Air-Conditioning, Heating and Refrigeration Technology Institute

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LEAK DETECTION OF A2L REFRIGERANTS IN HVACR EQUIPMENT

Final Report

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List of Acronyms

AC	Air-Conditioning
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CFC	Chlorofluorocarbon
CO	Carbon Monoxide
EC	Electrochemical Cell
GWP	Global Warming Potential
HART Signal	Highway Addressable Remote Transducer signal
H_2S	Hydrogen Sulfide
HC	Hydrocarbon
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
HVACR	Heating, Ventilation, Air-Conditioning, and Refrigeration
IEC	International Electrotechnical Commission
IPCC AR4	Fourth Assessment Report of the Intergovernmental Panel on Climate Change
IR	Infrared
ISO	International Organization for Standardization
LEL	Lower Explosive Limit
LFL	Lower Flammability Limit
MOS	Metal Oxide Semiconductor
NDIR	Non-Dispersive Infrared
NH_3	Ammonia
NO_2	Nitrogen Dioxide
O_2	Oxygen
ODS	Ozone Depleting Substance
OEL	Occupational Exposure Limit
PIR	Photo-acoustic Infrared
ppm	Parts per Million, volume basis [as used throughout this document]
SO_2	Sulphur Dioxide
TLV-TWA	Threshold Limit Value - Time Weighted Average
VDC	Voltage Direct Current

Executive Summary

Over the past several years, climate-friendly alternatives, such as lower-GWP HFCs and HFOs, have been developed to replace the current suite of HFCs in use. Several of these proposed refrigerants fall into the ASHRAE safety category created in ASHRAE Standard 34-2010: *Designation and Safety Classification of Refrigerants*, A2L, which are a sub-class of A2 (i.e., lower flammability) refrigerants.

Current international and U.S. standards for HVACR systems are anticipated to be updated with new or revised requirements specific for A2L refrigerants, including refrigerant sensor requirements, such as response time and measurement ranges:

- International Standard IEC 60335-2-40: Household and similar electrical appliances – Particular requirements for electrical heat pumps, air conditioners, and dehumidifiers (Edition 5.1, April 2016)
- ASHRAE Standard 15-2016: Safety Standard for Refrigeration Systems
- International Organization for Standardization (ISO) 5149-3:2014 Refrigerating systems and heat pumps – Safety and environmental requirements

According to the proposed requirements, HVACR systems containing an A2L refrigerant would be required to include one or more refrigerant sensor/detection systems that previously did not have refrigerant sensor requirements, such as for certain smaller commercial/industrial and residential applications. Large industrial and commercial applications (e.g., machine and cold rooms) are already required to have refrigerant detection systems.

Currently available technologies including IR, EC, MOS, catalytic, and heated diode sensors were reviewed to determine whether they can meet the proposed sensor requirements under standards ASHRAE 15, IEC 60335-2-40, and ISO 5149-3. These sensors were reviewed and evaluated against certain criteria to determine the applications and equipment types the technology could be installed in and whether they would be appropriate for detecting A2L refrigerants (e.g., HFC-32, HFO-1234yf, HFO-1234ze(E), and blends thereof). In addition, due to the flammability of A2L refrigerants, potential failure modes of the sensors (i.e., how the sensor can fail) were evaluated and a reliability testing procedure was developed to address these failure modes. The evaluation of sensor technologies and potential failure modes was based on a review of product literature and discussions with sensor manufactures; actual testing of refrigerant sensors was not performed for this analysis.

Based on research of available refrigerant sensor technologies and discussions with sensor manufacturers, both IR and MOS sensors were found to be the most promising sensor technologies that could be used for A2L refrigerant detection and meet the proposed requirements in residential and commercial/industrial settings. These sensor technologies were both found to be least susceptible to the effects of potential failure modes in commercial/industrial and residential settings. Sensor models using IR and MOS technology currently exist that detect A2L refrigerants; however, most sensors that are currently available or are coming available this year cannot measure A2L refrigerants up to the specified detection ranges and have additional concerns for adaptation, particularly in residential settings, including relatively short lifetimes, maintenance requirements, and costs. However, sensor manufacturers are becoming aware of the proposed requirements for A2L refrigerant sensors and it is expected that manufacturers will focus research and development efforts to ensure that appropriate sensors are available to meet the updated standards, although the timeline for development is still uncertain.

Introduction

In light of global efforts to phase out ODS (i.e., CFCs and HCFCs), HFCs are now the most commonly used refrigerant in a variety of air conditioning (AC) and refrigeration applications. HFCs used in these applications have low toxicity and are non-flammable; however, these commonly used HFCs typically have GWP_{100} values that range from 1,430 to 3,985 per IPCC AR4. Recognizing the harmful impact these chemicals have on the climate, as well as anticipated regulatory restrictions on their use, industry is in the process of transitioning to less harmful, lower-GWP alternatives.

Over the past several years, climate-friendly alternatives, such as lower-GWP HFCs and HFOs, have been developed to replace the current suite of HFCs in use. Several of these proposed refrigerants fall into an ASHRAE safety category created in ASHRAE Standard 34-2010: *Designation and Safety Classification of Refrigerants*, A2L.[1] A2L refrigerants are a sub-class of A2 (i.e., lower flammability) refrigerants that have a burning velocity of $\leq$10 cm/sec when tested at 23°C and 101.3 kPa. Common A2L refrigerant alternatives include HFC-32, HFO-1234yf, HFO-1234ze(E), and other refrigerant blends containing HFOs.

As a result of the flammability of these refrigerants, codes and standards will require the use of sensors to detect a refrigerant leak for both commercial/industrial and residential applications to mitigate the potential for a combustible event. Currently, refrigerant detectors are only required in restricted-access machine rooms that contain HVACR equipment with several hundred (or thousand) pounds of refrigerant charge. These detectors use a set point value to trigger an alarm and mechanical ventilation to prevent the refrigerant concentration in the room from exceeding the occupational exposure limit, as well as to prevent exceeding flammability, toxicity, and oxygen deprivation limits in the case of a large leak or accidental release. The proposed requirement for sensors in human comfort applications is dictated by the charge quantity of the refrigerant, which takes into account the room size where the equipment is installed and the LFL for that refrigerant.

Current international and U.S. standards for HVACR systems are anticipated to be updated with new or revised requirements specific for A2L refrigerants, including refrigerant sensor requirements, such as response time and measurement ranges:

- International Standard IEC 60335-2-40: Household and similar electrical appliances – Particular requirements for electrical heat pumps, air conditioners, and dehumidifiers (Edition 5.1, April 2016)
- ASHRAE Standard 15-2016: Safety Standard for Refrigeration Systems
- International Organization for Standardization (ISO) 5149-3:2014 Refrigerating systems and heat pumps – Safety and environmental requirements

[1] A2L refrigerants were first introduced in Addendum ak to ASHRAE Standard 34-2007. A2L refrigerants were later incorporated into the ASHRAE Standard 34-2010 edition.

If switched to an A2L refrigerant, some HVACR systems would be required to include one or more refrigerant sensor/detection systems that previously did not have refrigerant sensor requirements, such as for certain residential applications. Industrial and commercial equipment in machine rooms per ASHRAE Standard 15 are already required to have refrigerant detection systems. Currently available sensor technologies may not necessarily meet the proposed requirements and be able to be integrated into HVACR equipment across all applications. In addition, due to the flammability of A2L refrigerants, an important consideration for selecting a suitable sensor technology are the potential failure modes of the sensor (i.e., how the sensor can fail).

The most recent summaries of refrigerant detector technologies that discuss the ability to measure halocarbon refrigerants in residential and commercial settings are from the 1990s (e.g., McClure et. al., (1990) and USACERL (1996)); therefore, this analysis reviews currently available sensor technologies and evaluates whether these sensors can be incorporated into HVACR equipment for both commercial/industrial and residential applications and meet the proposed requirements for detecting A2L refrigerants. In addition, key known failure modes were also identified for available sensor technologies and suitable reliability testing procedures to address these potential failure modes were developed to allow industry to best evaluate the current market of refrigerant sensors and inform decisions regarding the use of A2L refrigerants. The evaluation of sensor technologies and potential failure modes was based on a review of product literature and discussions with sensor manufactures; actual testing of refrigerant sensors was not performed for this analysis.

Evaluation of Refrigerant Sensor Technologies

Currently, refrigerant detectors are required in machine rooms that contain HVACR equipment. Detectors must be located in an area where refrigerant from a leak will concentrate and activate an alarm and mechanical ventilation upon detection of a concentration equal to the corresponding TLV-TWA of the refrigerant, a type of occupational exposure limit based on intermittent exposure not exceeding 8 hours per day and 40 hours per week. As such, there are multiple refrigerant sensor technologies available and in use in the market today for fluorinated refrigerants (e.g., HCFCs and HFCs) in large commercial HVACR equipment. All commonly known Class A2L refrigerants (e.g., HFC-32, HFO-1234yf, and HFO-1234ze(E)) are also fluorinated gases, and therefore, commercially available sensor technologies may be appropriate for these new refrigerants; however there may be additional requirements for Class A2L refrigerant sensors that available sensor technologies are not capable of meeting.Table 1 lists the A2L refrigerants and blends currently defined by ASHRAE Standard 34-2016 and published addenda to date. Additional refrigerant designations are in process and will be added in future editions of the standard.

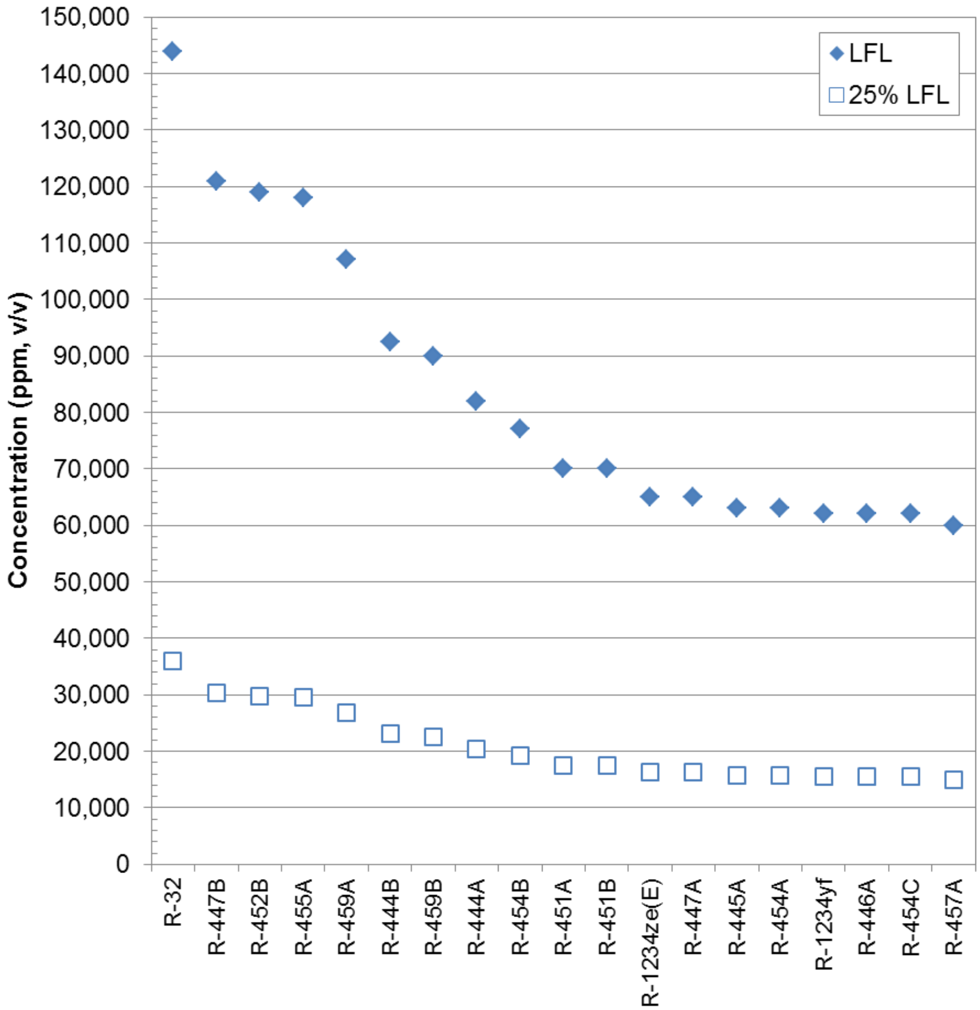
Table 1: Summary of A2L Single Component Fluids and Blends

A2L Refrigerant	Composition (% mass)
Single Component Refrigerants	
R-32	
R-1234yf	
R-1234ze(E)	
Refrigerant Blends	
R-444A	R-32/152a/1234ze(E) (12.0/5.0/83.0)
R-444B	R-32/152a/1234ze(E) (41.5/10.0/48.5)
R-445A	R-744/134a/1234ze(E) (6.0/9.0/85.0)
R-446A	R-32/1234ze(E)/600 (68.0/29.0/3.0)
R-447A	R-32/125/1234ze(E) (68.0/3.5/28.5)
R-447B	R-32/125/1234ze(E) (68.0/8.0/24.0)
R-451A	R-1234yf/134a (89.8/10.2)
R-451B	R-1234yf/134a (88.8/11.2)
R-452B	R-32/125/1234yf (67.0/7.0/26.0)
R-454A	R-32/1234yf (35.0/65.0)
R-454B	R-32/1234yf (68.9/31.1)
R-454C	R-32/1234yf (21.5/78.5)
R-455A	R-744/32/1234yf (3.0/21.5/75.5)
R-457A	R-32/1234yf/152a (18.0/70.0/12.0)
R-459A	R-32/1234yf/1234ze(E) (68,0/26,0/6,0)
R-459B	R-32/1234yf/1234ze(E) (21,0/69,0/10,0)

Source: ASHRAE (2016d)

Figure 1 shows the LFL (at nominal composition for blends), and 25% of the LFL for each refrigerant as defined by ISO 817:2014 and pending Amendment 1. The value 25% of LFL is the maximum detector set point value for existing and proposed requirements for Class A2L sensor technologies under IEC 60335-2-40 and ASHRAE 15. ISO 5149-3:2014 requires a maximum detector set point value of 20% of the LFL, as described in Table 2. The LFL for currently known A2L refrigerants ranges from 60,000 to 144,000 ppm, and the corresponding maximum detector set points range from 15,000 to 36,000 ppm (25% of LFL) and 12,000 to 28,800 ppm (20% of LFL).

Figure 1: LFLs of Select A2L Refrigerants



The remainder of this section reviews the existing and proposed requirements for Class A2L sensor technologies under IEC 60335-2-40, ASHRAE 15, and ISO 5149-3:2014 and evaluates existing and new sensor technologies against these requirements.

1. A2L Sensor Requirements

A new draft of IEC 60335-2-40 (for future edition 6) and several addenda to ASHRAE Standard 15-2016 are expected in the next few years. Both standards are anticipated to be updated with specific requirements for A2L refrigerants, including refrigerant sensor requirements. Additionally, ISO 5149-3:2014 specifies the detector requirements for all classes of refrigerant, including A2L. ISO 5149-3:2014 allows the use of an oxygen deprivation sensor in lieu of a refrigerant detector; however those sensor types are outside the scope of this study. Table 2 summarizes the existing and proposed sensor requirements for Class A2L refrigeration systems.

Table 2: Summary of Existing and Proposed Requirements for Class A2L Refrigerant Sensors

Evaluation Criteria	ASHRAE 15/ ASHRAE 15 Addendum H (existing and proposed for Machinery Rooms)	ASHRAE 15 Addendum D (proposed for Human Comfort Cooling)	IEC 60335-2-40 (proposed)	ISO 5149-3 (existing)
Features				
Placement and number of sensors	• **Existing:** Detector should be located in an area where refrigerant from a leak will concentrate • **Proposed:** One or more detectors should be located in an area where refrigerant from a leak will concentrate	• Detector should be located: ○ Within the self-contained system, in a place where leaked refrigerant will be detected, ○ In the air supply duct that connects the self-contained system to the occupied space, not farther than 6 ft. (1.8 m) from the self-contained system, or ○ In the occupied space not farther than 6 ft.(1.8 m.) and underneath the air supply inlet to the room	• Detector should be located where leaking refrigerant is likely to stagnate: ○ Within the unit for appliances connected via an air duct system to one or more rooms, ○ Within the unit where the release height is not more than 1.5 m, ○ Where the release height is more than 1.5 m, the sensor may be located: ▪ Within the unit ▪ 100 mm or less directly below the unit ▪ Remotely located within 300 mm above the floor See Appendix GG for additional specific placement requirements.	• Detectors should be located in relation to where the refrigerant from a leak will concentrate • At least one detector should be installed per machinery room or occupied space ○ At the lowest point for refrigerants heavier than air or ○ At the highest point for refrigerants lighter than air
Calibration	• **Existing:** Detectors shall be periodically tested in accordance with manufacturer's specifications and the requirements of the authority having jurisdiction	• No specific requirements	• Detectors systems shall be pre-set from the factory for the refrigerant used. • Detectors shall be calibrated in a refrigerant-free area.	• No specific requirements

Evaluation Criteria	ASHRAE 15/ ASHRAE 15 Addendum H (existing and proposed for Machinery Rooms)	ASHRAE 15 Addendum D (proposed for Human Comfort Cooling)	IEC 60335-2-40 (proposed)	ISO 5149-3 (existing)
Detection system response	• **Existing:** The refrigerant detector shall annunciate visual and audible alarms inside and outside all entrances to the refrigeration machinery room • **Existing:** The refrigerant detector shall activate machinery room ventilation automatically • **Existing:** The alarm must have a manual-reset with the reset located inside the refrigerant machinery room	• When the refrigerant detector activates it shall: ○ Turn on the supply air fan at the highest air flow rate available, and ○ Turn off the compressor and other devices. ○ Open any air flow control devices that supply air to the occupied space.	• If the refrigerant detection system is activated the following actions shall be taken and continue for at least five minutes after the refrigerant detection system has been reset: ○ The fan shall be switched on ○ Disable the compressor operation unless the compressor operation reduces the leak rate or the total amount released to the indoor space ○ Disable all ignition sources in the appliance	• When the refrigerant detector activates it shall: ○ Actuate an alarm, ○ Start mechanical ventilation, and ○ Stop the system
Limitations				
Measurement range	• Existing: Detector must trigger alarm at a value not greater than the TLV-TWA; Additional alarms set at other levels are permitted • **Proposed**: Detector must trigger alarm at a set point not greater than the OEL; Additional alarms set at other levels are permitted	• Detector must trigger alarm at a value not exceeding 25% of the LFL	• Detector must trigger alarm at a value not exceeding 25% of the LFL • Detectors may have settings for lower measurements to help detect small leaks	• Detector must trigger alarm at a value not exceeding 20% of the LFL and shall continue to activate at higher concentrations • The detector shall be set lower for toxicity, if applicable
Response time[a]	• **Proposed**: Detector, including any sampling tubes, shall activate	• Detector, including any sampling tubing, shall activate responses in 15	• The refrigerant detection system will make outputs within 30 seconds of reaching the limit	• The delay of the detector shall be 30 seconds or less at a concentration of

Evaluation Criteria	ASHRAE 15/ ASHRAE 15 Addendum H (existing and proposed for Machinery Rooms)	ASHRAE 15 Addendum D (proposed for Human Comfort Cooling)	IEC 60335-2-40 (proposed)	ISO 5149-3 (existing)
	responses in 30 seconds or less after reaching set point	seconds or less after reaching set point		1.6 times the pre-set value.
Vibration	• No specific requirements	• No specific requirements	• Must withstand vibration without breakage or damage	• No specific requirements
Reliability				
Self-testing abilities and/or indication of malfunction	• **Proposed**: Detector shall provide a means for automatic self-testing. If a failure is detected, an alarm shall be activated.	• Detector shall provide a means for automatic self-testing. If a failure is detected, an alarm shall be activated.	• The detection system shall include a means for self-testing the sensor to determine the output is at proper range. The test shall be run at least every hour and if a failure is detected an alarm shall be activated.	• No specific requirements

Sources: ASHRAE (2016a), ASHRAE (2016b), IEC (2016), ISO (2014)

[a] The response time refers to the amount of time required for the sensor to read the refrigerant concentration value and produce an alarm and/or other mitigation requirements.

2. Available Sensor Technologies

There are a number of sensor technologies currently employed for detection of refrigerants in the HVACR sector, including photoacoustic infrared, nondispersive infrared, electrochemical cells, metal oxide semiconductors, catalytic beads, and heated diode sensors. The fundamental process used to measure concentration varies between the technologies. Infrared technologies utilize light absorption; electrochemical cells and metal oxide semiconductors utilize oxidation/reduction reactions; and catalytic bead and heated diode sensors utilize ionization.

These sensors were reviewed and evaluated against certain criteria to determine the applications and equipment types the technology could be installed in and whether they would be appropriate for detecting A2L refrigerants. The sensors that were reviewed are appropriate for detecting refrigerant gases. Although within the refrigerant circuit for HVACR equipment refrigerant may take the form of a liquefied gas, the sensors are not anticipated to come into contact with the refrigerant in liquid form. Throughout this section, instances where other liquids (e.g., water) can damage or interfere with sensor technologies are noted.

Certain sensor requirements summarized in Table 2 are anticipated to be met by all existing sensor technologies. For example, proposed sensor requirements indicate sensors must activate the alarm within 15 to 30 seconds of reading the set point concentration. Several sensor manufacturers indicated that once the sensor reads the concentration and produces an output signal, the alarm and/or other mitigation steps (e.g., turning on ventilation) would be almost instantaneous (Genesis 2017). Therefore it is anticipated that all current sensor technologies would be able to meet the response time requirements. In addition, all reviewed stationary sensor models produce standard output signals (e.g., 4-20 mA analog output or HART signals) that can be connected to an alarm system that could trigger the necessary emergency responses (e.g., turn off compressor, turn on ventilation).

Conversely, there are sensor requirements summarized in Table 2 that will need to be addressed across all technologies. For example, sensors may require the use of batteries (or a battery back-up) in order to continue operating even if the system is not currently powered or in use (e.g., in case of a power outage or if a unit is stored in a closet during the winter months). Such issues could be discussed by the safety standards committees. Sensor manufactures would need to consider how long sensor batteries would last and whether consumers would have access to the sensor in order to replace the batteries. Proposed requirements also indicate that sensors should have self-testing abilities in order to alert the user of malfunction. Some currently available monitoring devices do incorporate self-testing capabilities, such as active diagnostics, to indicate whether the sensor is operating properly. While electrical components can be tested for proper function through automated diagnostics, the only certain way of knowing that a gas sensor is functioning properly is to test the sensor with a measured quantity of gas (i.e., a bump test) (EHS Today 2014). Some sensor manufacturers are producing additional modules that attach to sensors and periodically test sensors through bump testing (Sensidyne 2017); however, it is unclear whether these modules would be practical in a residential setting and at what additional cost for installation and maintenance.

In addition to reviewing whether the sensor could meet the proposed requirements for A2L refrigerant sensors, as summarized in Table 2, additional features of the sensor technology and detector apparatus were taken into account, such as operating conditions and limitations, cost, size, and power requirements. Some of these criteria are dependent on the number of zones, desired precision, and the required robustness of the sensor model. The evaluation criteria are summarized in Table 3.

Table 3: Summary of Evaluation Criteria for Refrigerant Sensor Technologies

Evaluation Criteria	
Features	**Definition**
Cost range	Indicates the range of costs. Costs are designated as those for handheld devices, stationary elements, and/or costs for individual sensing elements, as applicable
Size	The dimensions of the complete system and/or the weight of the sensor
Power requirements	Indicates the supply voltage or power consumption required to operate the sensor
Refrigerant types	The specific types of refrigerant that can be detected by the sensor. If sensor models have been identified that can detect specific A2L refrigerants, those refrigerants will be identified.
Calibration	Indicates whether and how often the sensor requires recalibration or re-zeroing
Detection system response	The response of the system when high levels of refrigerant are detected
Limitations	
Measurement range	The refrigerant concentration range that the sensor can detect, specified in ppm
Response time	Indicates the amount of time for the sensor to sample and read the refrigerant concentration. The response time is generally measured as the amount of time to reach T90, which represents the amount of time needed from introduction of a sample to when a sensor indicates 90% of the real concentration.
Operating Temperature	Indicates temperatures at which sensor can operate.
Humidity	Indicates humidity levels at which sensor can operate
Vibration	Indicates whether the sensor can withstand vibration
False-triggering chemicals	Identifies chemicals that could falsely trigger the sensor
Interfering Chemicals	Identifies chemicals that could interfere or block the sensor from identifying or accurately measuring the refrigerant concentration
Reliability	
Lifetime	Indicates the average number of years a refrigerant sensor is expected to last (assuming regular maintenance)
Repairable	Indicates whether components of the sensor can be replaced or repaired
Self-testing abilities and/or indication of malfunction	Indicates whether the sensor features the ability to self-test or indicate to the user that it is malfunctioning

The evaluation criteria in the sections below are summarized from a range of models using the class of sensor technology in order to provide a complete overview of the technology based on a review of product literature from multiple manufactures and technical reports. In addition, multiple sensor manufacturers were contacted to discuss the current state of sensor technologies, the potential challenges associated with using these sensors to detect A2L refrigerants, and sensor technologies currently under development that could be used to detect A2L refrigerants. Feedback from manufacturers is incorporated throughout the analysis; however, some information regarding development and sensors that are not commercially available are discussed, but not attributed to a specific manufacturer in order to protect confidential business information.

This summary does not necessarily provide an exhaustive review of all the models available from manufacturers, but the approach provides a representative review of all technologies on the market.

2.1 Infrared Sensors

Infrared detection technology relies on a beam of light in the infrared range (between 700 nm and 1 mm) that is used to measure the concentration of gases in sampled air. The two most widely used infrared technologies in refrigerant sensors are photo-acoustic infrared (PIR) and non-dispersive infrared (NDIR). Although the detection method differs between these two technologies, most of the operating conditions, costs and potential uses are the same, and therefore these sensors are likely to provide similar potential benefits and disadvantages for use in detecting A2L refrigerants.

2.1.1 Overview of Technology

PIR technology is a fixed point infrared technology in which gas molecules are exposed to a specific wavelength of infrared light and the response is measured. When using a PIR instrument, a gas sample is introduced into the monitor’s measurement chamber and then exposed to a specific wavelength of infrared light. The infrared light passes through an optical sensor and is absorbed by the gas molecule of interest. As the molecules absorb the infrared light, an audible pulse is created and measured by a microphone in the measurement chamber. The magnitude of the pulse is used to determine the concentration of the desired gas within the sample (MSA 2014).

NDIR technology is a fixed point infrared technology in which a detector measures the infrared light that is passed through a gas sample while an inert gas sample (e.g., nitrogen) is simultaneously present in a separate measurement chamber that serves as a reference. Using an inert gas ensures that no absorption takes place and that all infrared light passes through the chamber, which provides an accurate baseline. The detector compares the amount of light transmitted through the sample and reference cells. The sensor determines the concentration of the desired gas in the sample by comparing the ratio of light that is transmitted through the two chambers (MSA 2014). Since the measurement is comparative, there is no need to periodically recalibrate the detector; rather it must be “re-zeroed.” Some detectors in the market require manual re-zeroing, while other, more expensive and robust detectors do it automatically. One sensor manufacturer indicated that the re-zeroing process for certain IR sensors requires an equipment owner or technician to push a button at which point, the sensor takes a sample of air and re- calibrates itself for the new baseline sample (Genesis 2017). Another manufacturer indicated that sensors are recalibrated by exposing the sensor to air or nitrogen gas in order to zero the sensor and then the sensor is exposed to up to 50% of the target concentration and tested for accuracy (Draeger 2017b).

Infrared technology is commonly used across a wide range of HVACR applications including equipment rooms, cold rooms, supermarket refrigeration, and refrigerant handling centers. It is also used in petrochemical plants and off-shore platforms, mainly for sensors detecting HC gases (but in these cases not for detecting refrigerants) (Draeger 2016). Models are available on the market for single-zone detection, multi-zone detection, and handheld devices. Both single-zone and multi-zone detection models have a centralized PIR sensor. The multi-zone detection models also contain a pump that brings in air from multiple intakes, but only measures concentration from one intake at a time (though in some installations individual intake ports may in turn use splitters in the sample tubing). The use of sampling pumps could introduce additional concerns due to the limited lifetime of the electrical motor and additional potential for electrical failure. Handheld IR devices currently on the market have a similar detection range to the stationary devices; however, their precision and sensitivity are lower.

The infrared systems that are commonly available target two primary classes of refrigerants fluorinated refrigerants (i.e., CFCs, HCFCs, HFCs, and HFOs) or HCs. The sensor technology itself is capable of detecting any gases within the infrared spectrum, with the exception of hydrogen, which does not absorb infrared light. In addition, acetylene is difficult for PIR sensors to detect due to the triple bond, which cannot be measured at certain wavelengths, causing it to act as a blocking gas (ISHN 2014). The presence of a blocking gas can lead to incorrect measurements when in the presence of the compound being monitored; however it is not expected to falsely trigger the alarm system. Furthermore, refrigeration system installations using detectors where acetylene would be routinely present are uncommon, but this may be a short term concern during building construction, renovation, or maintenance activities. IR sensors can detect blends; however adjusting the absorption band to encompass all chemicals within a blend is expensive. Typically, sensors are calibrated to detect either the most prevalent compound within the blend or the most sensitive (Draeger 2017b).

2.1.2 Comparison of Evaluation Criteria

This section presents a summary of key features and evaluation criteria for infrared detectors based on the proposed A2L refrigerant sensor requirements presented in Table 2.

Table 4: Summary of Evaluation Criteria for PIR & NDIR Infrared Sensor Technology

Evaluation Criteria	
Features	
Cost range	Handheld $300-$400; Stationary $1,000-$12,000; Sensing element NA
Size	6.3 in x 3.5 in (diameter) (sensor without display) 11 in x 5.9 in x 5.1 in (including docking station) 1 to 20 lbs.
Power requirements	13-30 VDC, 4-5 Watts (Power requirements largely dependent on number of zones and the distance from the sensor as it influences the power required by the sampling pump).
Refrigerant types	All types (HFCs, HFOs, HCs, CFCs, HCFCs)
Calibration	PIR: Required every 6 months (and when a change in gas measurement is required) NDIR: Calibration is not required. Re-zeroing is required every 0.5ºC internal temperature change or every year
Detection system response	Produces either a 4-20 mA or HART signal; connects to alarm system
Limitations	
Measurement range	0-10,000 ppm
Response time	Single-Zone: 5-30 seconds; Multi-Zone: 5-300 seconds
Operating Temperature	-40 to 167ºF (-40 to 75ºC)
Humidity	0-100% (some sensors require non-condensing environment)
Vibration	Depends on application (the sensor can be placed inside a strong structure that protects it from harm)
False-triggering chemicals	None
Interfering Chemicals	Acetylene; overexposure of refrigerant gas
Reliability	
Lifetime	Handheld: 5 years; Stationary: 10-15 years; Sampling pumps have limited electrical motor life expectancy
Repairable	Replace air filters every year to prevent particles from entering the cell and contaminating sensor
Self-testing abilities and/or indication of malfunction	Certain monitoring devices incorporate active diagnostics that continuously monitor the system for proper operation

Sources: MSA (2011), Det-tronics (2015), Honeywell (2014a), Honeywell (2016), Thermal Gas Systems (2006), Draeger (2015), Trane (1998), Asada (2016), Bacharach (2011), Danfoss (2016a), Enmet Gas Detection (2014), Javac (2015), Sensidyne (2016), Genesis (2014), TQ Environmental (2015), Draeger (2017b), Genesis (2017)

Infrared technology is currently used within a wide range of applications and is capable of detecting HFC and HFO refrigerants across the infrared spectrum, including models that are marketed for use detecting HFO-1234yf (Honeywell 2016, Bacharach 2011). Sensors, intake filters, and docking system are relatively small, allowing them to be placed close to any potential leaks; some currently available IR sensors might be considered too large for integration within smaller residential equipment; however one sensor manufacturer indicated that IR sensor sizes could be significantly reduced (i.e., 3 in. x 3 in. x 1in.). Furthermore, certain types of monitoring devices are equipped with self-testing abilities, such as active diagnostics that indicate whether the system is operating properly (Bacharach 2011).

The sensor detection range of 0-10,000 ppm would likely be sufficient for the measurement range requirements proposed for A2L sensors (as presented in Table 2) for certain A2L refrigerants and blends, such as HFO-1234yf or HFO-1234ze(E) where 20 to 25% of the LFL for those gases is close to 10,000 ppm; however, for systems using HFC-32 or other blends with higher LFLs, sensor detection ranges will need to be increased. Sensor manufacturers indicated that detection ranges for sensors could be increased.

Potential areas for concern regarding these sensors would be cost, as currently available small, stationary units ranged in price from $1,000 to $2,000, while larger units with multiple intakes can range from $4,000 to $12,000. Handheld refrigerant detectors using PIR technology are available for as low as $400 and could potentially be adapted for integration into smaller HVACR equipment; however, there could be sacrifices in lifetime of the system (e.g., 5-8 years), as the sensing element for a handheld IR sensor is not designed for continuous operation (Draeger 2017b). One sensor manufacturer indicated that IR sensor costs could be further reduced to the $30-50 range, because reduction in detection accuracy reduces costs (Honeywell 2017); this could be a considerable additional cost for certain types of air conditioners, although very small systems below a certain refrigerant charge quantity will not require refrigerant sensors.

Lifetimes for currently available sensors (i.e., 5-10 years) could also present a concern for incorporation into household HVACR equipment with longer lifetimes. IR sensors that utilize sampling pumps could also affect the longevity of the sensing device or could require additional maintenance and repair, although it is unlikely that household HVACR equipment would be large enough to need this type of IR sensor.

Another area of concern for use inside self-contained systems, particularly in residential applications, is the need for bi-annual recalibration (for PIR sensors) or re-zeroing (for NDIR sensors) and the need to replace air filters annually to protect the sensors and cells from contamination. It is expected that users in these applications would not know how, or potentially forget, to perform routine maintenance on the detectors or the equipment owner could inadvertently recalibrate the system while refrigerant or other interfering gases are present, thus setting the sensor’s baseline to a sample that isn’t necessarily clean, which could affect future readings if a catastrophic leak does occur (Genesis 2017).

Sensor manufacturers are aware of these concerns and have indicated that sensors are currently being developed that do not require annual recalibration or zeroing. One NDIR model researched indicated that the system is capable of automatically re-zeroing, thus eliminating the need for technicians or skilled users to be present (Bacharach 2011). This model re-zeroes every 5 minutes or on a 0.5 ºC internal temperature change, and the process can take up to 30 seconds during which the detector cannot measure concentration. The re-zeroing time could be a potential issue, because the proposed standard requirements presented in Table 2 require a response time of no more than 30 seconds in certain applications.

The presence of acetylene is not expected to be a concern for PIR or NDIR detectors, particularly in residential applications, however it could cause a problem in commercial or industrial settings if welding was occurring nearby. If the IR sensor is exposed to large concentrations of refrigerant gas, it can fail; however, sensors are typically designed to fail-safe and would alarm if they were exposed to too much refrigerant (Genesis 2017); however, it is unclear whether permanent damage to the sensor would occur from overexposure. Other IR sensors are immune to sudden changes in temperature, humidity, and over-exposure (Bacharach 2017).

2.2 Electrochemical Cell (EC)

2.2.1 Overview of Technology

In electrochemical cell (EC) technology, a detector measures the electric current passing between electrodes within an electrolyte medium, one of which is exposed to a gas sample. A typical electrochemical cell sensor consists of three electrodes; sensing, counter, and reference. The gas sample enters the detector and passes through a hydrophobic membrane. The gas then reacts with the sensing electrode involving either an oxidation or reduction mechanism. The reactions are catalyzed by the electrode materials specifically developed for the gas of interest. With a resistor across the electrodes, a current flows between the anode and the cathode. The magnitude of the current is measured by the detector and is proportional to the concentration. The reference electrode is required for sensors that require an external driving voltage (Anderson 1999).

EC technology is commonly used in small or portable instruments in confined space applications with human traffic (e.g. homes, workshops). EC detectors are popular in these applications because the power requirement is the lowest of comparable detection technologies. Models are available for single-zone detection and as part of a detection system using multiple sensors. An example of multiple sensor technologies within a detection system is a household fire alarm; which contains an EC sensor for carbon monoxide (CO) monitoring and an optical smoke sensor for particulate matter.

EC sensors are commonly used to detect toxic and/or combustible gases: CO, H_2S, O_2, NO_2, NH_3, and SO_2. The only refrigerant that is commonly measured with EC detectors is NH_3 (R-717), classified as a B2L refrigerant. No models were identified that had the capability of detecting A2L refrigerants; however one sensor manufacturer indicated that EC detectors could utilize a highly customized electrolyte (e.g., containing chlorine) in order to detect a fluorinated refrigerant, but this is not considered to be practical (Honeywell 2017). EC detectors are also vulnerable to poisoning mechanisms, and it is not recommended to use sensors in environments that are exposed to organic solvent vapors, high humidity, or high temperatures. Sensors in these environments are more likely to have issues with the electrolyte medium, which would shorten the lifetime of the sensor and compromise the detecting ability of the sensor.

2.2.2 Comparison of Evaluation Criteria

This section presents a summary of key features and evaluation criteria based for electrochemical cell detectors on the proposed A2L refrigerant sensor requirements presented in Table 2.

Table 5: Summary of Evaluation Criteria for EC Sensor Technology

Evaluation Criteria	
Features	
Cost range	Handheld NA; Stationary $250-$1,600; Sensing element $100-$200
Size	8 x 6 in 0.5 to 4 lbs. (can include the weight of the entire system)
Power requirements	12-30 VDC, 4-10 Watts
Refrigerant types	NH_3
Calibration	Required every 12 months
Detection System Response	Detector connects to alarm system
Limitations	
Measurement range	0-1000 ppm
Response time	<90 seconds to T90
Operating Temperature	-4 to 122ºF (-20 to 50ºC)
Humidity	15-90%
Vibration	Sensor can be placed inside a protective structure
False-triggering chemicals	Organic solvents (e.g., alcohols, acetone); some sensors subject to cross-sensitivity with other gases
Interfering Chemicals	None
Reliability	
Lifetime	1-3 years (varies based on exposure to target gas)
Repairable	Electrochemical sensor cell can be replaced
Self-testing abilities and/or indication of malfunction	Certain monitoring devices incorporate active diagnostics that continuously monitor the system for proper operation

Sources: Anderson (1999), Baldigowski (2011), Critical Environment Technologies (2016), Danfoss (2016b), Danfoss (2016c), Delphian (Undated), Honeywell (2014b)

Electrochemical cell technology is currently used to measure toxic gases in small or portable instruments for confined space applications. The only refrigerant that can currently be measured by the technology is NH_3; however, Honeywell (2017) indicates that it is feasible to adapt an EC sensor to detect fluorinated refrigerants, but it is not practical. The sensor requirements identified in Table 2 apply to A2L refrigerants, none of which are measured by EC detectors. The response time is higher than is accepted by the standards, and the current detection range would likely be unable to detect up to 20 to 25% of the LFL of most A2L refrigerants.

The primary benefit to electrochemical cell technology is cost. While small stationary IR units regularly cost over $1,000, similarly sized EC units cost as little as $250. In addition, the units have the lowest power requirements of commonly used detection technologies. In these situations, the limited lifetime and calibration schedule of the sensor are potential areas of concern, as HVACR appliances would outlast the limited lifetime (1-3 years) of EC detectors.

In addition, the sensor requires annual calibration, which involves changing the air currents drastically inside the sensing chamber and requires users to follow a multi-step procedure in which the user connects the calibration gas canister to the inlet valve and sets an artificial zero by running N_2/O_2 gas through the sensor. Once a zero level is established, the user runs the measured refrigerant gas through the sensor. This process could be a concern for residential uses as it is anticipated that users in these applications would not know how, or forget, to recalibrate the detectors.

Ultimately, given that this technology cannot currently detect fluorinated compounds (nor is it practical to adapt EC cell sensors to detect fluorinated refrigerants), the short sensor lifetimes, and the intensive recalibration requirements, this technology is not likely to be appropriate for use in HVACR systems containing A2L refrigerants.

2.3 Metal Oxide Semiconductor (MOS)

2.3.1 Overview of Technology

Metal Oxide Semiconductor (MOS) sensors are activated by changes in resistance caused by presence of gases. In P-type semiconductor sensors, positive holes are the majority charge carriers, so the conductivity increases in the presence of oxidizing gases. N-type semiconductors, in which the majority charge carriers are electrons, are used for the detection of combustible (reducing) gases. In clean air, oxygen is adsorbed onto the metal oxide, attracting free electrons and preventing electrical flow in the sensor. In the presence of a reducing gas, oxidation on the metal oxide surface lowers the concentration of adsorbed oxygen and lowers the potential barrier, allowing electricity to flow in the sensor (Fine 2010). The empirical relationship between combustible gas concentration and MOS sensor resistance is well-described (Siegel 1990).

2.3.2 Comparison of Evaluation Criteria

This section presents a summary of key features and evaluation criteria for metal oxide semiconductor detectors based on the proposed A2L refrigerant sensor requirements presented in Table 2.

Table 6: Summary of Evaluation Criteria for MOS Sensor Technology

Evaluation Criteria	
Features	
Cost range	Handheld NA; Stationary $500-$1,300; Sensing element $3-$100
Size	4.3 x 2.4 x 1.2 in 1 x 1 x 1 in
Power requirements	12 – 24 VDC, 1-5W
Refrigerant types	CFC, HFCs, HCFCs, HFOs
Calibration	Recommended every 6 months
Detection System Response	Connection to alarm system
Limitations	
Measurement range	20-10,000 ppm
Response time	15 – 90 seconds to T90
Operating Temperature	-30 to 158ºF (-34 to 170ºC)
Humidity	0-95%
Vibration	Depends on application. Operating principles of the technology shouldn't be affected by normal workplace vibrations
False-triggering chemicals	Gasoline, diesel, and propane exhaust; Fumes from solvents, paints, and cleansers
Interfering Chemicals	Ethanol, silicones, highly corrosive gases, alkaline metals, overexposure to refrigerant, heavy condensation
Reliability	
Lifetime	3-5 years; Sensor lifetime decreases with continued exposure to poisoning/false-triggering gases
Repairable	Sensing element can be replaced if damaged by poisoning or once lifetime is exceeded
Self-testing abilities and/or indication of malfunction	None observed

Sources: Genesis (2016), RKI Instruments (2017), SGX Sensortech (Undated), FIS (2017), Figaro (2017a) Figaro (2017b), Shuler (2014)

The aforementioned empirical relationship between the concentration of reducing gases and metal oxide conductivity makes this technology adaptable to a wide range of refrigerants. MOS sensors are primarily used to detect CO, NH_3, and HFCs, including HFC-32 (e.g. Genesis International 82-0101 CMOS). Several MOS sensors are expected to become available in 2017 that are designed to detect A2L refrigerants, such as HFC-32 and HFC-1234yf (e.g., FIS SB-43, Figaro TGS 2630). Individual MOS sensing elements are relatively inexpensive. Several manufacturers indicate that MOS sensors for use in residential systems would become cost competitive and could cost approximately $20 for a complete system (i.e., housing, alarm, and sensing element). Manufacturers also indicate that sensors would be coming available that could detect 20 to 25% of the LFL for A2L refrigerants; however, currently available models have detection ranges up to 10,000 ppm which could be a concern for some A2L refrigerants.

A potential area of concern for MOS sensors would be installation in environments where the presence of gases such as exhaust from gasoline, diesel, and propane, solvents, or highly corrosive gases could potentially cause false triggering or poisoning of the sensors, although the typical concentrations of these gases in residential and commercial settings is variable and difficult to quantify. This could impact residential systems in which HVACR systems and sensors are located near a garage and could falsely trigger the alarm system and other protective measures (e.g., turn off compressor, turn on ventilation) even though there was no refrigerant leak. MOS sensor characteristics may also be temporarily affected by soaking or splashing with water, heavy condensation, or salt water (Figaro 2017a). If sensors are exposed to a small amount of interfering gases or condensate, they can recover without permanent damage occurring; otherwise, the sensing element would need to be replaced (FiS 2017). Some sensors are being manufactured with a filter that would prevent poisoning of the sensor from certain interfering or poisoning gases, such as ethanol and silicones. In addition to sensitivity to a variety of different gases, MOS sensor requirements for periodic calibration and a relatively short lifetime (3-5 years) could also be concerns in residential applications. There was also limited information available regarding whether self-testing capabilities are or could be incorporated into currently available sensors.

2.4 Catalytic-type (Pellistor)

2.4.1 Overview of Technology

Similar to MOS sensors, catalytic-type (also known as pellistor) sensors are triggered by resistance changes in the presence of flammable gases. Flammable gases are oxidized or burned on a catalytic surface, releasing heat and increasing the electrical resistance of the circuit to which the catalyzed sensing element is connected (Sensitron 2010). The resultant voltage increase has a direct linear relationship to the concentration of flammable gas present. Some systems measure the resistance of a catalytic bead directly, while others measure the voltage in a Wheatstone bridge circuit formed with the detector (catalyzed) element and a compensator element. Because catalytic sensors use oxidation to detect gases, oxygen must be present for the sensor to work. In addition, some catalytic sensors are prone to be poisoned by certain compounds, such as sulfur- phosphor-, lead-, or silicone-compounds; however, some catalytic sensors are manufactured to be resistant to these poisons (Draeger 2009). In situations where a high gas concentration is present, the combustion process may be incomplete which can leave a layer of soot on the active bead and either partially or completely impair performance of the sensor (Crowcon 2015).

Catalytic sensors are sold almost exclusively to detect HCs and NH_3, but some sensors (e.g., NET NP-17) are reported to measure the presence of any flammable gas. These general-purpose catalytic gas sensors are indicated to detect flammable gases from 0-100% LEL[2] but only have

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[2] The LFL is sometimes referred to as the lower explosive limit (LEL). These limits, while similar and somewhat interchangeable, are calculated using different methods.

effective linearity up to 60% LEL. The non-linearity refers to a slight deviation of the sensors' output from the ideal input/output relationship to which the sensor is calibrated. However, catalytic sensors are not recommended to detect fluorinated refrigerants, because the combustion products of fluorinated gases (i.e., HF) can poison the catalytic sensor as it is simultaneously measuring the concentration of the fluorinated refrigerant (Draeger 2017b).

2.4.2 Comparison of Evaluation Criteria

This section presents a summary of key features and evaluation criteria for catalytic-type detectors based on the proposed A2L refrigerant sensor requirements presented in Table 2.

Table 7: Summary of Evaluation Criteria for Catalytic-type Sensor Technology

Evaluation Criteria	
Features	
Cost range	Handheld NA; Stationary $700-$1,500; Sensing element $50-$100
Size	Sensing element: 2 x 1.1 x 1 in. Stationary detector: 8.3 x 8.9 x 3.4 in. 2-3.5 lbs.
Power requirements	12 – 24 VDC, 1-10W
Refrigerant types	HCs, NH_3, other flammable gases
Calibration	Calibrated to response rates of individual gases prior to installation; required every 3-6 months depending on environment where used
Detection System Response	Connection to alarm system
Limitations	
Measurement range	0-1,000 ppm, 0-100% LEL
Response time	5-10 seconds to T50, 20-30 seconds to T90
Operating Temperature	-40 to 300ºF (40 to 150ºC)
Humidity	0-95%
Vibration	Typically not impactful – Sensors are mounted on a single header and protected by a metal mesh enclosure and a metal or plastic external enclosure
False-triggering chemicals	None
Interfering Chemicals	Substances containing silicone or sulfur (e.g., hydrogen sulfide, hexamethyldisiloxane), heavy metals, halogenated hydrocarbons, overexposure of refrigerant gas; Once sensor is used, it is more susceptible to poisoning.
Reliability	
Lifetime	2-5 years
Repairable	Sensing element can be replaced if damaged by poisoning or once lifetime is exceeded
Self-testing abilities and/or indication of malfunction	Compensator element acts as a constant control mechanism

Sources: NET (2016), Draeger (2017a), Draeger (2017b)

Catalytic-type sensors are compatible with a wide range of commercially available gas detection systems and remote flammable gas detection beads. Catalytic sensors maintain precision well, with maximum long term drifts (i.e., sensitivity loss) of ±0.5 mV/month and maximum temperature and humidity drifts of ±2% LEL, however they have relatively short lifetimes (i.e., 2-5 years). There are also concerns with the sensor performing correctly when a high concentration of gas is present and the combustion process cannot be completed. The presence of poisoning gases is less of a concern in residential settings and could be addressed in industrial/commercial settings through the use of poison-resistant sensors. The catalytic sensor technology, however, is well developed, and there is a range of options in terms of cost and uses.

Ultimately, given that this technology is susceptible to poisoning from the combustion products of fluorinated compounds, the short sensor lifetimes, and the frequent recalibration requirements, this technology is not considered to be appropriate for use in HVACR systems containing A2L refrigerants.

2.5 Heated Diode

2.5.1 Overview of Technology

Heated diode technology is currently well established in the handheld portable refrigerant detector market due to its ability to quickly and effectively locate leaks of different refrigerants without the need for recalibration for each gas. The technology is capable of identifying the presence of halogenated compounds and several models are available that are capable of detecting HFC-32 and HFO-1234yf. These sensors do not measure the presence of a specific compound, but rather heat the refrigerant, thus breaking the molecules apart and measuring the concentration of the newly created positively charged chlorine or fluorine ions (Siegel 2003).

2.5.1 Comparison of Evaluation Criteria

This section presents a summary of key features and evaluation criteria for heated diode detectors based on the proposed A2L refrigerant sensor requirements presented in Table 2. Because heated diode sensors are currently only used in handheld detectors, some features or operating conditions are not known or are not applicable.

Table 8: Summary of Evaluation Criteria for Heated Diode Sensor Technology

Evaluation Criteria	
Features	
Cost range	$100-$500
Size	n/a (handheld system)
Power requirements	Battery-operated (alkaline, Li, NiMH, AC adapter)
Refrigerant types	HFCs, HFOs, and blends
Calibration	Automatic or manual zeroing
Detection System Response	Alarm (audio/visual)
Limitations	
Measurement range	6.6oz/yr to <0.1oz/yr, High/low sensitivity range,
Response time	0.5-1 seconds (30 second warm-up time, ~9 second recovery time)
Operating Temperature	-4 to 122 °F (-20 to 50 °C)
Humidity	Unknown, but can be affected by moisture
Vibration	n/a
False-triggering chemicals	Moisture, oils, other fluorinated refrigerants (sensor cannot selectively detect refrigerants)
Interfering Chemicals	Moisture, oils, overexposure to refrigerant gas
Reliability	
Lifetime	2-3 years, up to 5 years
Repairable	Sensing element and filters can be replaced
Self-testing abilities and/or indication of malfunction	n/a

Sources: Fieldpiece (2017a), Fieldpiece (2017b), Siegel (2003), Inficon (2015a), Inficon (2015b)

Heated diode technology is currently only employed in handheld devices used by service technicians to detect the source of refrigerant leaks. Heated diode sensors have fast response times, but it is not clear whether sensors could detect refrigerant at the required refrigerant concentrations. Potential concerns with heated diode technology in stationary equipment are the relatively short lifetimes and susceptibility to the presence of moisture or oils. In addition, because the detectors do not selectively detect a particular refrigerant, there could be concerns with use in environments where multiple halogenated compounds are in use, though they could be appropriate for use in areas where only one halogenated refrigerant is present. There is also limited information available regarding whether currently available handheld sensors incorporate any form of self-testing, such as whether the sensor has been damaged from overexposure or moisture. The user would likely need to introduce the refrigerant gas to the sensor in order to verify detection.

It is unclear whether heated diode technology is a viable option for use detecting A2L refrigerants in stationary applications and meeting the proposed standard requirements outlined in Table 2. Furthermore, sensor manufacturers are not aware of ongoing efforts to develop heated diode technology for stationary refrigerant sensors (Fieldpiece 2017c).

3. Alternative Sensor Technologies

The following section identifies alternative technologies with varied uses that cannot be used in standard refrigerant monitoring. Although the sensors could detect A2L refrigerants, these technologies are disqualified from widespread use for several reasons.

3.1 Open Source Infrared

Open source infrared detectors are primarily used for monitoring of large areas where leaks are most likely to concentrate along a straight line. The most common use of this technology is with flammable gases (e.g., HCs) across pipelines in petrochemical plants. The detector can be set up to measure concentration along the length of a pipeline, reaching up to several hundred feet. Open source infrared sensors work by sending infrared light in a straight beam between the source and receiver units and detecting gas anywhere along the path. The quantity of gas intercepted by the beam is measured by the receiver. The measurement has a natural bias towards the total size of a gas release, rather than the concentration at any one point (General Monitors 2009).

The open source IR technology does not meet the requirements of the ASHRAE, IEC, and ISO standards, because the unit measures concentration over a certain distance, and therefore the sensor cannot differentiate between a dense gas cloud in a small location and a dispersed gas cloud and properly measure the LFL concentration required by safety standards.

3.2 Virtual Refrigerant Charge Sensor

Virtual refrigerant charge sensors use an algorithm that employs non-invasive measurements to estimate refrigerant charge level for HVACR systems. The algorithm uses surface mounted temperature measurements to estimate charge level. These sensors can be embedded within a portable device for a technician’s use or permanently installed on units. The sensor does not measure refrigerant that is present in the air, and cannot determine concentration; however it could be used to check for leaks by monitoring the change in charge over time (Kim 2010).

Additional information on the response time, detection range, and operating parameters of the sensors were not available.

Review of Failure Modes

The following sections present a cumulative review of the sensor technologies discussed in Section II.2. The sensors are ranked based on the impact that common failure modes have on the ability to detect refrigerants. Based on the failure mode analysis, and the performance of detectors in other categories, recommendations are made for suitable sensors for A2L refrigerants in commercial/industrial and residential applications. A reliability testing procedure is proposed to ensure that sensor technologies are suitable for commercial/industrial and residential applications where the user is unfamiliar with detector operation and maintenance.

4. Ranking of Key Failure Modes

Failure modes are the specific manner or way by which a failure occurs in terms of failure of the item (part or [sub] system) function. For purposes of this analysis, a failure of the refrigerant detector includes false-positive readings, failure to detect a positive reading, poisoning of the system, or other damage to the sensor or its electrical components. Section I.2 identified the conditions that cause failure modes across the evaluated sensor technologies (i.e., the sensing element and any electrical components) including: operating conditions (e.g., humidity, temperature, vibration), contaminants (e.g., false triggering gases, air contaminants), and refrigerant over-exposure. Table 11 and Table 12 present a ranked matrix approach to analyze the individual sensor failure modes based on the likelihood and severity of the failure event occurring.

Every sensor technology is assigned a score for a failure mode based on the combined likelihood and severity of the event occurring. The likelihood of an event occurring in the commercial/industrial or residential sectors is scored on a scale of 1-4 with the following categories: *Unlikely*, *Moderately Unlikely*, *Moderately Likely*, and *Likely*. The severity of the event can affect the ability of the sensor to detect refrigerant and is scored on a scale of 1-4 with the following categories: *Low*, *Moderately Low*, *Moderately High*, and *High*. Failure modes that are not applicable to a given sensor technology are given a score of 0.

Table 9: Description of Severity and Likelihood Rankings for Failure Modes

<table>
<tr><th rowspan="6">Likelihood</th><th rowspan="2"></th><th colspan="4">Severity</th></tr>
<tr><th>Low (L)</th><th>Moderately Low (ML)</th><th>Moderately High (MH)</th><th>High (H)</th></tr>
<tr><td>Unlikely (U)</td><td colspan="2" rowspan="2">The failure mode is not expected to occur in the lifetime of the sensor and is expected to result in a minor loss of detection accuracy in the sensor.</td><td colspan="2" rowspan="2">The failure mode is not expected to occur in the lifetime of the sensor and is likely to damage the integrity and/or detection abilities of the sensor.</td></tr>
<tr><td>Moderately Unlikely (MU)</td></tr>
<tr><td>Moderately Likely (ML)</td><td colspan="2" rowspan="2">The failure mode is expected to occur at least once in the lifetime of the sensor and is expected to result in a minor loss of detection accuracy in the sensor.</td><td colspan="2" rowspan="2">The failure mode is expected to occur at least once in the lifetime of the sensor and is likely to damage the integrity and/or detection abilities of the sensor</td></tr>
<tr><td>Likely (L)</td></tr>
</table>

Note: Failure modes that are not applicable or do not occur with a particular sensor technology are designated as “not applicable (NA)”

In this analysis, the likelihood and severity scores are added to provide an impact score for each failure mode, as shown in Table 10. The scores from all the failure modes of a certain technology are summed to provide a total ranking failure ranking score for each sensor technology. The lower the score, the smaller the impact and likelihood that failure modes have on the safe operation of the detector.

Table 10: Failure Mode Ranking

		Severity				
		Not Applicable (NA)	**Low (L)**	**Moderately Low (ML)**	**Moderately High (MH)**	**High (H)**
Likelihood	**Not Applicable (NA)**	0	-	-	-	-
	Unlikely (U)	-	2	3	4	5
	Moderately Unlikely (MU)	-	3	4	5	6
	Moderately Likely (ML)	-	4	5	6	7
	Likely (L)	-	5	6	7	8

Two separate rankings are provided to facilitate sensor evaluation across both commercial/industrial and residential applications, as the likelihood and severity of failure modes to the sensing element or its electrical components, including sampling pumps, may be different depending on the application (e.g. presence of false-triggering gases in an industrial setting). These rankings are intended to be used for comparing the applicability of sensor technologies in conjunction with the operating parameters and features (e.g. cost, size and detection range) discussed in Section I.2.

There were certain failure modes that could not be quantified or ranked, due to a wide range of likelihood and severity of occurrence, such as vibration, power outages, or extreme events (e.g., flood, fire). The likelihood and severity of vibration, for example, is highly dependent on the type of system and setting in which the refrigerant sensor is installed and the magnitude of the vibration.

Table 11: Failure Mode Ranking for Commercial/Industrial Applications

Failure Mode		IR		EC		MOS		Catalytic		Heated Diode	
Humidity	Likelihood	U	3	MU	5	U	4	U	2	L	7
	Severity	ML		MH		MH		L		MH	
Temperature	Likelihood	U	3	U	3	MU	4	MU	3	U	2
	Severity	ML		ML		ML		L		L	
False Triggering Gases	Likelihood	NA	0	ML	6	ML	5	NA	0	ML	5
	Severity	NA		MH		ML		NA		ML	
Poisoning or Blocking Gases	Likelihood	ML	4	ML	6	U	2	ML	5	NA	0
	Severity	L		MH		L		ML		NA	
Overexposure	Likelihood	U	2	L	6	ML	5	ML	5	ML	5
	Severity	L		ML		ML		ML		ML	
Air Contaminants	Likelihood	U	3	U	2	MU	3	MU	3	U	2
	Severity	ML		L		L		L		L	
Total		**15**		**28**		**23**		**18**		**21**	

As shown in Table 11, infrared sensors have the best (i.e., lowest) ranking in the failure mode assessment for commercial and industrial applications, as these sensors operate across a wide range of operating conditions (i.e., humidity and temperature) and are not affected by false-triggering gases, over-exposure, or air contaminants (due to the presence of an air filter). Furthermore, these types of refrigerant sensors are already in use in HVACR equipment within different commercial and industrial applications. Electrochemical cells are the most susceptible to the effects from common failure modes in refrigerant detection, mainly due to the likelihood of over-exposure and moderately high impacts of false-triggering gases.

Table 12: Failure Mode Ranking for Residential Applications

Failure Mode		IR		EC		MOS		Catalytic		Heated Diode	
Humidity	Likelihood	U	3	U	4	U	4	U	2	U	4
	Severity	ML		MH		MH		L		MH	
Temperature	Likelihood	U	3	U	3	U	3	U	2	U	2
	Severity	ML		ML		ML		L		L	
False Triggering Gases	Likelihood	NA	0	MU	5	U	3	NA	0	MU	4
	Severity	NA		MH		ML		NA		ML	
Poisoning or Blocking Gases	Likelihood	MU	3	ML	6	U	2	ML	5	NA	0
	Severity	L		MH		L		ML		NA	
Overexposure	Likelihood	U	2	U	3	U	3	U	2	U	3
	Severity	L		L		L		L		ML	
Air Contaminants	Likelihood	U	3	U	2	MU	3	MU	3	U	2
	Severity	ML		L		L		L		L	
Total		**14**		**23**		**18**		**14**		**15**	

For residential applications, both infrared and catalytic sensors have the best (i.e., lowest) ranking in the failure mode assessment, as shown in Table 12. Infrared sensors are anticipated to have the same likelihood and severity of failure modes in residential applications as for commercial and industrial applications, except in the likelihood of blocking gases. In a residential setting, catalytic sensors have an overall lower failure ranking than for industrial and commercial settings, because it is less likely that the sensor would come in contact with gases that could poison the sensor. Electrochemical cells are anticipated to be the most susceptible to the effects from common failure modes in refrigerant detection in residential settings. Heated diode sensors are anticipated to have lower likelihood and severity of most failure modes in residential applications than for commercial and industrial applications; however, if these sensors are adapted for use in stationary systems, the susceptibility or likelihood to failure modes in both applications should be reexamined.

5. Recommended Reliability Testing Procedure

As discussed in Section I.4, all available refrigerant sensor technologies are susceptible to failure modes with varying degrees of severity and likelihood. To address these failure modes, sensors should be tested for reliability while under stress, as well as the full range of possible operating environments to ensure that the refrigerant detector functions according to the proposed requirements outlined in ASHRAE, IEC and ISO standards.

Table 13 summarizes testing procedures to specifically address the failure modes. These reliability testing procedures are based on numerous sources, including:

JRA 4068T	Requirements of refrigerant leak detector and alarm for air conditioning and refrigeration equipment
UL 2075	Gas and vapor detectors and sensors

All testing procedures (with the exception of temperature and humidity/condensation testing) should be conducted between 68-77°F (20-25°C) and approximately 65% relative humidity. Following each test, the detector should be inspected for damage and an accuracy test should be performed. During and/or after each reliability test takes place, the sensor should be tested. The sensor readout can be verified by either introducing a known quantity of refrigerant gas or using a backup or handheld sensor to check the accuracy of the sensor readout.

Table 13: Recommended Reliability Testing Procedure

Failure Modes	Testing Parameters
Accuracy	• Detection component is exposed to test gas at specified concentration within the detection range of the sensor.
Temperature	• Tests should be performed at the highest and lowest ambient conditions defined in the operation manual, or each of the two conditions below: o 120 °F, relative humidity 40 ±10% o 32 °F, relative humidity 15 ±5% o Oxygen concentration = 20.9 ±1% • Expose sensor to refrigerant samples at the maximum and minimum sensitivity levels of the sensor (or single level, if the sensor if the sensitivity is non-adjustable), maintained at both ambient temperatures for at least 3 hours. Measure samples before and during the test. • For sensors intended for permanent installation in unconditioned areas, two samples (one at maximum sensitivity and one at minimum sensitivity) should be independently maintained at the following ambient temperatures for 14 days: o 150 °F, relative humidity 40 ±10% o -40 °F, relative humidity 0%
Humidity (non-condensing)	• **High Humidity:** Two detectors or sensors (one at the maximum and one at the minimum sensitivity level) shall operate for their intended signaling performance when exposed for 168 hours to air having a relative humidity of 95 ±4% at a temperature of 125 ±5°F (52 ±3°C). • **Low Humidity:** Two detectors or sensors (one at the maximum and one at the minimum sensitivity level) shall operate for their intended signaling performance when exposed for 168 hours to air having a relative humidity of 7.5 ±0.5% at a temperature of 72 ±5°F (22 ±3°C).

Failure Modes	Testing Parameters
Condensation Resistance	• With the power on, the detector is placed into an isothermal chamber at its lower limit temperature. • Once it reaches the temperature, the detector is removed and placed into an environment with a temperature of 25 °C or higher and 60% relative humidity until condensation occurs. • Repeat 36 times (if sensor is waterproof) or 1000 times • Remove moisture and perform accuracy test
Durability Tests	• Spray the detection component with 10,000 ppm of methane gas (at a rate of 100 mL/min) for 30 seconds, then pause for 1 minute. • Repeat 1000 times. • Let detector stand for 1 hour. • Introduce refrigerant sample and examine difference between specified concentration value and concentration at output.
Overexposure	• Expose sensing element to a step-change in gas concentration from 0-100% by volume. ○ For manually aspirated devices, connect sample inlet to a gas concentration of 100% by volume. • Expose sensing element to a step-change in liquid concentration from 0-100% by volume. • Expose sensing element to a step-change in two-phase (liquid and gas) concentration from 0-100% by volume
Resistance to other Gases	• Expose sensing element to 1,000 ppm concentration of ethyl alcohol for 1 minute. Confirm no signal or alarm initiation. • After removing ethyl alcohol sample and keeping detector under test conditions for 1 hour, expose sensing element to 500 ppm of hydrogen. Confirm no signal or alarm initiation. Note, depending upon the application, the user may, in addition, decide to test the effect of additional gases than mentioned here.

Vibration	• Two sensors (at maximum and minimum sensitivity range) shall be secured in their intended mounting position and securely fastened to a variable speed vibration test machine having an amplitude and frequency as follows:
	  ○ - 10 Hz to 30 Hz, with 1.0 mm total excursion and
	  ○ - 31 Hz to 150 Hz, with 2 g acceleration peak
	• The sensors shall be vibrated over the specified frequency range, displacement and acceleration for a period of 1 hour in each of the three mutually perpendicular planes. The frequency rate of the change shall not exceed 10 Hz/min.

Sources: JRAIA (2016a), JRAIA (2016b), UL (2013)

Additional failure modes, such as the presence of certain compounds that can either poison, interfere, block, or falsely trigger the sensor should be noted by the sensor manufacturer so that equipment owners are aware of installation requirements. Moreover, the user should consider combining certain tests cited above to more realistically mimic real conditions.

This reliability testing procedure is intended to provide parameters for testing sensors against common failure modes that could result in a failure of the detector, including false-positive readings, failure to detect a positive reading, poisoning of the system, or other damage to the sensor or its electrical components. It is anticipated that refrigerant sensors sold on the market or incorporated into HVACR equipment are manufactured in accordance with relevant safety and manufacturing standards (e.g., UL 2075 Standard for Gas and Vapor Detectors and Sensors and UL 61010-1 Safety Requirements for Electrical Equipment for Measurement, Control, and Laboratory Use) and will follow required testing procedures. Furthermore, it is anticipated that manufacturers would provide guidance to equipment owners regarding installation parameters to ensure that the sensor is not located in an area with conditions outside its operating limits.

Summary of Findings

Refrigerant sensor technologies are considered appropriate residential and commercial/industrial applications for A2L refrigerant detection if they can detect the desired A2L refrigerants (e.g. HFC-32, HFO-1234yf, HFO-1234ze, and refrigerant blends thereof) and if they can conform to the requirements proposed in HVACR equipment safety standards set by ASHRAE, IEC, UL and ISO. In addition, a low unit cost for the refrigerant sensor is important to the viability of refrigerant monitoring, particularly for residential applications where costs could be passed-down to the consumer.

The remainder of this section discusses limitations and uncertainties of the analysis and next steps for the analysis.

6. Limitations and Uncertainties

Conducting a full evaluation of the refrigerant detection market presented several challenges. Product literature of available sensor models were reviewed to determine the range of operating parameters, lifetime, and cost. These models were reviewed across various manufacturers and vendors; however conducting an exhaustive review of all sensor models across all manufacturers was not possible. In addition, information on new sensor technologies was not readily available, as the information is generally considered proprietary by the manufacturers. An extensive library search of technical reports, scientific journals, and academic databases also did not identify any new technologies or technological improvements to existing sensor technologies in the developmental pipeline. Furthermore, based on discussions with a variety of refrigerant sensor manufacturers, some manufacturers are actively pursuing the adaption of current sensor technologies to detect A2L refrigerants and meet proposed requirements, while others are within preliminary research stages.

The full range of costs for refrigerant sensors, in particular high-end robust systems, was difficult to establish based on the variety of factors that can affect the value. Many of the detectors are manufactured by one company and sold by a retailer with various warranties and supplementary parts or accessories. Robust systems with multiple detection points require installation by a trained technician. These additional costs may be included in the cost ranges presented in Section I.2, although they are not directly tied to a particular product.

The scope of this report in residential and commercial/industrial A2L refrigerant detection is different from what many of the detectors in the market are designed to monitor. Most technologies reviewed were capable of monitoring gasses on the single-digit ppm range, while the detection limits for A2L refrigerants is in the thousands of ppm. It is unclear to what degree manufacturers could simplify their products to minimize cost and size.

Furthermore, many of the operating parameter data collected for the evaluation of the sensor technologies are dependent on the specifications of individual models, in addition to the underlying technology. For example, the operating ranges, such as humidity and temperature limits varied significantly within sensor technologies based on the design of the model. The summary information presented in Section I.2 provides ranges across all models reviewed and do not necessarily represent the operating range of one particular model.

7. Summary of Findings

Based on current research of available refrigerant sensor technologies, there are a number of promising sensor technologies that could be used for A2L refrigerant detection in residential and commercial/industrial settings.

Infrared technology (both PIR and NDIR) are widely used in industrial and commercial settings and satisfy many of the proposed required criteria for A2L sensors. Although systems are not currently on the market with high enough detection ranges to measure 20 to 25% of the LFL for certain A2L refrigerants, existing sensors would have detection ranges high enough to alarm at lower levels (e.g., 10% of the LFL) without falsely-triggering on typical pollutants present in residential or commercial environments. IR sensors are not anticipated to be susceptible to many failure modes in both residential and commercial/industrial applications; however cost is likely to be a major inhibitor to use in residential systems. Discussions with IR sensor manufacturers indicate that it is possible that IR sensors could be adapted for use in residential systems at a lower price point and fewer calibration requirements while meeting the proposed detection requirements, potentially through the adaption of IR sensors currently used in portable systems for stationary use.

MOS sensor technology also satisfies many of the proposed requirements for A2L sensors and performs fairly well in the failure mode ranking. The primary risks associated with MOS sensors are cross-sensitivity with multiple chemicals, including exhaust from gasoline, diesel, and propane, solvents, and ethanol, which could be problematic in an industrial or residential environment. MOS sensors also experience drift from over exposure to refrigerant, which is unlikely to happen in a residential environment. Individual sensing units are inexpensive and small, which allow them to be placed in as many locations as necessary or be integrated into smaller appliances.

Although catalytic bead sensors are considered the least susceptible to failure modes in both residential and commercial settings, they are not considered a viable option for detection of A2L refrigerants because the byproducts formed during the measurement (which is conducted via combustion) of fluorinated compounds would poison the sensor. EC sensors are anticipated to be the most susceptible to the effects from common failure modes in refrigerant detection in commercial and residential settings and, although EC sensor technology could be used to detect fluorinated refrigerants, industry does not consider it to be practical; therefore, these sensors are not considered viable for A2L refrigerant detection. Heated diode technology could potentially be adapted for use detecting A2L refrigerants in stationary systems; however sensor manufacturers were unaware of ongoing efforts to do so. Furthermore, the effects of failure modes on heated diode systems are relatively high in commercial/industrial settings given the sensitivity to moisture, oils, and other refrigerant gases (i.e., refrigerants used in nearby systems, because heated diode sensors cannot selectively detect refrigerants). Although the effects of failure modes on these handheld sensors are anticipated to be much lower in residential settings, the rankings could be different if these sensors are adapted for stationary use.

Within the commercial/industrial sector, IR sensors are likely to be the most practical option, assuming the detection range can be increased. These sensors are already widely used in commercial/industrial settings and are considered to be less susceptible to potential failure modes in commercial/industrial settings. The requirements for IR sensors regarding recalibration/re-zeroing and other maintenance would be less of a concern in commercial/industrial settings, because equipment and sensors are already regularly serviced and maintained by trained technicians. MOS sensors could also be viable for use with commercial/industrial HVACR equipment if installed in a clean environment, as MOS sensors are susceptible to poisoning or interference from a number of gases.

In residential settings, MOS sensors are anticipated to be the most practical option, assuming the detection range can be increased. These sensors are not susceptible to many failure modes within residential settings considered to be less susceptible to potential failure modes in commercial/industrial settings and are already commercially available at lower price points than other sensors; however, the burden of annual maintenance is an issue for small systems. Furthermore, current availability of monitoring devices with self-testing abilities for MOS sensors is limited.

In conclusion, sensor models using IR and MOS technology currently exist that are capable of detecting A2L refrigerants, in particular in Japan, where the use of HFC-32 is well established; however, most sensors that are currently available or are coming available this year cannot measure all A2L refrigerants at 20 to 25% of the LFL and there are other uncertainties regarding whether these sensors can fully meet the proposed self-testing requirements. However, sensor manufacturers are becoming aware of the proposed requirements in ASHRAE 15, IEC 60335-2-40, and ISO 5149-3 for A2L refrigerant sensors and it is expected that manufacturers will focus research and development efforts to ensure that appropriate sensors are available to meet the updated standards, although the timeline for development is still uncertain.

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