds with the chosen leak rate. Results for sensors placed above PTAC fan blowers are shown in Table 4 below. Example leak concentration profile for Leak 1 in Table 4 is shown in Figure 10.

Table 4: Gage R&R results for 3 leaks, two sensors above PTAC blowers using peak CO_2 concentrations

Sensor	Leak 1 (ppm)	Leak 2 (ppm)	Leak 3 (ppm)
1	4390	4390	4390
2	4016	4017	4016
Tolerance		250 ppm	

Source	Std. Dev.	% Study Variation	% Tolerance
Total Gage	0.495	0.19	9.90
Repeatability	0.495	0.19	9.90
Part-to-Part	264.3	100.0	5286.2
Study Variation	264.309	100	634.34

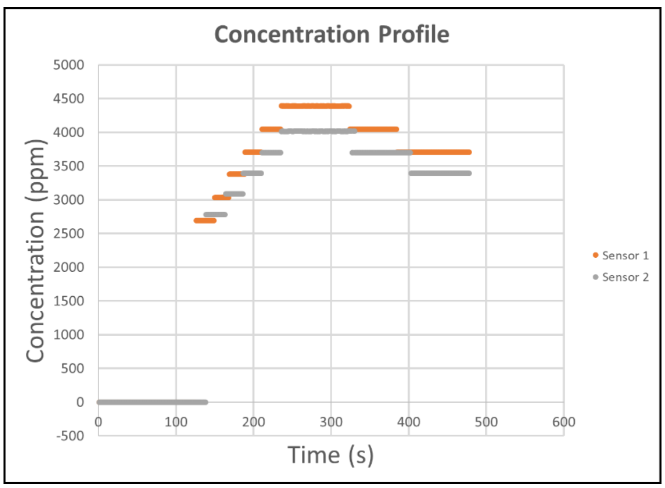

Figure 10: Leak profile for Leak 1 data in Table 4. Peak concentrations for both sensors are observed around the 250 s timestamp

Concentrations in Table 4 are also reported in ppm (v/v of CO_2 in air). The time between peak concentration reporting between the two sensors was less than eight seconds across the three leaks. A 250 ppm tolerance specification was again used for the Gage R&R. Process variation was calculated similarly as in the six sensor analysis. Percentages of study variation and tolerance were 0.19% and 1.19% respectively. This indicates an acceptable measurement system, like the first six sensors. Tolerance was lowered in subsequent analyses until the tolerance percent was greater than 10%. This occurred with a tolerance of 30 ppm, also indicating adequate system performance beyond equipment specifications. However, the 30 ppm was the result of data from only two sensors. This can be improved by testing additional sensors.

The range between the two sensors across the three leaks was 374.7, which is greater than the sensor accuracy. However, the results of the Gage R&R produced a similar conclusion, the measurement system was validated. Time between leak beginning to sensors detecting 2500 ppm minimum for the chosen locations was about 130 seconds. As indicated in Figure 7, the two sensors were placed above the fan blowers, but not in front of the unit. This indicates detection point influencing response time. Influences on leak behavior and sensor response time will be reviewed in future work.

3. Conclusions

A refrigerant-in-air monitoring system was setup to monitor real-time refrigerant leak behavior from a PTAC air conditioning system at various points in a test room. CO_2 was used as a surrogate for propane in the testing. The Bacharach MGS 550 gas detector was chosen due to IR sensing technology (minimum impact to room air flow), remote sensing capability, and ease of integration with data acquisition. Data acquisition utilizes NI SignalExpress 2015 and several National Instruments modules for recording of refrigerant concentrations, leak pressure, and leak temperature. System results were subject to Gage R&R analysis for measurement system verification. Eight sensors with detection range of 2500 to 50,000 ppm were placed in two areas (in front and above the PTAC fan blowers). Continuous refrigeration concentration data over a 4-minute leak were collected and subject to the analysis.

Sensor response time was determined to have a normal distribution, with repeatability within several seconds. This is adequate considering peak concentration data was observed hundreds of seconds after leak begins. Following sensor response sensitivity determination, two groups of sensors, in front of the PTAC and above the PTAC blowers, were subject to three leak tests. Variation significance was determined through Minitab™ Gage R&R. A tolerance of 250 ppm was specified because of the MGS 550 accuracy (5% of upper detection limit). Results for the 6 sensor Gage R&R included percentages from study variation and tolerance were 1.22% and 2.18% respectively, which are both less than 10%. Values less than 10% indicate acceptable system performance. For the remaining two sensors, percentages from study and tolerance were 0.19% and 1.19%. Both values were less than 10%, further validating the measurement system. Using sensors in two different areas relative to the PTAC, the measurement system was successfully verified beyond the equipment tolerance specifications.

Sensor response time and accuracy both play critical roles in the refrigerant detection space, particularly with flammable refrigerants. Quick and repeatable response times protect both equipment and end-users from entering potentially dangerous areas. Tight measurement variation among repeat sensors demonstrates repeatable build quality and performance. With test sensor accuracy and reliability now confirmed, these real-time gas monitors can be used for refrigeration concentration mapping, which will be beneficial for equipment design.

NOMENCLATURE

A (Equations 1 & 2)	Amps
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
GWP	Global Warming Potential
IEC	International Equipment Standards
IR	Infrared
ISO	International Organization for Standardization
LFL	Lower Flammability Limit
mA	Milliamps
ODP	Ozone Depletion Potential
ppm	Parts Per Million
psig	Pounds Per Square Inch Gauge
PTAC	Packaged Terminal Air Conditioner

REFERENCES

American Society of Heating, Refrigerating, and Air-Conditioning Engineers (2008). *Addenda to ANSI/ASHRAE Standard 34-2007, Designation and Safety Classification of Refrigerants* (ANSI/ASHRAE Standard 34-2007).

Bacharach (2017). *Multi-Zone (MZ)* [Product Data Sheet]. https://ss-usa.s3.amazonaws.com/c/308475912/media/28125d42f6aa80cb355693953667226/multi-zone_datasheet.pdf

Bacharach (2017). *Single-Zone (SZ)* [Product Data Sheet]. https://ss-usa.s3.amazonaws.com/c/308475912/media/28135d42f8ca1448709559663025793/single-zone_datasheet.pdf

Bacharach. *MGS-250 Infrared Gas Detector* [Product Data Sheet]. https://ss-usa.s3.amazonaws.com/c/308475912/media/60405d640a4b0dca762336561815561/mgs250-ds-MKTG00017-en-1.pdf

Bacharach. *MGS-550 Refrigerant Gas Detector* [Product Data Sheet]. https://ss-usa.s3.amazonaws.com/c/308475912/media/128225e164e115858b79979701398602/mgs550-mktg00012-en-4.pdf

HARP International (2018). *HARP 290, Propane* [Safety Data Sheet]. http://www.harpintl.com/downloads/pdf/msds/HARP-R290-CLP.pdf

Inficon (2003). *Irwin Methane Leak Detector* [Product Data Sheet]. https://products.inficon.com/getattachment.axd/?attaName=f03a167c-4737-4f04-b2f2-71e5233ec1b1

International Equipment Standards (2017). *Household and similar electrical appliances - Safety - Part 2-24: Particular requirements for refrigerating appliances, ice-cream appliances and ice makers* (IEC 60335-2-24:2010/AMD2:2017 Amendment 2).

International Equipment Standards (2018). *Household and similar electrical appliances - Safety - Part 2-40: Particular requirements for electrical heat pumps, air-conditioners and dehumidifiers* (IEC 60335-2-40:2018).

International Equipment Standards (2019). *Household and similar electrical appliances - Safety - Part 2-89: Particular requirements for commercial refrigerating appliances and ice-makers with an incorporated or remote refrigerant unit or motor-compressor* (IEC 60335-2-89:2019).

International Organization for Standardization (2014). *Refrigerating systems and heat pumps — Safety and environmental requirements — Part 3: Installation site* (ISO 5149 ISO 5149-3:2014).

IPCC, 2007: Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp. http://www.ipcc.ch/report/ar4/syr

Mine Safety Appliances (2018). *Model IR400* [Product Data Sheet]. http://s7d9.scene7.com/is/content/minesafetyappliances/IR400%20Data%20Sheet

Minitab (2018). Minitab 18 Statistical Software [Computer Software]. State College, PA.

National Instruments (2015). *SignalExpress 2015* [Product Manual]. https://www.ni.com/pdf/manuals/374767b.html

National Instruments (2015). SignalExpress 2015 [Computer Software]. Columbia, MD

National Refrigerants (2017). *Refrigerant R744, Carbon Dioxide* [Safety Data Sheet]. https://nationalref.com/wp-content/uploads/2019/08/SDS_R744_CLP.pdf

Omega. High Accuracy Pressure Transducers: PX409 Series [Product Data Sheet]. https://assets.omega.com/pdf/test-and-measurement-equipment/pressure/pressure-transducers/PX409_Series.pdf