Air-Conditioning, Heating and Refrigeration Technology Institute

Final Report

AHRTI Project 9014

**Refrigerant Detector Characteristics for Use in HVACR Equipment**

Final Report

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By

Jiao Zheng, Ph.D., Fiona Zang, Cheng-Nien Yu, Ph.D., and Stefan Elbel, Ph.D.

Creative Thermal Solutions, Inc.

2209 N. Willow Rd., Urbana IL 61802, USA

Prepared for

AIR-CONDITIONING, HEATING AND REFRIGERATION TECHNOLOGY INSTITUTE, INC.

2311 Wilson Boulevard, Suite 400, Arlington, Virginia 22201

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# Executive Summary

As the shift toward low-GWP working fluids becomes more prevalent, the HVACR industry is opening up to the usage of flammable refrigerants. Safety codes require sensors to be installed in the refrigeration system when using these flammable refrigerants to mitigate the potential fire hazards. This work, supported by AHRTI Project 9014, with a focus on class A2L refrigerants for use in indoor heating, ventilating, air-conditioning, and refrigeration (HVACR) equipment, investigated the suitability of commercially available and developmental sensor technologies to meet the safety standard requirements; and developed and demonstrated methods for assessing the performance and reliability of refrigerant sensors and detectors.

This final report is a consolidated document, which includes three consecutive phases of work. Primary findings are summarized at the end of each Phase section in this report. A brief outline for each section is as follows:

**Phase 1A** reviewed existing requirements for refrigerant detectors as found in the refrigerating system safety standards. This segment of the work assessed the capability of currently commercially available and developmental refrigerant detectors to meet the response time required by the safety standards, and selected the candidate sensors to be experimentally evaluated for Phase 1B.

**Phase 1B** tested the selected candidate refrigerant sensors for their capability to meet the response time requirements. The work in this phase (i) configured the test facility for evaluation of the sensors response time, (ii) tested the sensors' performance for the response time to both step-change and time-varying concentrations of refrigerant-air mixtures, and (iii) developed a model to predict the sensor performance in the real-word application by using the step-change test data.

**Phase 2** focused on the development of test methods for the assessment of robustness and reliability of refrigerant detectors. Relevant existing standards were reviewed and summarized according to the proposed requirements and procedures for the sensor reliability assessment. Based on different types of stressors and test procedures, five categories of the test have been established.

**Phase 3** demonstrated harshness tests, which have been developed in Phase 2. Six sensors from different manufacturers were tested. The tested sensors cover five different major sensing principles. Five categories of harshness tests have been investigated: fluid resistance and poisoning test (Category A), extreme storage condition test (Category B), operation condition test (Category C), vibration and drop test (Category D), and repeatability test (Category E).

This project was started in April 2019 and lasted more than two years. As a preliminary result, the reports of Phase 1 and 2 were published on AHRI's website separately. With the study going deeper, the understanding of the sensors become more thorough; so, some of the conclusions in the previous versions of the report have been modified or improved:

- In section 1.3.1, Equation (2) has been improved; the effect of the time delay on the entire sensor response procedure has been taken into account. The model verification result (Figure 1-13) has been updated accordingly;

- In section 2.2.2, a note has been added to refer to Phase 3 for the detailed calibration procedure for the gas injection method;
- In section 2.3.2.1, a note has been added to point out that based on the test result of Phase 3, a new oil spray test method has been developed and demonstrated in section 3.2.2.3;
- A high temperature survival test has been added to the extreme operation condition category for the sensor reliability assessment while conducting Phase 3. Table 2-3 has been modified accordingly. A note has been added in section 2.5.1 to refer to section 3.4.1.3 for the recommended test method and procedure.

**Note: the letter codes used in Phase 1 refer to different sensors than in Phase 3.** This randomized designation has been made intentionally, because this study aims to investigate refrigerant sensor technologies and establish a methodology for sensor assessment, rather than evaluating a particular sensor and/or manufacturer. Most sensor samples used in this project were prototypes. It should also be noted that further sensor development and improvement efforts by the suppliers took place in parallel with the project. Therefore, participating sensor manufacturers supplied different sensor versions for Phases 1 and 3. Also, one additional sensing technology has been included in Phase 3. To assist readers, a reminder regarding the sensor designation repeatedly appears in relevant locations throughout this report.

# Phase 1

## 1.1 Introduction

The objective of this project is to assess refrigerant sensor and refrigerant detector performance requirements for flammable refrigerants with a focus on class A2L refrigerants for use with indoor Heating, Ventilating, Air-Conditioning, & Refrigeration (HVACR) equipment. This report is for the first phase of the project which includes two stages:

**Phase 1A: Requirements review and initial assessment:**

Review existing and proposed requirements for refrigerant detectors as found in the refrigerating system safety standards. Assess the capability of currently commercially available refrigerant detectors to meet the response time required by the safety standards, with setpoint(s) determined in a manner to meet the safety standard considering related issues such as upper detection limits, accuracy and calibration, drift over time, sensitivity to environmental conditions (temperature, pressure, humidity and vibration).

**Phase 1B: Response time testing verification:**

Test the selected candidate refrigerant sensors to evaluate the capability to meet the response time requirements. Configure and setup the sensors in a test fixture, then expose to both step-change and time-varying concentrations of refrigerant-air mixtures, measure the response time characteristics of the tested sensors.

## 1.2 Current standards requirements and sensors compliance (Phase 1A)

### 1.2.1 Requirements from the standards

Five recently published or modified refrigerating system safety standards have been selected and reviewed; they are:

- IEC 60335-2-40 Edition 6 (Jan-2018) [1]
- UL/CSA 60335-2-40 (Nov-2019) [2, 3]
- ASHRAE Standard 15-2019 [4]
- ASHRAE proposed Standard 15.2P (Advisory Public Review) [5]
- JRA Standard 4068T: 2016R [6]

The requirements for the refrigerant detector were summarized in a table and are shown in Appendix A.

### 1.2.2 Sensor information collection and compliance check

A 'Sensor Information Collection List' has been designed and sent out to 26 sensor manufacturers to collect the sensor specifications directly from the manufacturers through a survey. Table 1-1 shows the list of the manufacturers. Eleven completed lists were returned. Table 1-2 lists the sensing principles used by these 11 sensors. The specifications provided directly by the manufactures were then cross-checked with the standards requirements. The compliance of each sensor is summarized in Table 1-2.

As shown in Table 1-2, there are four sensors that use Metal Oxide Semiconductor (MOS) and another four sensors that use Non-Dispersive Infra-Red (NDIR) as the sensing technology, which together constitutes around 75% of the investigated sensors.

Looking at Table 1-2, requirement No. 15 (still functional after 100% refrigerant exposure for 480-490min) seems to be the major challenges for MOS sensors. This is the main reason why all the MOS sensors do not satisfy requirement No. 6, which is “comply with UL60335-2-40 Annex LL”. Note that, according to the information list, Sensor J is not designed for detecting A2L group refrigerants. Because of this, the compliance of the other requirements is not checked and was left blank. For the NDIR sensors, two of them failed requirement No. 18 while the other two passed. Sensor I is the only NDIR sensor to fail requirement No. 15.

Almost all of the sensors, except Sensors A, B and F, failed the temperature portion of requirement No. 19 (shall comply with the requirements over the full range of operating temperature and humidity as specified by the manufacturer). JRA 4068T 2016 listed the operating temperature ranges for different applications. The lowest required temperature is $-40^{o}$C for inside freezer applications, which exceeds the lower limit for most of the sensors’ operational temperature range.

Requirement No. 27 (end of life indication) is the other requirement most of the sensors failed. However, at this stage, most of the investigated sensors are comprised of only the sensing element, and disregard the fact that usually this indication function can be added through the communication board. Lastly, for requirement No. 22 (vibration resistance), most of the sensor manufacturers could not specify the allowable limits.

**Table 1-1. List of Sensor Manufacturers**

| No. | Manufacturer | Feedback Status | No. | Manufacturer | Feedback Status |
|---|---|---|---|---|---|
| 1 | NEVADA NANO | Received | 14 | ALPHASZENSZOR | Replied, no suitable sensor |
| 2 | SENSEAIR | Received | 15 | HONEYWELL | No feedback received |
| 3 | FIGARO | Received | 16 | DANFOSS | No feedback received |
| 4 | SENSIRION | Received | 17 | EMERSON | No feedback received |
| 5 | BACHARACH | No feedback received | 18 | MSA | No feedback received |
| 6 | PARKER | Received | 19 | LUMASENSE | No feedback received |
| 7 | FUJIKOKI | Received | 20 | NEROXIS BY VEOLIA | No feedback received |
| 8 | SENSATA | Received | 21 | FISINC | Received |
| 9 | N.E.T. | No feedback received | 22 | GOOD FOR GAS | No feedback received |
| 10 | SMARTGAS | Received | 23 | QBIT | Received |
| 11 | WISE | Received | 24 | KWJ ENGINEERING | No feedback received |
| 12 | WINSON | No feedback received | 25 | CITYTECH | No feedback received |
| 13 | SST SENSING | Replied, no suitable sensor | 26 | SGXSENSORTECH | No feedback received |

**Table 1-2. Compliance Check List**

Note: Information shown in this table was compiled by the contractor of this study based on answers provided by the sensor manufacturers at the time of the information survey. As manufacturers continuously update and improve their products, the contents shown in the table may therefore not necessarily reflect the most recent set of information available.

| No. | Priority | Requirement | Underlying Standard | | | | | Candidate Sensors[9] | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | IEC 60335-2-40 ED6 | UL/CSA 60335-2-40 ED3 | ASHRAE 15-2019 | ASHRAE 15.2P | JRA 4068T: 2016R | A | B | C | D | E | F | G | H | I | J | K |
| Sensing principle | | | | | | | | MMM[1] | NDIR[2] | TC[3] | NDIR | MOS[4] | MOS | SS[5] | MOS | NDIR | MOS | NDIR |
| 1 | primary | Capable of sensing presence of refrigerant (for A2L group) | ● | ● | ● | ● | ● | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | NO | Yes |
| 2 | secondary | Capable to be installed "within the unit" when required | ● | ● | ● | ● | ● | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | | Yes |
| 3 | secondary | Capable to be installed "remote from unit" when permitted | ● | ● | ● | ● | ● | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | | Yes |
| 4 | secondary | Capable to be installed "indoor coil cased assembly" when required | | ● | | | | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | | Yes |
| 5 | secondary | Capable to be installed "in air supply duct work" when permitted | | | | ● | | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | | Yes |
| 6 | primary | Comply with UL60335-2-40 Annex LL | ● | ● | | | | Yes | Yes | Yes | NS[6] | NO | NO | Yes | NO | NS | | NS |
| 7 | secondary | Sensor should work when the voltage applied is varied by ±10% rated voltage | | | | | ● | Yes | Yes | Yes | Yes | NO | Yes | Yes | Yes | Yes | | Yes |
| 8 | primary | Capable of number of cycles of operation (300 for self-resetting, 30 for non-self-resetting) | ● | ● | | | | Yes | Yes | Yes | Yes | Yes | NS | Yes | Yes | Yes | | Yes |
| 9 | primary | Sensor should not be a multiport-type device | | | ● | | | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | | Yes |
| 10 | primary | Capable of using a setpoint less than 25% of LFL[8] | ● | ● | ● | ● | ● | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | | Yes |
| 11 | primary | Sensor should have an output to indicate the presence of a refrigerant concentration exceeding the set point | ● | ● | ● | | | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | | Yes |
| 12 | secondary | For indicating type, setpoint should be preset (e.g. Factory set) | ● | ● | | | | yes | yes | yes | yes | yes | yes | yes | yes | NS | | yes |
| 13 | secondary | Pre-set setpoint level should not be adjustable by user | | ● | | | | Yes | Yes | Yes | NO | Yes | Yes | Yes | Yes | NS | | NO |
| 14 | primary | Complies with the requirements IEC 60079-29-1 for Group II equipment | | ● | | | | Yes | Yes | Yes | Yes | NO | NS | NS | Yes | NS | | NS |

| No. | Priority | Requirement | Underlying Standard | | | | | Candidate Sensors[9] | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | IEC 60335-2-40 ED6 | UL/CSA 60335-2-40 ED3 | ASHRAE 15-2019 | ASHRAE 15.2P | JRA 4068T: 2016R | A | B | C | D | E | F | G | H | I | J | K |
| 15 | primary | Sensor should still function after 100% refrigerant exposure for 480-490min (used for long term stability Group II test) | | • | | | | Yes | Yes | Yes | Yes | NS | NO | Yes | NO | NO | | Yes |
| 16 | primary | Sensor should not show false or nuisance trips or show signs of poisoning after being subjected to the gas and vapor types specified by Table LL.4A.1DV | | • | | | | Yes | Yes | Yes | Yes | Yes | NS | Yes | Yes | NO | | Yes |
| 17 | primary | Capable of meeting response time requirement | • | • | • | • | • | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | | NO |
| 18 | primary | Sensor should withstand condensation condition | | | | | • | Yes | Yes | Yes | Yes | Yes | NO | Yes | NO | NO | | NO |
| 19 | primary | Shall comply with the requirements over the full range of operating temperature and humidity as specified by the HVACR equipment manufacturer | | • | | | • | Yes | yes | NO | NO | NO | Yes | NO | NO | NO | | NO |
| 20 | primary | Accuracy of setpoint meets requirements | • | • | | | • | Yes | Yes | Yes | Yes | NA[7] | NA | Yes | Yes | NS | | Yes |
| 21 | primary | Includes output for signal or trigger of mitigation and ventilation | • | | • | | • | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | | Yes |
| 22 | primary | Resistance to vibration, can pass required vibration test | • | | | | | Yes | NS | NS | NS | Yes | NS | Yes | NS | NS | | NS |
| 23 | primary | Includes means for self-testing | • | • | • | • | • | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | | Yes |
| 24 | primary | Self-test at least every hour | • | • | | • | | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | | Yes |
| 25 | primary | Active trouble alarm if a failure is detected | • | • | • | • | • | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | | Yes |
| 26 | primary | Does refrigerant sensor have a defined life? | • | • | | • | | Yes | Yes | No | No | Yes | No | Yes | Yes | No | | No |
| 27 | primary | If there is a defined life, sensor should have end of life indication meeting the requirements | • | | | • | | Yes | Yes | No | No | No | No | No | Yes | Yes | | Yes |
| 28 | secondary | Sensor marking and identification meets requirements | • | • | | | | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | | Yes |

1. MMM: Micro Machined Membrane
2. NDIR: Nondispersive Infrared
3. TC: Thermal Conductivity
4. MOS: Metal-Oxide Semiconductor
5. SS: Speed of sound
6. NS: Not specified
7. NA: Not applicable
8. LFL: Lower Flammability Limit, as defined by ASHARE standard 34 LFL for R-32 is 14.4% v/v
9. Sequence of sensor letter code in Phase 1 is different from Phase 3.

Based on the compliance check result and the availability, Sensors A through F were selected as the candidate sensors for the tests of Phase 1B

## 1.3 Testing verification (Phase 1B)

Currently, all the refrigerating system safety standards use the gas concentration step-change response to define the requirements for the sensor response time. "Step-change" here means, the test gas concentration at the sensing element location changes from zero to a certain value instantaneously. This definition provides a consistent basis for the comparison of different sensors and also makes the experimental assessment of sensor response feasible. However, in reality, even in the worst-case leakage scenario, the refrigerant concentration has to go through a ramp-up process, which may cause the sensor response to differ from the "step-change" condition.

The main objective of this phase is to consider the distinction between step-change response of gas detectors, which are relative to a step change in gas concentration, and the actual response time as applied with a particular choice of setpoint and time-varying gas concentrations.

### 1.3.1 Dynamic response theory and test strategy

Dynamic response theory [7] was used in this project to express the sensor's response to a step change in gas concentration, which will then be used to show the difference between step-change response and the actual response.

The first step in finding this difference is to express the sensor "step-change" response using dynamic response theory. Dynamic response theory has described the step response for a first-order system shown in Figure 1-1. Using the response of a gas sensor as an example, $y(t)$ is the sensor output and is initially stabilized as $y_0$. At time 0, the test gas concentration instantly increases by $\Delta u$. After a time of $\theta$ has passed, the output of the sensor starts to increase as well, where $\theta$ is defined as the time delay. The sensor output will continue to increase and will eventually reach another steady state reading of $y(\infty)$, which is equal to $y_0 + \Delta y(\infty)$. The sensor output can be expressed as shown in Equation (1), where $\tau$ is the time constant defined as the additional time (after the time delay $\theta$) it takes for the sensor output to reach 63.2% (more precisely, a fraction $1 - e^{-1}$= 1 − 0.3679 ≈ 0.632 of its total change $\Delta y(\infty)$).

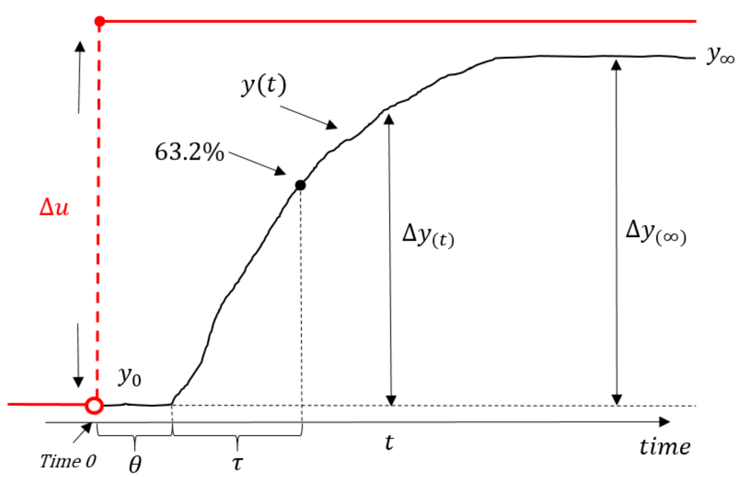



**Figure 1-1. First Order System Step-change Response**

$$y(t) = \begin{cases} y_0 & t \le \theta \\ y_0 + \Delta u \left(1 - e^{-\frac{t-\theta}{\tau}}\right) & t > \theta \end{cases} \quad (1)$$

Both $\theta$ and $\tau$ can be determined experimentally by a step-change test, and then used to predict the sensor response to the actual condition.

Under the actual condition, the concentration of the test gas gradually changes over time, and is shown in Figure 1-2(a) as a function of time $u(t)$. Taking a short time period ($\Delta t$) as a segment, the test gas concentration can be treated as a constant value, provided that the segment is short enough. This will allow the step change Equation (1) to still work for this segment. As shown by Figure 1-2(b), Equation (1) can be rewritten as Equation (2) for the short time segment. Then by using Equations (2) and (3) together, the sensor output for the gas concentration under time-varying conditions can be described.

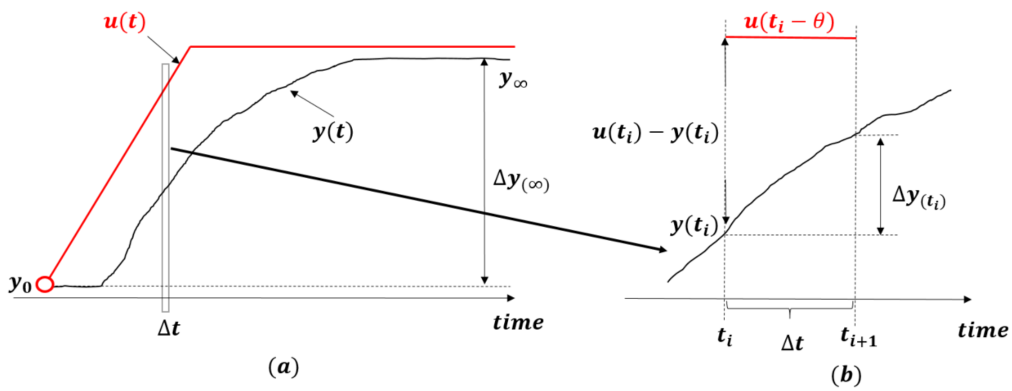



**Figure 1-2. First Order System Time-varying Response**

$$\Delta y(t_i) = [u(t_i - \theta) - y(t_i)](1 - e^{-\frac{\Delta t}{\tau}}) \quad (2)$$

$$y(t_i) = \begin{cases} y_0, & t_i \le \theta \\ y_0 + \sum_{t=\theta}^{t_i} \Delta y(t) & t_i > \theta \end{cases} \quad (3)$$

With the proper equations defined, the following strategy with three steps has been designed:

a) Run step-change concentration tests to:
   - Compare the tested sensor response with the requirements of the safety standards
   - Get the time delay $\theta$ and time constant $\tau$.
b) Run time-varying concentration tests to:
   - Get the sensor output curve under the actual leaking scenario
   - Distinguish the sensor step-change response with the actual leaking scenario response
c) Put the determined $\theta$ and $\tau$ into Equations (2) and (3) to predict the sensor response under the actual leaking condition. Compare the predicted curve with the tested sensor output curve to verify the equation.

The verified equation will allow for the prediction of the sensor output under an actual condition.

### 1.3.2 Test facility and instruments

#### 1.3.2.1 Test facility

A test facility has been built in order to test the provided sensors with both the step-change and the time-varying conditions, with its pictures and schematic shown in Figure 1-3 and Figure 1-4. An oil free air compressor has been used to provide background gas to be mixed with refrigerant for the tests. To avoid any possible test gas recirculation, air was taken from a conditioned enclosure outside the building away from the test section. An air cooler and a humidifier have been installed downstream of the air compressor to adjust the air temperature and humidity to a certain range. The air stream then splits into two parts. The main stream of the air flow was controlled to be at a constant mass flow rate of 3.5g/s and was monitored by a mass flow meter before being sent into a mixer to be mixed with refrigerant. The rest of the air flow was sent to a zero-air chamber, where the test sensor can be kept to protect it from contacting any refrigerant before conducting the tests.

For the refrigerant side, pure refrigerant was taken from a cylinder, sent through a flow controller and mass flow meter before mixing with the air in the static mixer. After mixing, the mixture was sent through the bottom of the test chamber to be used for the test. The concentration of the test gas can be calculated based on the measured mass flow rates by Equation (4), where $\dot{m}_{ref}$ is the measured refrigerant mass flow rate, $\dot{m}_{air}$ is the measured air mass flow rate, and $M_{Ref}$ and $M_{air}$ are the molar masses of the refrigerant and the air, respectively. The concentration here is defined as the relative refrigerant concentration expressed as a volumetric fraction of refrigerant per unit of air-refrigerant mixture. A 1 inch 4-way cross pipe fitting has been used as the diffuser to equally distribute the test gas in the test chamber. A thermocouple, pressure transducer, dew point sensor, and gas concentration sensor (reference sensor in the schematic) have been installed to monitor the test gas condition. A micro switch was attached to the sensor to be used to indicate the moment for starting to count the response time.


**Figure 1-3. Pictures of the Test Facility**

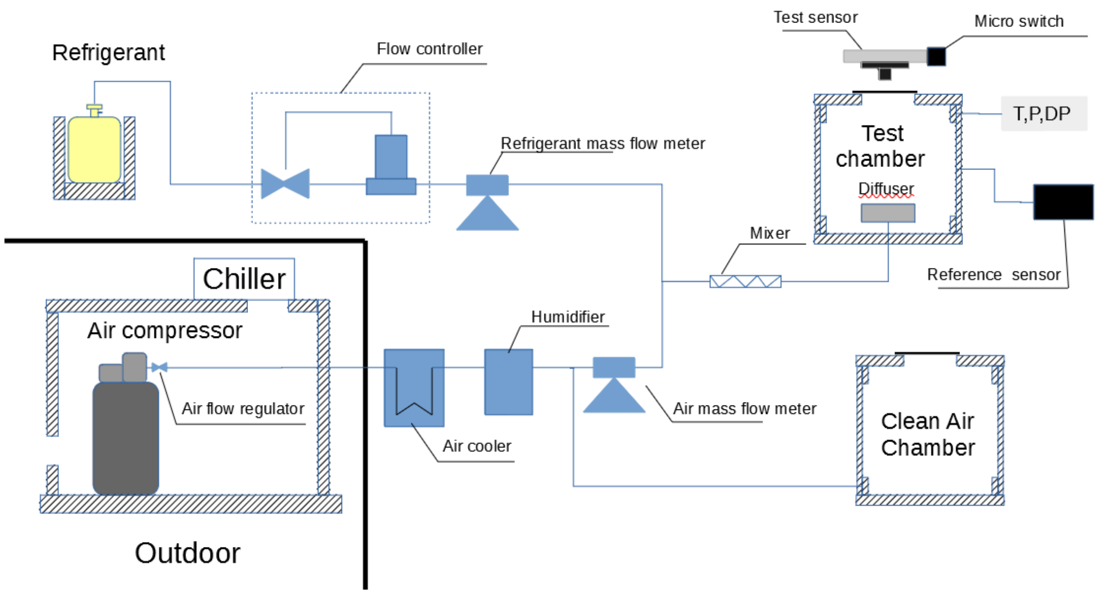



**Figure 1-4. Schematic of the Test Facility**

$$\text{conc} = \frac{\dot{m}_{ref}/M_{Ref}}{\dot{m}_{ref}/M_{Ref}+\dot{m}_{air}/M_{air}}\ , \% \text{ v/v} \quad (4)$$

### 1.3.2.2 Instrumentation

Table 1-3 shows the instruments used on the test facility. It is worth pointing out, the concentration of the test gas is the most critical parameter for both the step-change and time-varying tests. Before conducting the tests, the following approach has been adopted to ensure the accuracy of the test gas concentration measurement:

1) Calibrate the reference sensor by four different known concentrations of test gas
2) Use another three different known concentrations of test gas to check the calibration result
3) Adjust the flow controller to get four different concentrations of test gas, and use the measured mass flow rates with Equation (4) to calculate the test gas concentration and compare it with the reference sensor reading.

The deviation of measured gas concentrations between these three steps was within +/-5%.

**Table 1-3. List of Instruments**

| No. | Instrument | Model | Accuracy |
|---|---|---|---|
| 1 | Air side mass flow meter | Micro motion CMF025 | ±0.25% of reading |
| 2 | Refrigerant side mass flow meter | Micro motion CMF010 | ±0.25% of reading |
| 3 | Flow controller | EL-FLOW F-112-AC | NA |
| 4 | Reference sensor | Henze-Hauck WLD gas sensor | <1% of the range |
| 5 | Thermocouple | Omega T-type | ±0.25K |
| 6 | Pressure transducer | Rosemount 1153 | ±0.25% of range (0-747Pa) |
| 7 | Dew point sensor | EdgeTech Com.Air | ±0.2K |

#### 1.3.2.3 Tested sensors and conditions

As shown by Table 1-4, six sensors with four different sensing principles have been tested for Phase 1B of this project. R-32 has been selected as the test gas. This choice was made because R-32 is a pure fluid which facilitated the development and accuracy of the test method. Furthermore, R-32 is a component in many of the low-GWP blends that are being considered by industry. Table 1-5 shows the test matrix for both step-change and time-varying tests.

**Table 1-4. Tested Sensors**

| **Sensor letter code*** | **A** | **B** | **C** | **D** | **E** | **F** |
|---|---|---|---|---|---|---|
| **Sensing principle** | Micro Machined Membrane | Nondispersive Infrared | Thermal Conductivity | Nondispersive Infrared | Metal-Oxide Semiconductor | Metal-Oxide Semiconductor–Indicating Type |

* Sequence of sensor letter code in Phase 1 is different from Phase 3.

There are two different types of tests that have been carried out with this test facility: step-change concentration tests and time-varying concentration tests.

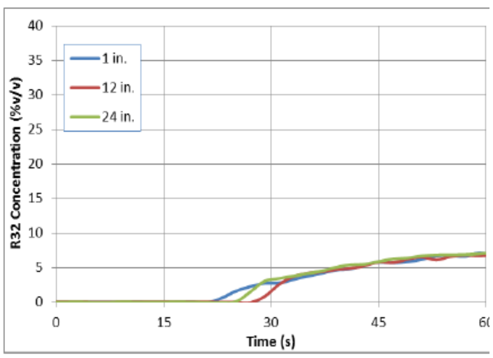
**Table 1-5. Test Conditions**

| **Test type** | **Conditions[1]** | **Temperature** | **Relative Humidity** | **Pressure** | **Test gas** |
|---|---|---|---|---|---|
| Step-change | 20%LFL (2.88% v/v) | 19-22°C | 45%-65% | Atmospheric pressure | R-32 and air mixture |
| | 25%LFL (3.60% v/v) | | | | |
| | 50%LFL (7.20% v/v) | | | | |
| | 100%LFL (14.40% v/v) | | | | |
| Time-varying | 0.2%/s | | | | |
| | 0.4%/s | | | | |
| | 1.0%/s | | | | |

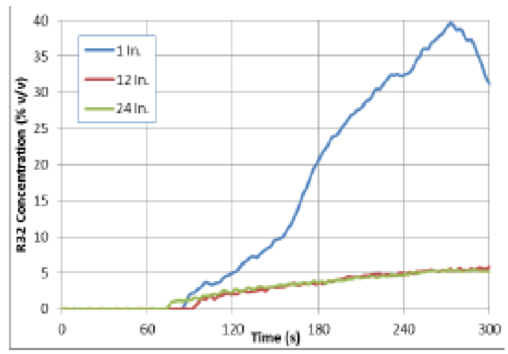
1. Step-change conditions defined as different test gas concentrations; time-varying conditions defined as different ramp-up rate of the test gas concentration

The previous AHRTI Project 9007-01 [8], conducted a leakage scenario study based on review of prior research and CFD simulations. Typical commercial scenarios including (i) Packaged Terminal Air Conditioner (PTAC) unit in a motel room; (ii) Rooftop unit in commercial kitchen; (iii) Walk-in cooler; and (iv) Reach-in refrigerator in a convenience store, and residential scenarios including (v) Split HVAC unit with evaporator section in a utility closet; (vi) Split HVAC unit servicing error were considered in their tests. As a result, a test matrix with three different refrigerant release rates, three different release locations, and two different release openings was developed to simulate the typical leakage scenarios. As required by AHRI to cover the major leakage scenarios, four refrigerant concentration profiles were selected in this project to present the influence of refrigerant release rate (profile a vs. b), release height (profile a vs. c) and release opening size (profile c vs d), as shown by Figure 1-5.

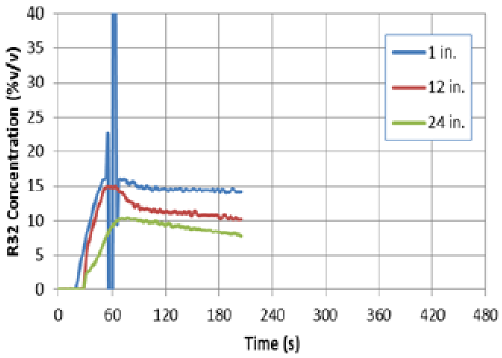
Therefore, three different test gas concentration ramp-up rates have been selected in the time-varying concentration tests. Profile (d) was covered by the step-change test due to the fairly large ramp-up rate. Per the requirements of the safety standards for the test gas concentrations, four different concentrations have been selected for the step-change tests. The test conditions are listed in Table 1-5. The conditions for step-change tests are defined for each test gas concentration. For the time-varying concentration tests, the test conditions are defined ramp-up rates of the test gas concentration.



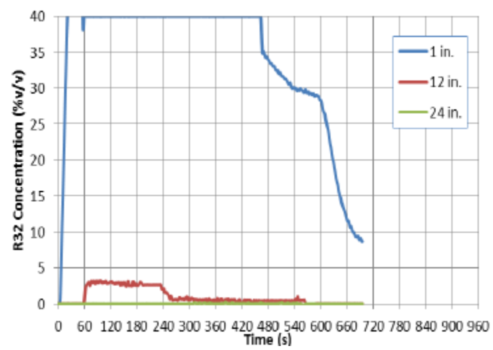

**(a) Release rate 100g/s, height 2.2m, opening size 25mm**




**(b) Release rate 13.5g/s, height 2.2m, opening size 25mm**




**(c) Release rate 100g/s, height 0.2m, opening size 25mm**




**(d) Release rate 100g/s, height 0.2m, opening size 365 mm**

**Figure 1-5. Refrigerant Concentration Profiles for Typical Leakage Scenarios [8]**

### 1.3.2.4 Test method

For the step-change tests, the test gas concentration in the test chamber was pre-adjusted to a desired value. After the condition of the test chamber had stabilized, the test sensor was quickly moved from the clean air chamber into the test chamber. At the moment when the test sensor came into contact with the test gas, the micro switch was triggered by hitting the lid of the test chamber, thereby sending a 5 VDC signal to the DAQ system. This signal was used to determine the zero time point for counting the response time. The mass flow rates, temperature, pressure, dew point, and micro switch signal have been recorded at a sampling rate of 10Hz, corresponding to a response time resolution of less than 0.2 seconds for the test facility.

Depending on the configurations of the different test sensors, 4 out of 6 sensors (Sensors A, B, C, and D) were using the data logging software provided by the manufacturers to record the sensor output through a digital interface. The sampling rates of these sensors were determined by the setup of the sensor and would vary from 0.5 to 1Hz. For the other two tested sensors, Sensor E provides an analog output and Sensor F provides a relay output. The sensor outputs of these two were integrated into the facility DAQ system.

When running the time-varying tests, the test sensor was kept in the test chamber initially with the clean-air condition. The air side mass flow rate was controlled to a constant value. The refrigerant mass flow controller was programed to open at different speeds to achieve different test gas concentration ramp-up rates of 0.2%/s, 0.4%/s and 1.0%/s.

### 1.3.3 Data reduction and test results

#### 1.3.3.1 Step-change concentration tests

As mentioned before, depending on the different sensor configurations, Sensors A, B, C, and D used a separate data logging software provided by the manufacturer to record the sensor output during the tests. Figure 1-6 shows the typical original sensor reading curve. These sensors read at a much slower sampling rate (0.5 to 1 Hz) compared with the test facility DAQ system (10 Hz). Therefore, the sensor reading was converted into a 'stair-type' curve as shown by Figure 1-7. The 'stair-type' curve is preferred because it shows the effect of the sampling rate on the tested response time. For example, a sensor reading at a sampling rate of 0.5Hz (every 2s), and a particular reading is slightly lower than the setpoint, but the subsequent reading is much higher, the sensor can only trigger the alarm at the second reading. Therefore, the effect of the sampling rate needs to be included when counting the response time. The unit of the sensor outputs were also all converted to %LFL (except Sensors E and F) for easy comparison.

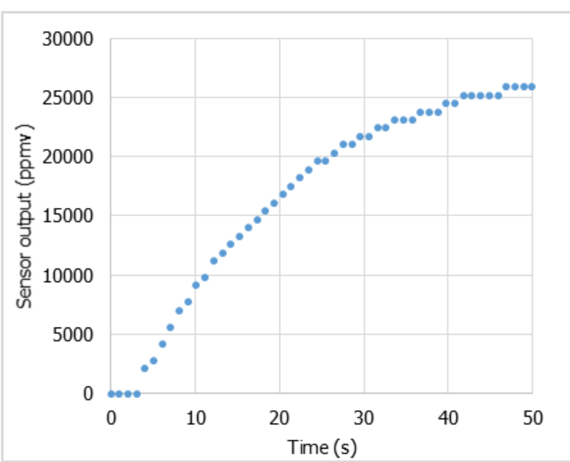



**Figure 1-6. Original Sensor Output Data**

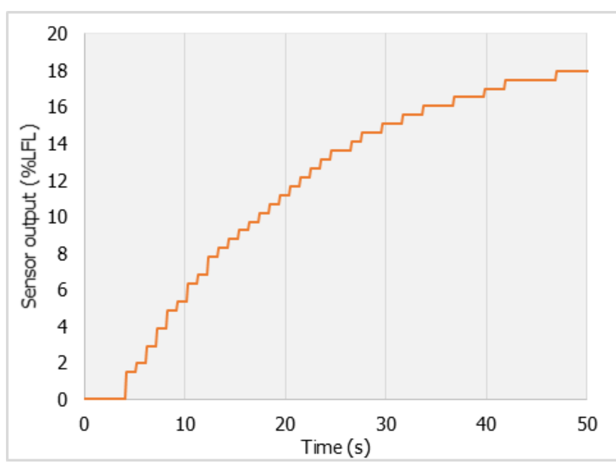



**Figure 1-7. 'Stair-type' Sensor Output Curve**

The converted 'stair-type' curve was then synchronized with the recorded DAQ data based on the time stamp. The micro switch signal was used to find the time zero and determine the "elapsed time" as shown by the x-axis of Figure 1-8.

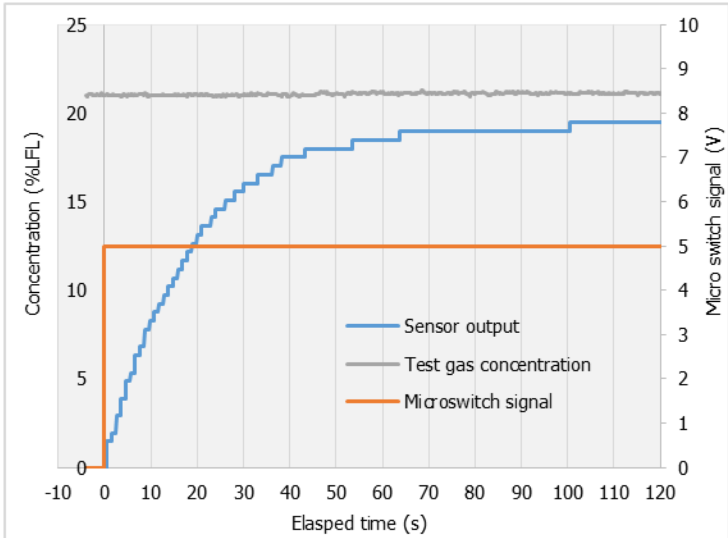



**Figure 1-8. Synchronized Data**

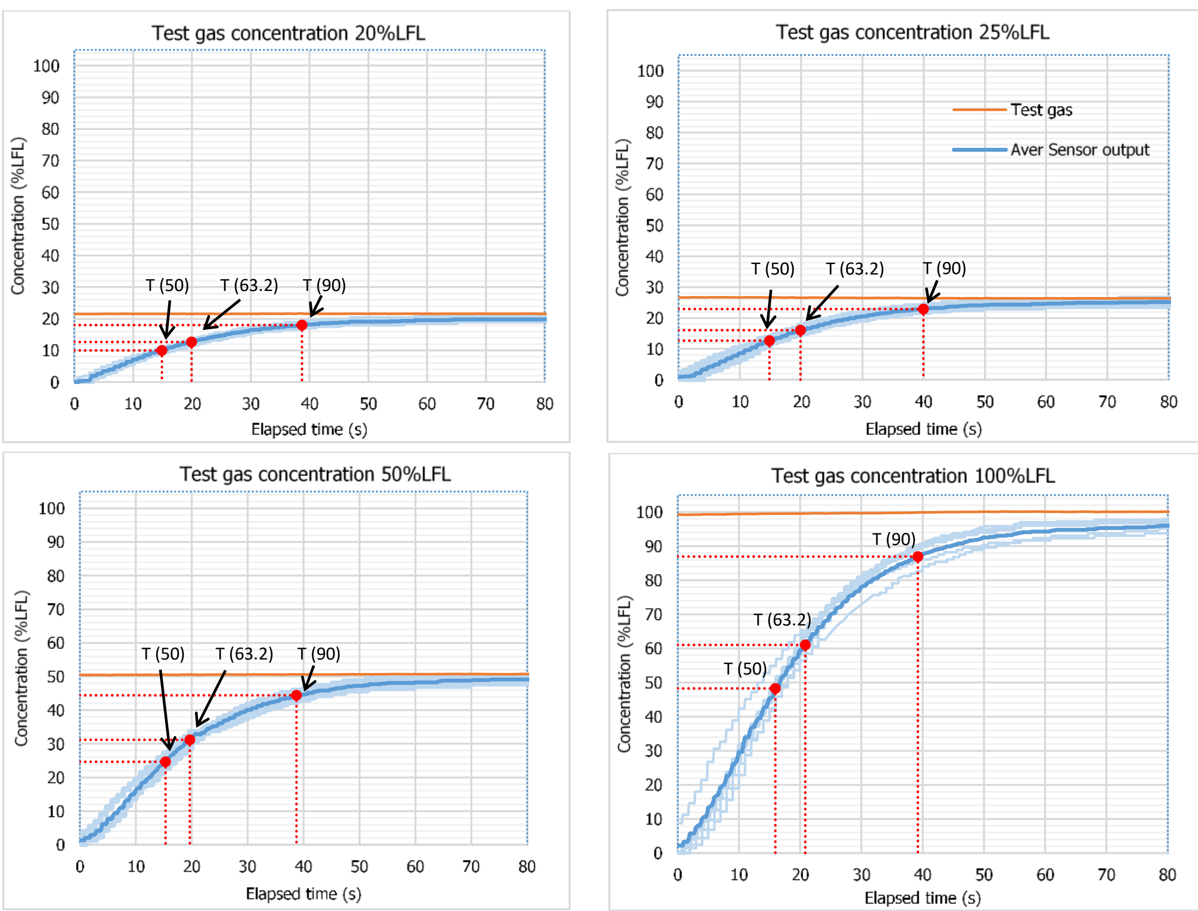



**Figure 1-9. Step-change Response Time Test Result (Sensor B)**

**Table 1-6. Tested Sensor Step-change Response[i]**

| Sensor[ii] | | | Time delay $\theta$ (s) | Time constant $\tau$ (s) |
|---|---|---|---|---|
| A | Micro Machined Membrane | Sample 1 | 4.4 | 4.7 |
| | | Sample 2 | 6.3 | 6.6 |
| | | Average | 5.4 | 5.6 |
| B | NDIR | Sample 1 | 1.4 | 18.1 |
| | | Sample 2 | 2.4 | 18.3 |
| | | Average | 1.9 | 18.2 |
| C | Thermal Conductivity | Sample 1 | 0.0 | 0.1 |
| | | Sample 2 | 0.0 | 0.1 |
| | | Average | 0.0 | 0.1 |
| D | NDIR | Sample 1 | 0.2 | 17.2 |
| | | Sample 2 | 0.0 | 10.2 |
| | | Average | 0.1 | 13.7 |

(i) Detailed test results can be found in Appendix D.

(ii) Sequence of letter code in Phase 1 is different from Phase 3.

The synchronized data can then be used to determine the response time. Figure 1-9 shows the step-change test result for Sensor B as an example. T(90), T(50), and T(63.2) of the tested sensor have been pointed out by the dashed lines on the charts of Figure 1-9. Here T(90), for example, represents the response time for a sensor to have an output reach 90% of the final sensor reading when experiencing a step-change condition. Both T(90) and T(50) are commonly used parameters for the evaluation of the sensor response. T(63.2) represents the time constant $\tau$ in Equation (1). For each sensor, two identical samples (S) and two runs (R) per sample (four runs in total) have been carried out. The light-colored lines in the charts show the result for each run and the dark colored line shows the averaged value of these four runs.

Table 1-6 shows the test time delay and time constants for Sensors A, B, C, and D, which are so-called measuring type, meaning the sensor output shows the measured gas concentration. By using Equation (1) with the $\theta$ and $\tau$ shown in Table 1-6, T(50) and T(90) can be easily calculated. It is important to note that the calculated sensor output should have the same units of measure as the test gas concentration used in these equations.

Sensor E is a MOS sensor with an analog output. According to the data sheet, the sensor output is not linear to the gas concentration and is saturated at about 5000ppmv (3.47%LFL). Due to the saturated concentration of the sensor being much lower than the test gas concentrations used in these tests, the time constant cannot be reasonably determined. This is because $y(\infty)$ is no longer mainly determined by $\Delta u$.

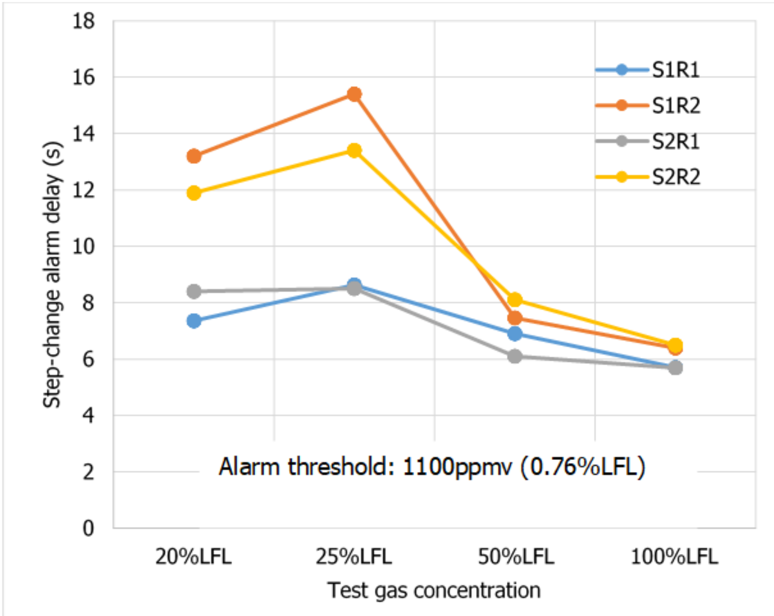



**Figure 1-10. Sensor F Step-change Test Result**

Sensor F is another MOS type sensor with a relay output, which is a so-called indicating type, i.e. it only indicates when a certain concentration threshold has been reached. Figure 1-10 shows the step-change alarm delay of Sensor F. Step-change alarm delay is the time length between time zero and the time when the relay output is triggered.

#### 1.3.3.2 Time-varying concentration tests

There are two major objectives for the concentration time-varying tests:

a) Distinguish the gas concentration step-change response and the actual condition response,
b) Verify the response prediction from Equations (2) and (3) with the actual condition response.

The conditions of the time-varying tests are defined by the different ramp -up rates of the test gas concentration. The rates were set to about 0.2%/s, 0.4%/s and 1.0%/s to mimic the different leakage scenarios from a previous AHRTI project [8]. In the tests, the test gas concentration was determined by the refrigerant mass flow rate and air mass flow rate only. The reference sensor was not used because of its sensing delay. To ensure the measured concentration is the real current concentration in the test chamber, the mass flow meter response times had to be checked.

As shown by the step-change test results, Sensor C has been proven to have a response time less than 0.2s. So, Sensor C was used as a reference to verify the method for concentration measurement using date from the mass flow meters. Figure 1-11 compares the Sensor C output with the mass flow rate based test gas concentration. The agreement between the two curves proves that the mass flow meters have an acceptable response time.

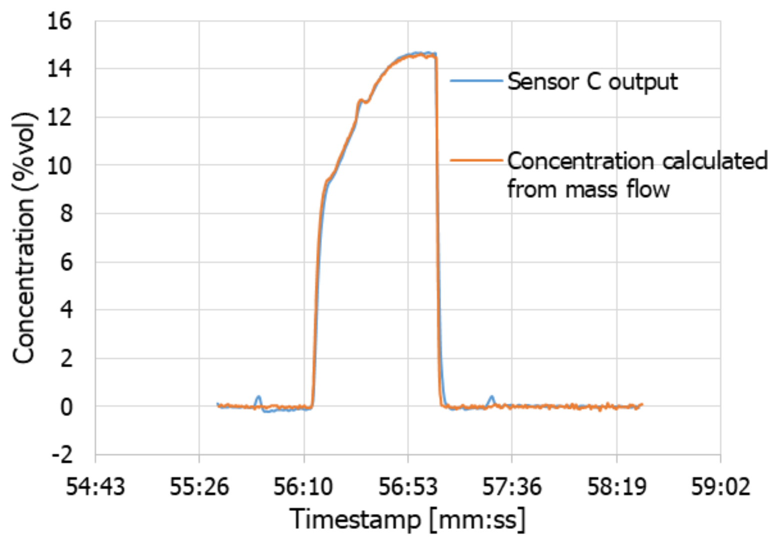



**Figure 1-11. Sensor C Time-varying Test Data**

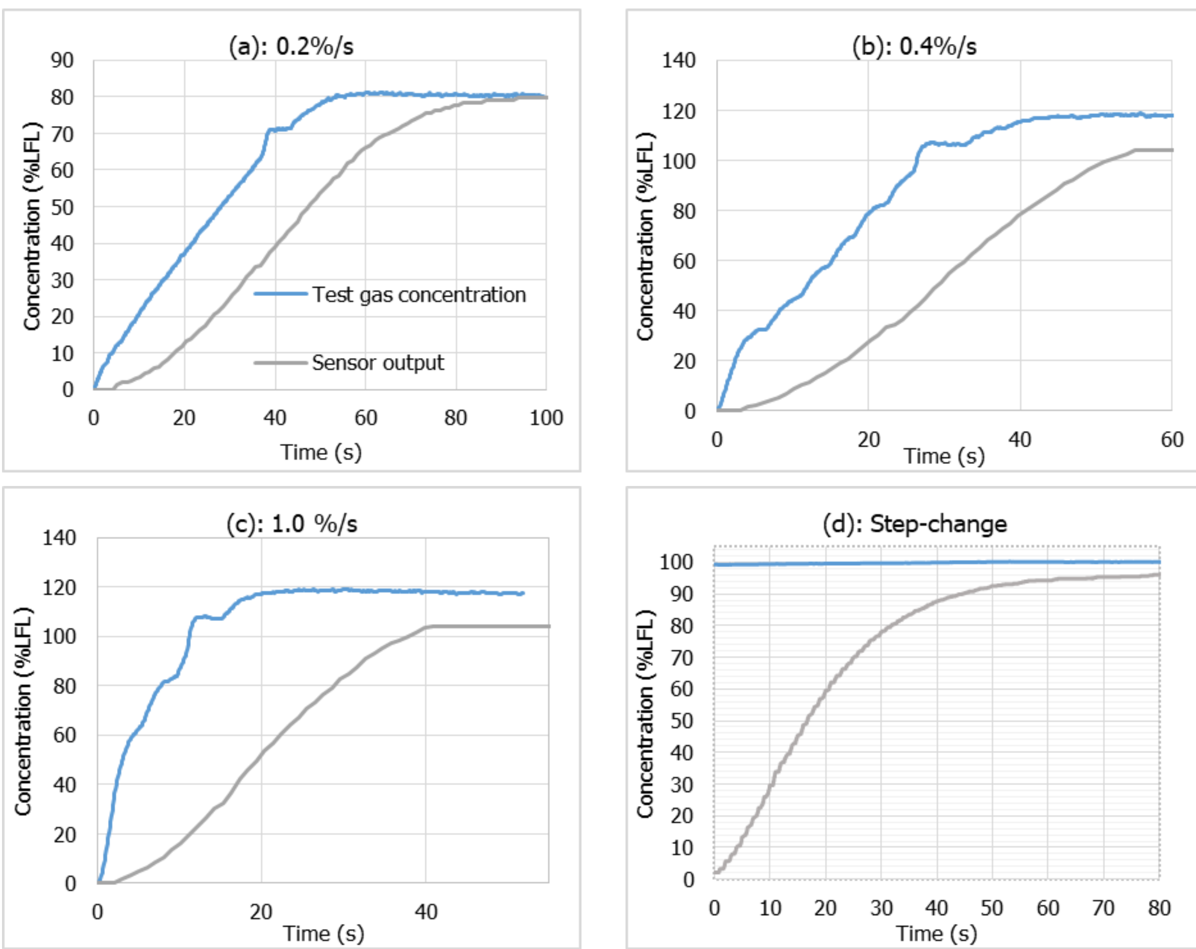



**Figure 1-12. Time-varying Test Data (Sensor B)**

The time-varying tests results, which are the sensor responses to different test gas concentration ramp-up rates from 0.2%/s to 1.0%/s, are shown in Figure 1-12 as well as the step-change condition for comparison, using Sensor B as an example.

#### 1.3.3.3 Prediction model

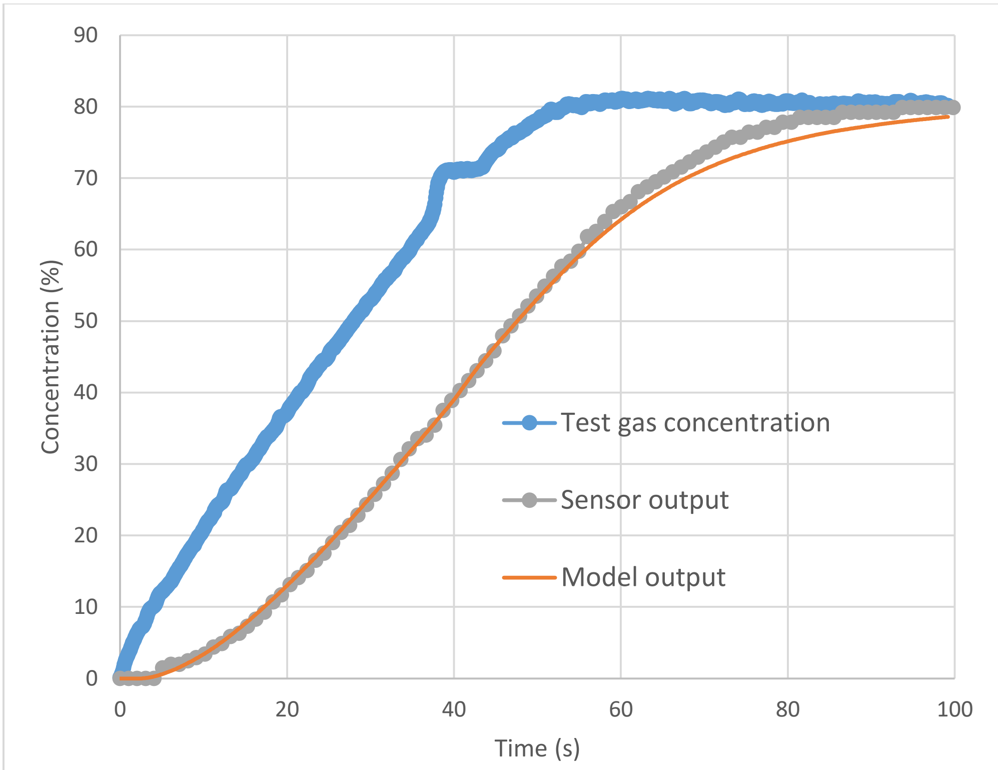



**Figure 1-13. Prediction Model Output**

By knowing the actual test gas concentration profile or $u(t_i)$ in Equation (2), the sensor output $y(t_i)$ can be calculated. The curve shown in Figure 1-13 named as model output is the calculated sensor output based on the known time delay $\theta$ and time constant $\tau$ determined by the step-change tests and the controlled test gas concentration profile, $u(t_i)$. The result shows Equations (2) and (3) have good accuracy in predicting the sensor output under the known actual refrigerant concentration profile condition.

## 1.4 Analysis

### 1.4.1 Maximum allowable setpoint

When defining the requirements of sensor response, the safety standards specify the maximum test gas concentration and the required response time. For example, IEC 60335-2-40 Edition 6.0 requires the sensor to make an output (meaning triggering the alarm) within 30 seconds when exposed to a refrigerant concentration of 25 % of LFL or lower. Using a lower concentration for the sensor setpoint allows that sensor to trigger the alarm faster. Looking at the 25%LFL tested data for Sensor A in Figure 1-14(a), the sensor is found to have a 16.4%LFL maximum allowable setpoint in order to trigger the alarm at 30 seconds, thus meeting the requirements of IEC 60335-2-40.

For the three reviewed safety standards, as shown in Table 1-7, different test gas concentrations and response times are specified. Therefore, each tested sensor has three different maximum allowable setpoints in order to meet the requirements of the relevant standard.

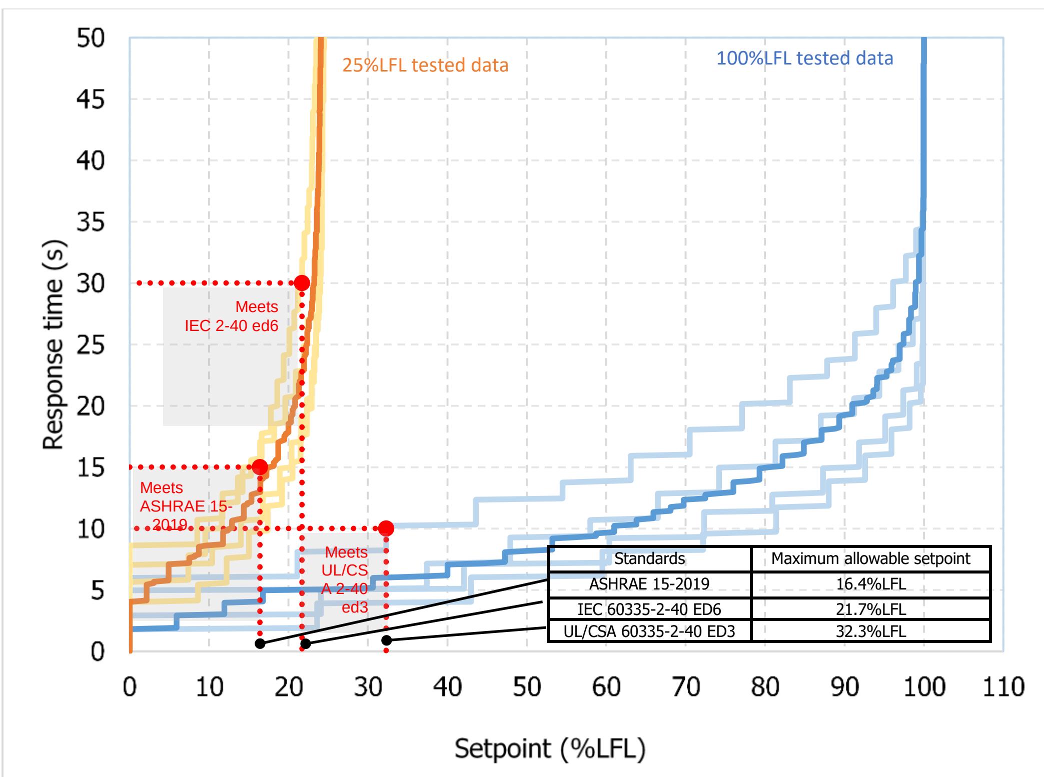
The maximum allowable set point as determined by this project was based only on 4 tests (2 runs for each of 2 samples). Given the response time variability observed in just four runs, the maximum allowable set points may be lower when considering a larger number of sensor samples and test runs

**Table 1-7. Maximum Allowable Setpoint(i)**

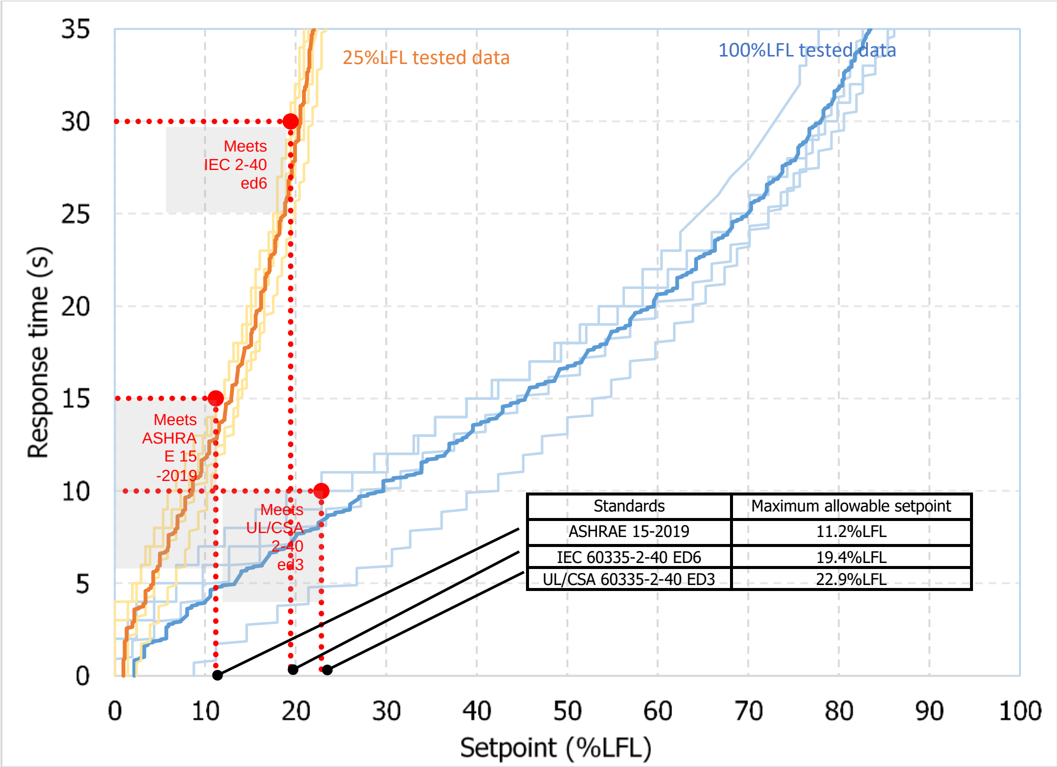
| Standard | Test gas concentration | Response time requirement | Maximum allowable setpoint of sensor(ii) (%LFL) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | A | B | C | D | E | F |
| ASHRAE 15-2019 | ≤25%LFL | ≤15s | 16.4 | 11.2 | 22.2 | 14.2 | 3.1(V) | Indicating type |
| IEC 60335-2-40 ED6 | ≤25%LFL | ≤30s | 21.7 | 19.4 | 22.6 | 20.8 | 3.8(V) | |
| UL/CSA 60335-2-40 ED3 | ≤100%LFL | ≤10s | 32.3 | 22.8 | 97.7 | 41.7 | 4.0(V) | |

(i) Detailed test results can be found in Appendix D.

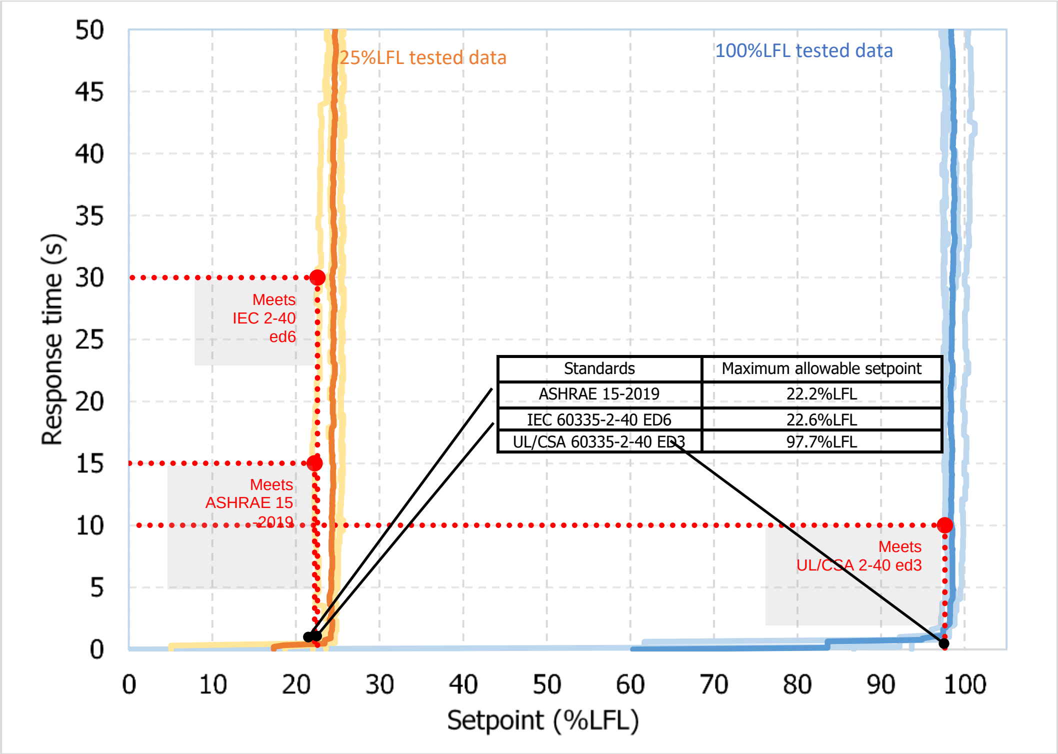
(ii) Sequence of sensor letter code in Phase 3 is different from Phase 1.



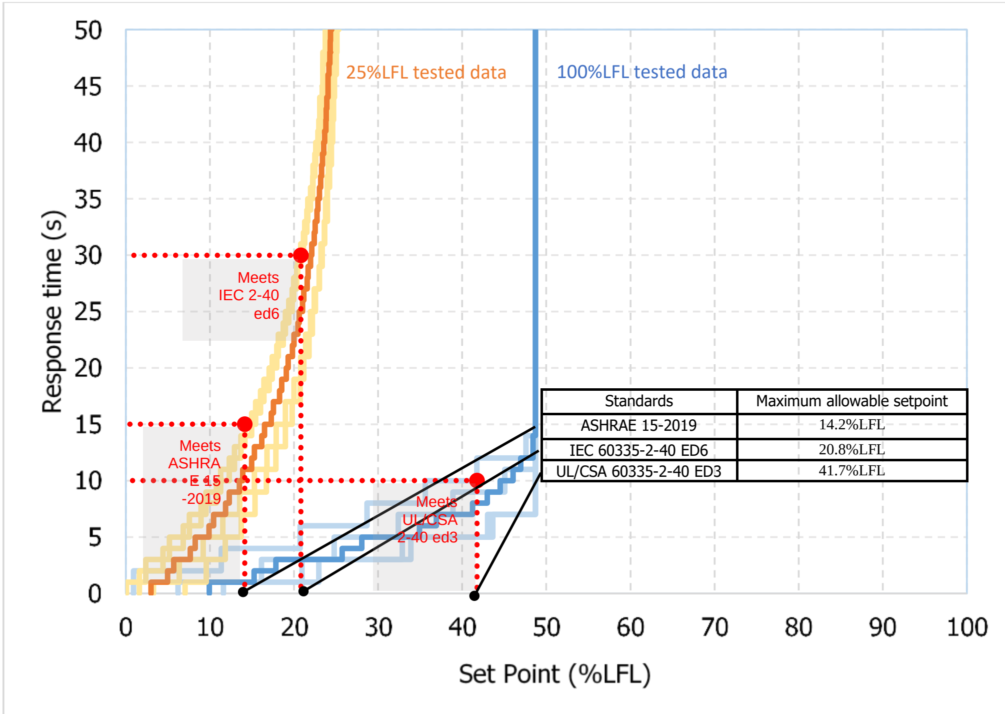

**(a) Sensor A**



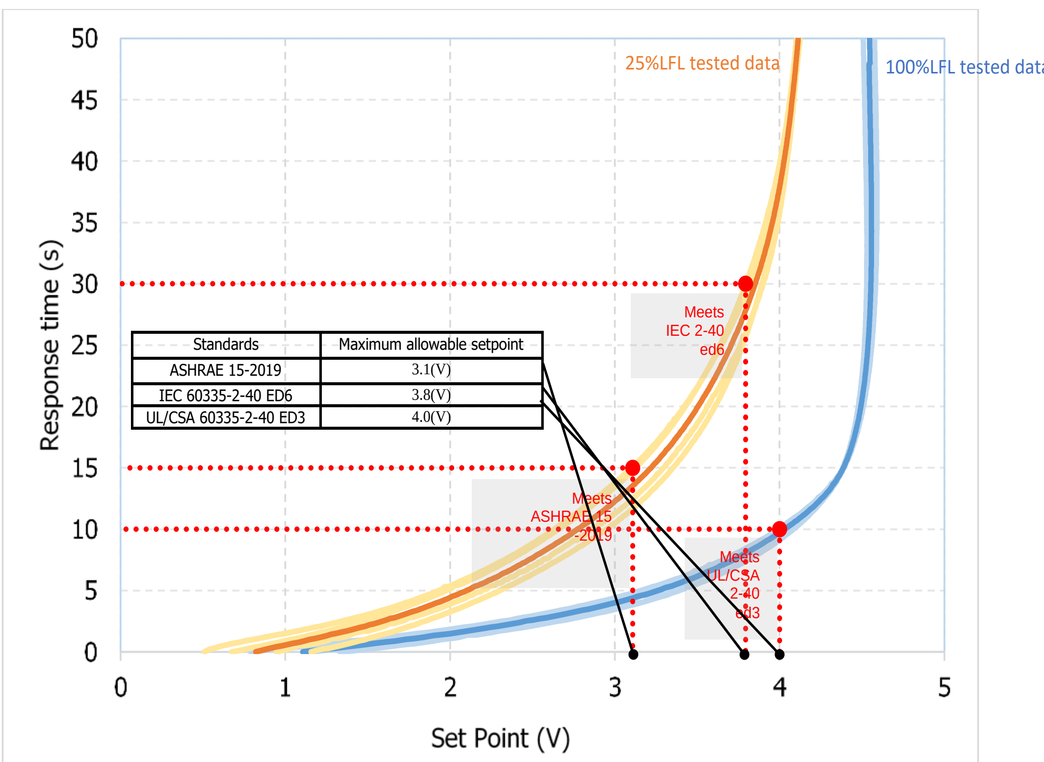

**(b) Sensor B**




**(c) Sensor C**




**(d) Sensor D**




**(e) Sensor E**

**Figure 1-14. Determination of Maximum Allowable Setpoint**

### 1.4.2 Time-varying alarm delay and Time over RCL

As shown by Table 1-7, each sensor has a maximum allowable setpoint to meet the response time requirement of relevant standards. No matter which number has been selected as the setpoint, there is always a time delay between when the actual gas concentration reaches the setpoint concentration and when the sensor output reaches the setpoint. This delay is defined as the time-varying alarm delay.

Table 1-8 summarizes the time-varying alarm delay for Sensors A, B, C, and D with different maximum allowable setpoints as the alarm threshold. Sensors E and F have no output for the measured test gas concentration; therefore, no alarm delay can be obtained.

**Table 1-8. Time-varying Alarm Delay and Time over RCL(i)**

| Sensor(ii) | Standard to meet | Setpoint (%LFL) | Time-varying alarm delay (s) | | | Time Over RCL(i) (s) | | |
|---|---|---|---|---|---|---|---|---|
| | | | 0.2%/s | 0.4%/s | 1.0%/s | 0.2%/s | 0.4%/s | 1.0%/s |
| A | ASHRAE 15-2019 | 16.4 | 8.1 | 3.1 | 4.6 | 3.2 | 2.0 | 4.3 |
| | IEC 60335-2-40 ED6 | 21.7 | 7.3 | 6.7 | 4.4 | 5.3 | 6.3 | 4.3 |
| | UL/CSA 60335-2-40 ED3 | 32.3 | 6.4 | 6.7 | 6.1 | 11.0 | 9.8 | 6.4 |
| B | ASHRAE 15-2019 | 11.2 | 14.8 | 10.7 | 8.1 | 6.9 | 9.0 | 7.5 |
| | IEC 60335-2-40 ED6 | 19.4 | 17.2 | 14.9 | 9.7 | 14.1 | 14.1 | 9.5 |
| | UL/CSA 60335-2-40 ED3 | 22.9 | 18.4 | 15.5 | 11.6 | 17.1 | 15.1 | 11.6 |
| C | ASHRAE 15-2019 | 22.2 | 1.4 | 0.0 | 0.5 | 0.0 | 0.0 | 0.4 |
| | IEC 60335-2-40 ED6 | 22.5 | 1.3 | 0.0 | 0.5 | 0.0 | 0.0 | 0.4 |
| | UL/CSA 60335-2-40 ED3 | 97.7 | - | - | 0.0 | - | - | 29.8 |
| D | ASHRAE 15-2019 | 14.2 | 9.5 | 6.5 | 4.6 | 3.4 | 6.5 | 4.1 |
| | IEC 60335-2-40 ED6 | 20.8 | 10.0 | 11.1 | 6.3 | 7.4 | 10.5 | 6.3 |
| | UL/CSA 60335-2-40 ED3 | 41.7 | 13.2 | 13.6 | 9.3 | 23.4 | 18.5 | 10.1 |
| E | ASHRAE 15-2019 | 3.1(V) | - | - | - | 6.8 | 15.7 | 19.7 |
| | IEC 60335-2-40 ED6 | 3.8(V) | - | - | - | 8.7 | 14.4 | 16.5 |
| | UL/CSA 60335-2-40 ED3 | 4.0(V) | - | - | - | 7.5 | 12.3 | 13.8 |
| F | Indicating type with fixed setpoint (0.76%LFL or 1100ppm,v) | | - | - | - | 10.5 | 18.9 | 12 |

(i) Detailed test results can be found in Appendix D.
(ii) Sequence of sensor letter code in Phase 1 is different from Phase 3.

By using the maximum allowable setpoint, all the tested sensors were supposed to have identical step-change response times (30, 15, or 10 seconds) under the conditions (test gas concentration of 25%LFL or 100%LFL) as required by different standards. For instance, when Sensor A uses 16.4%LFL as the alarm threshold, it will have the same response time to trigger the alarm as Sensor B with 11.2%LFL as the alarm threshold, under the 0 to 25%LFL step change condition. In conclusion, lowering the setpoint of a slower sensor allows it to still meet the step-change response requirement defined by the safety standards. However, the time-varying alarm delay for each sensor will still be different. It was found in the step-change tests that Sensor A has a quicker response than Sensors B and D. Therefore, Sensors B and D have a smaller maximum allowable setpoint to offset the slower response. Figure 1-15 compares the time-varying alarm delay of Sensors A, B, and D by using the maximum allowable setpoints of three different standards at the test gas concentration ramp-up rate of 0.2%/s. The reason why Sensor C was not included in the comparison is because Sensor C has a step-change response of less than 0.2s, so the time-varying alarm delay is negligible. It is obviously shown by Figure 1-15, under the time-varying conditions, slower sensors will still have significantly longer alarm delays, even when using smaller setpoint.

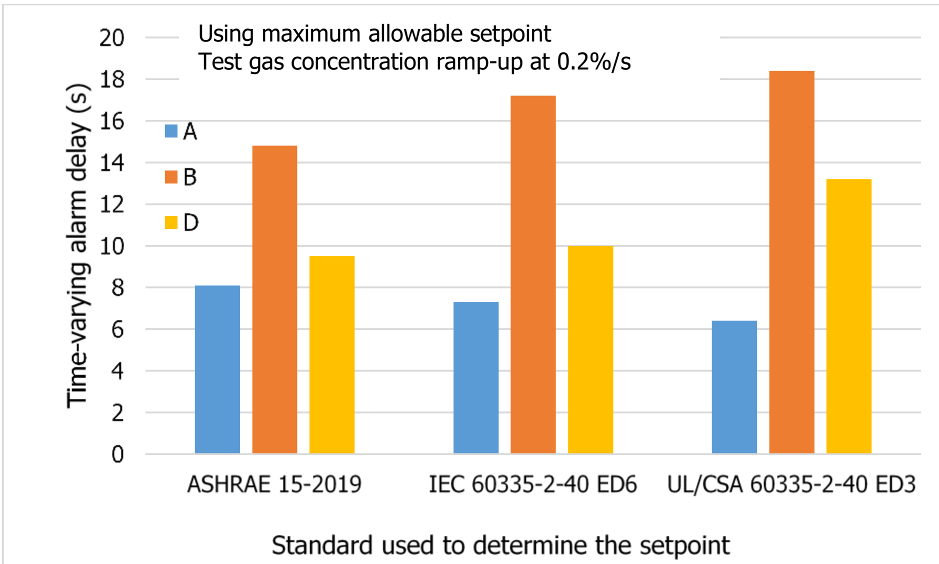



**Figure 1-15. Time-varying Alarm Delay**

ASHRAE Standard 34-2019 [9] defines a Refrigerant Concentration Limit (RCL) for refrigerants to reduce the risks of acute toxicity, asphyxiation, and flammability hazards in normally occupied, enclosed spaces. For R-32, the RCL is equal to 25%LFL. The time length between when the actual test gas concentration reaches the RCL and when the alarm is triggered by the sensor output is defined as the Time over RCL (TOR). The TOR of Sensors A, B, C, D, and E was found by using the maximum allowable setpoints which are also listed in Table 1-8.

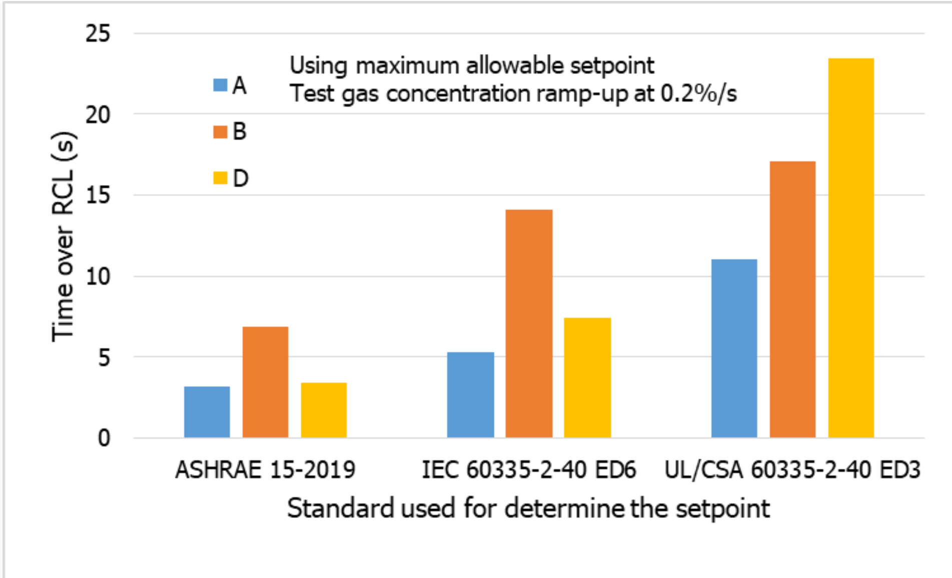



**Figure 1-16. Time over RCL**

The RCL for A2L group refrigerants is mainly defined for reducing the risk of flammability hazards, which means when the refrigerant concentration gets higher than the RCL, there is a risk of flammability hazards. By using the RCL as the safety criteria, larger TOR means higher risk. Figure 1-16 compares the TOR of Sensors A, B, and D by using the maximum setpoints at the test gas concentration increase rate of 0.2%/s.

Both IEC 60335-2-40 and ASHRAE 15-2019 require the use of test gas concentrations equal to or less than 25%LFL to determine the sensor response time. Using the maximum allowable setpoint by ASHRAE 15-2019 will have the shortest TOR compared to the other two. UL/CSA 60335-2-40 ED3 requires less than 10s to trigger the alarm but with equal or less than 100%LFL as the test gas concentration, which ends up with the longest TOR.

The comparison of the sensors shows that Sensor A, which has the fastest step-change response time, also has shorter TOR than Sensors B and D. When using the allowable maximum setpoint of IEC 60335-2-40 and ASHRAE 15-2019, Sensor D always has a smaller TOR than Sensor B. However, Sensor D, when using the maximum allowable setpoint of UL/CSA 60335-2-40 ED3, shows much longer TOR than B, although Sensor D has a faster step-change response than Sensor B. This is most likely due to Sensor D having its output saturated at around 50%LFL, keeping in mind that sensor response time slows down when approaching the saturation point.

It is important to note that for a fast sensor like Sensor C, the maximum allowable setpoint could be very close to the test gas concentration. When referring to UL/CSA 60335-2-40, it will be allowed to use a setpoint close to 100%LFL. Because of this high setpoint, it is possible that during an actual slow leakage scenario, the refrigerant concentration of the occupied space will remain over RCL for a longer time than desired.

## 1.5 Conclusions

After reviewing the major refrigerating safety standards including IEC 60335-2-40 Edition 6 (Jan-2018), UL/CSA 60335-2-40 edition 3 (Nov-2019), ASHRAE Standard 15-2019, ASHRAE proposed Standard 15.2P (Advisory Public Review), and JRA Standard 4068T: 2016R, the requirements of refrigerant sensors were summarized and listed in a table. The related specifications of 11 sensors have been collected through a specially designed survey. By cross checking the standard requirements list with the sensors' specifications, a compliance check list has been made. The results show that most of the sensors are able to meet the requirement in terms of response time. Both the resistance of long-term exposure to 100% refrigerant and the ability to withstand condensation conditions seems to be a challenge for some of the MOS and NDIR sensors. JRA 4068T 2016 listed the operating temperature ranges for different applications, the lowest temperature being -40$^{o}$C for inside freezer applications, which exceeds the lower limit for most of the sensors' operational temperature range.

Six sensors with four different sensing principles have been selected and experimentally assessed by both step-change and time-varying concentration tests. Based on the results of an earlier AHRI project and the requirements of the reviewed safety standards, a test matrix with four different test gas concentrations for step-change tests and three concentration ramp-up rates for time-varying tests was developed to experimentally assess the performance of the selected sensors under the typical leakage scenarios.

For the step-change tests, the sensor response curves were checked against the requirements of the standards, and as the results show, by using a setpoint lower than the maximum allowable setpoint, all tested sensors meet the response time requirements defined in the safety standards. The time constant and time delay of each sensor obtained are to be used in Equations (2) and (3) to predict the sensor response in the actual conditions. For the time-varying test, the time-varying alarm delay and the TOR (Time Over RCL) are found by using the maximum allowable setpoint as the alarm threshold. The results show that the slower sensors will still have a longer alarm delay and a longer TOR when using a lower setpoint. Overall, ASHRAE Standard 15-2019 was found to have the most strict response time requirement, and ends up having the shortest time-varying alarm delay and TOR. The prediction model was verified by comparing the time-varying test data with the model output.

# Phase 2

## 2.1 Introduction

For decades, great effort has been invested in the development of low GWP refrigerant solutions for the HVACR industry. Some of the alternative synthetic refrigerants have proven excellent potential to reduce the GWP without sacrificing the performance of the refrigeration system compared to the currently used family of refrigerants. Due to their mildly flammable nature, several of these alternative refrigerants fall into the A2L safety group according to the ASHRAE Standard 34 [4]. To use these refrigerants, refrigerant detectors are required by safety standards to mitigate the possible combustion events. As part of the safety-critical control system, it is important to assess the robustness and reliability of the detectors. Several existing standards have included methods for the sensor robustness evaluation. Some of them may include provisions that are not necessary for the application of A2L sensors to occupied spaces. Others have lists of the stresses and their test methods which are quite different from each other. Therefore, it is meaningful to review and summarize the reliability evaluation methods from the existing standards and establish a more complete list of stresses to develop the applicable test methods for the robustness and reliability of the detectors.

As the continuation of Phase 1 of AHRTI Project 9014, this Phase 2 section focuses on the development of the test methods for the assessment of the robustness and reliability of refrigerant detectors. Three existing relevant standards were reviewed, they are IEC 60079-29-1 Edition 2 (July-2016) [10], JRA 4068T-2016 [6] and UL/CSA 60335-2-40 Edition 3 (Nov-2019) [2]. The requirements and the procedures for the sensor reliability assessment were summarized. Based on the different types of stressors and the test procedures, five categories of tests have been established. Table 2-1 lists these categories and highlights the relevant sections in these existing standards. The test procedures, test facility design, and failure metric for each category are described in Section 2.3 to Section 2.7.

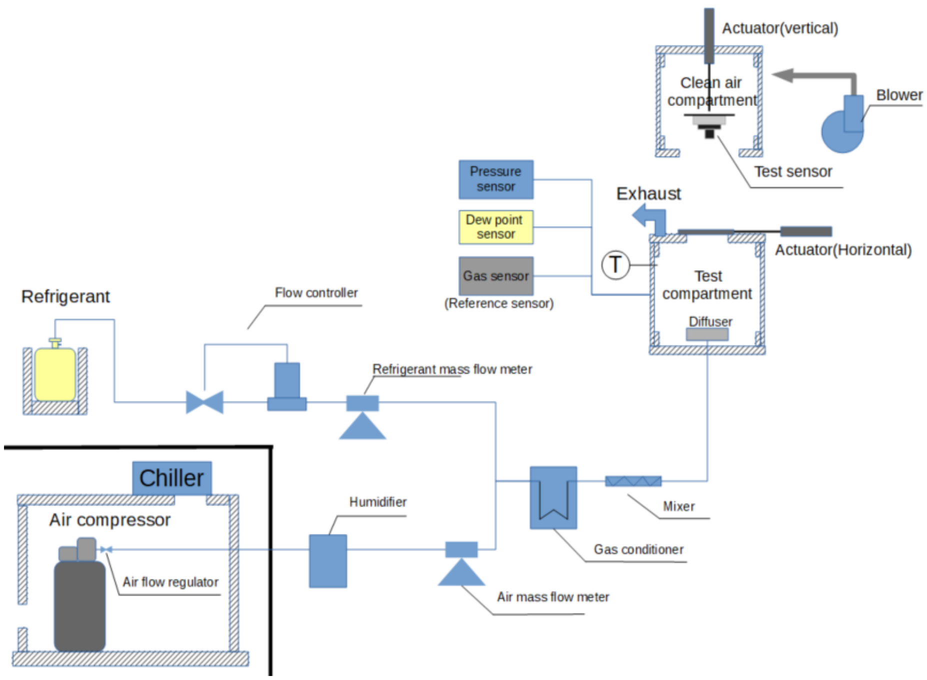
**Table 2-1. Categories of the Stress**

<table>
<tr><td colspan="3">Category A. Fluid resistance and poisoning test</td></tr>
<tr><td rowspan="2">JRA 4068T-2016 [6]</td><td colspan="2">10.3 Miscellaneous gas resistance test</td></tr>
<tr><td colspan="2">10.8 Durability test (gas resistance test and sensor durability test)</td></tr>
<tr><td>UL 60335-2-40 ED3 [2]</td><td colspan="2">LL.5DV Selectivity test and poisoning test</td></tr>
<tr><td rowspan="2">IEC 60079-29-1 [10]</td><td colspan="2">5.4.4.5 Long-term stability<br>*UL 60335-2-40 [2] LL.4DV requires 100% refrigerant as the test gas for long-term test</td></tr>
<tr><td colspan="2">5.4.16 High gas concentration operation above the measuring range</td></tr>
<tr><td colspan="3">Category B. Extreme storage condition test</td></tr>
<tr><td>JRA 4068T-2016 [6]</td><td colspan="2">None</td></tr>
<tr><td>UL 60335-2-40 ED3 [2]</td><td colspan="2">LL.1DV General (refer to IEC60079-29-1 [10])</td></tr>
<tr><td>IEC 60079-29-1 [10]</td><td colspan="2">5.4.2 Unpowered storage (-25±3°C and 60±2°C for 24hours)</td></tr>
<tr><td colspan="3">Category C. Operation condition test</td></tr>
<tr><td rowspan="3">JRA 4068T-2016 [6]</td><td colspan="2">10.4 Temperature test</td></tr>
<tr><td colspan="2">10.9 Condensation resistance test</td></tr>
<tr><td colspan="2">10.6 Power source voltage fluctuation test</td></tr>
<tr><td>UL 60335-2-40 ED3 [2]</td><td colspan="2">LL.1DV General (refer to IEC60079-29-1 [10])</td></tr>
<tr><td rowspan="3">IEC 60079-29-1 [10]</td><td>5.4.6 Temperature</td><td>5.4.9 Air velocity</td></tr>
<tr><td>5.4.7 Pressure</td><td>5.4.10 Orientation</td></tr>
<tr><td>5.4.8 Humidity of test</td><td>5.4.18 Power supply variations</td></tr>
<tr><td colspan="3">Category D. Vibration and impact</td></tr>
<tr><td>JRA 4068T-2016 [6]</td><td colspan="2">None</td></tr>
<tr><td>UL 60335-2-40 ED3 [2]</td><td colspan="2">LL.1DV General (refer to IEC60079-29-1 [10])</td></tr>
<tr><td rowspan="2">IEC 60079-29-1 [10]</td><td colspan="2">5.4.12 Vibration</td></tr>
<tr><td colspan="2">5.4.13 Drop test for portable and transportable equipment</td></tr>
<tr><td colspan="3">Category E. Repeatability test</td></tr>
<tr><td>JRA 4068T-2016 [6]</td><td colspan="2">10.7 Stability test</td></tr>
<tr><td>UL 60335-2-40 ED3 [2]</td><td colspan="2">LL.1DV General (refer to IEC60079-29-1 [10])</td></tr>
<tr><td>IEC 60079-29-1 [10]</td><td colspan="2">5.4.4.2 Short-term stability</td></tr>
</table>

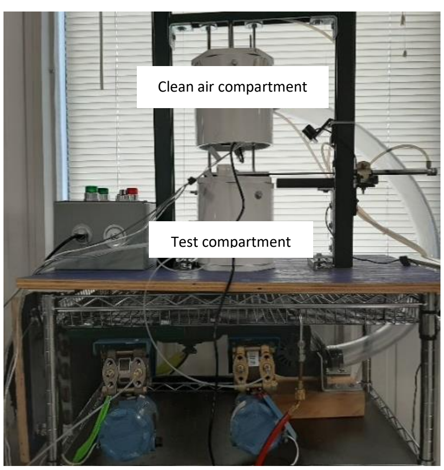
## 2.2 Sensor performance evaluation method

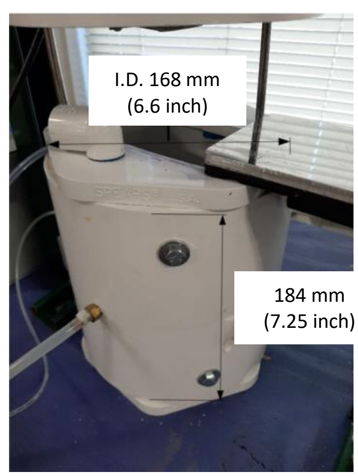
Depending on the durability of the sensor and the type of stresses, some sensors may instantly fail under a certain type of stress while some may show degradation in performance after exposure to stress. To uncover the effect of those stresses which cause performance degradation, comparing the sensor performance before and after exposure is a feasible approach. Therefore, a test method for the evaluation of the sensor performance is needed. Response time and accuracy are the most important parameters of sensor performance. The methods for evaluation of the sensor response time and accuracy are described below.

### 2.2.1 Sensor response time test method




**A: Schematic of Push-through Facility**




**B: Picture of Push-through Facility** **C: Test Compartment Dimensions**

**Figure 2-1. Schematic and Picture of Push-through Facility**

The sensor response time is defined as the duration between the moment when the sensor is put into the standard test gas and the moment when the sensor initiates an output signal. 25%LFL of R32 and air mixture is used as the standard test gas for this project. A Push-through test facility is recommended to be used for the sensor response time evaluation. Figure 2-1 shows the schematic and the picture of the Push-through Facility.

An oil-free air compressor is used to provide background gas to be mixed with refrigerant for the tests. To avoid any possible test gas recirculation, the air is taken from a conditioned enclosure outside the test room. A humidifier is installed downstream of the air compressor to adjust the air humidity to the specified range. The air stream is controlled to be at a constant mass flow and is monitored by a mass flow meter before being sent into a mixer to be mixed with refrigerant. A gas conditioner is used to adjust the test gas temperature to the temperature of the surrounding environment. For the refrigerant side, pure refrigerant is taken from a cylinder and sent through a flow controller and mass flow meter before mixing with the air in the static mixer. After mixing, the mixture is sent through the bottom of the test compartment to be used for the test. The concentration of the test gas can be calculated based on the measured mass flow rates by Equation (5):

$$conc_{mfr} = \frac{\dot{m}_{ref}/M_{Ref}}{\dot{m}_{ref}/M_{Ref} + \dot{m}_{air}/M_{air}} \quad , \% \; v/v \tag{5}$$

where $\dot{m}_{ref}$ is the measured refrigerant mass flow rate, $\dot{m}_{air}$ is the measured air mass flow rate, and $M_{ref}$ and $M_{air}$ are the molar masses of the refrigerant and the air, respectively. The concentration here is defined as the relative refrigerant concentration expressed as a volumetric fraction of refrigerant per unit of air-refrigerant mixture. A diffuser is installed in the test compartment at the outlet of the mixture to equally distribute the test gas. A thermocouple, pressure transducer, dew point sensor, and gas concentration sensor (reference sensor in the schematic) is installed to monitor the test gas condition. A clean air compartment is installed above the test compartment. A small blower is connected to the clean air compartment that provides sufficient air to keep the exhausting test gas away from the clean air compartment. The test gas is discharged horizontally from the test compartment. The opening on the top of the test compartment, which is used for the test sample to be pushed into the test compartment, is covered by a lid to minimize the chance of the exhausting gas going into the clean air compartment during the conditioning period. A vertical linear actuator is installed in the clean air compartment that holds the test sample vertically and a horizontal actuator is connected to the lid of the test compartment. Before the test, the test sample is placed in the clean air compartment for the warm-up in clean air. After the stabilization of the test conditions, the horizontal actuator opens the lid on the test compartment and the vertical actuator is synchronized to push down the test sample to the test compartment with 0.3-0.5 seconds delay. Simultaneously, an electric signal is sent to the data acquisition system to indicate the moment for starting to measure the response time.

The test compartment should be properly sized such that the gas velocity in the test compartment should be less than 0.2m/s. The test compartment dimensions shown in Figure 2-1C are for illustration purpose only; different dimensions may produce satisfactory results as well. The mass flow meters and the reference sensor should be calibrated separately. The test gas concentration determined by calculation using mass flow rates needs to be checked by comparing with the reference sensor reading. The allowable deviation between these two values should be no more than 0.1%v/v.

### 2.2.2 Sensor accuracy test method

Two methods may be used to perform the accuracy evaluation test: the mass flow rate method and the gas injection method. The mass flow method uses the same procedure used in the Push-through Facility as described in Section 2.2.1. Both the air flow rate and the refrigerant flow rate need to be accurately measured. The concentration of the test gas is determined by calculation using Equation (5).

For the gas injection method, a closed vessel with a known inner volume is used as the test chamber. Figure 2-2 shows the schematic of the "gas injection" test setup. A closed vessel with a known inner volume is used as the test chamber. The test chamber should be leak-free and installed with an agitator to improve the uniformity of the test gas concentration. The agitator should run at a suitable speed to provide sufficient turbulence to the test gas but not significantly change the air velocity near the test sensor. A syringe or equivalent device is used to add the refrigerant to the test chamber to get a certain concentration of test gas. An airbag is connected to the test chamber to compensate for the volume change after injection and minimize the pressure change of the test chamber. The air bag should be completely deflated before injection.

The test gas concentration is determined by calculation using Equation (6):

$$conc_{gi} = \frac{V_{in}}{V_v + V_{in}}, \%\mathrm{v/v} \qquad (6)$$

where $V_{in}$ is the volume of the injection gas and $V_v$ is the inner volume of the test vessel.

Since the volume of the connection tubing needs to be included in vessel volume, determination of $V_v$ through calibration is recommended. To calibrate the vessel volume, a reliable gas sensor with accuracy of no less than ±5% of reading is needed. The injection volume ($V_{in}$) is varied through at least 3 different points. The mixture concentrations ($conc_{gi}$) are measured after stabilization. The test vessel volume ($V_v$) can be obtained by solving Equation (6). The calibration method has been demonstrated in Phase 3, the detailed calibration procedure can be found in section 3.2.1.

The test procedures for the sensor accuracy evaluation by using gas injection method are as follows:

a) The test chamber should be well ventilated with fresh air before the test
b) Place the test sensor inside the test chamber and allow it to run for 15 minutes in clean air
c) Seal the test chamber to avoid any air infiltration
d) Calculate the injection amount of the refrigerant based on the known volume of the test chamber and the desired concentration of the test gas
e) Use the syringe or equivalent device to add the predetermined amount of the refrigerant to the test chamber

f) Keep the sensor exposed to the test gas and continually record the output signal until the stabilized output is obtained.

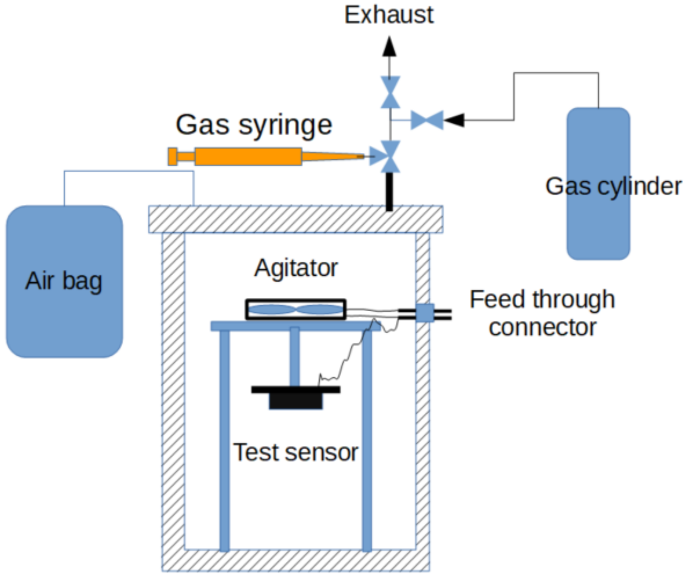



**Figure 2-2. Gas Injection Test Facility**

The sensor output should be recorded after exposure to the test gas. The criteria for the sensor accuracy are that the sensor should not send an output signal under the lower accuracy limitation concentration and should send an output signal at the higher accuracy limitation concentration. The accuracy limitation concentrations are determined by the sensor setpoint (the threshold for activating the alarm). The lower accuracy limitation concentration is 5%LFL below the sensor setpoint, but no lower than 1%LFL. The higher accuracy limitation concentration is 5%LFL above the sensor setpoint.

## 2.3 Category A: Fluid resistance and poisoning tests

### 2.3.1 Test fluids

Three typical scenarios including operating environment, service/maintenance, and leakage have been considered for the selection of the fluids for the tests. Table 2-2 shows the selected fluids.

**Table 2-2. Selected Test Fluids for Fluid Resistance and Poisoning Tests**

<table>
<tr><th rowspan="2">No.</th><th rowspan="2">Scenario</th><th rowspan="2" colspan="3">Test Fluid</th><th colspan="2">Concentration or Flow rate</th><th rowspan="2">NAAQS/EPA [11]</th><th rowspan="2">JRA 4068T [6]</th><th rowspan="2">UL 60335-2-40 [2]</th><th rowspan="2">PMS comments[c]</th></tr>
<tr><th>Value</th><th>Unit</th></tr>
<tr><td>1</td><td rowspan="5">Operation environment</td><td colspan="3">Carbon dioxide</td><td>5000±5%</td><td rowspan="9">ppm v/v</td><td>●</td><td></td><td>●</td><td></td></tr>
<tr><td>2</td><td colspan="3">Carbon monoxide</td><td>35±10%</td><td>●</td><td></td><td></td><td>●</td></tr>
<tr><td>3</td><td colspan="3">Nitrogen dioxide</td><td>0.1±10%</td><td>●</td><td></td><td></td><td></td></tr>
<tr><td>4</td><td colspan="3">Sulfur dioxide</td><td>0.075±10 %</td><td>●</td><td></td><td></td><td>●</td></tr>
<tr><td>5</td><td colspan="3">Ammonia</td><td>100±5%</td><td></td><td></td><td>●</td><td>●</td></tr>
<tr><td>6</td><td rowspan="7">Maintenance</td><td colspan="3">D4, Octamethylcyclotetrasiloxane</td><td>100±5%</td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2">●</td><td rowspan="2">●</td></tr>
<tr><td>7</td><td colspan="3">D5, Decamethylcyclopentasiloxane</td><td>100±5%</td></tr>
<tr><td>8</td><td colspan="3">Ethanol</td><td>200±5%</td><td></td><td>●</td><td>●</td><td></td></tr>
<tr><td>9</td><td colspan="3">Acetone</td><td>200±5%</td><td></td><td></td><td>●</td><td></td></tr>
<tr><td rowspan="3">10</td><td rowspan="3">Coil cleaner[a] (Indoor)</td><td>Ethylene glycol monobutyl ether</td><td>3-7%[b]</td><td rowspan="3">10±5%</td><td rowspan="3">ml/min</td><td></td><td></td><td></td><td rowspan="3">●</td></tr>
<tr><td>Alcohol, C7-21, ethoxylated</td><td>1-5%[b]</td><td></td><td></td><td></td></tr>
<tr><td>Sodium xylene sulphonate</td><td>1-5%[b]</td><td></td><td></td><td></td></tr>
<tr><td>11</td><td rowspan="6">Leakage</td><td colspan="3">Methane</td><td>500±5%</td><td>ppm v/v</td><td></td><td>●</td><td>●</td><td>●</td></tr>
<tr><td>12</td><td colspan="3">n-Butane</td><td>300±5%</td><td>ppm v/v</td><td></td><td></td><td>●</td><td></td></tr>
<tr><td>13</td><td rowspan="2" colspan="3">Refrigerant (R32)</td><td>100±5%</td><td>%vol</td><td></td><td></td><td></td><td>●</td></tr>
<tr><td>14</td><td>2000±5%</td><td>ppm v/v</td><td></td><td></td><td></td><td>●</td></tr>
<tr><td>15</td><td colspan="3">POE oil[a]</td><td>10±5%</td><td>ml/min</td><td></td><td></td><td></td><td>●</td></tr>
<tr><td>16</td><td colspan="3">50% Ethylene glycol water solution[a]</td><td>10±5%</td><td>ml/min</td><td></td><td></td><td></td><td>●</td></tr>
</table>

a: For liquid fluid, air is recommended to be used as the driving gas; the air flow rate should be kept within the range of 5-7L/min

b: The percentage values refer to the mass fraction of coil cleaner in water

c: PMS is the abbreviation for Project Monitoring Subcommittee

### 2.3.2 Test procedure

Before exposure to the test fluids, the response time and the accuracy of the test sample should be initially checked under the standard condition. Here the standard condition is defined as a temperature of 20±5$^oC$ and humidity of 50±10%. The test method for determining the response time and the accuracy of the sensor are described in Section 2.2.

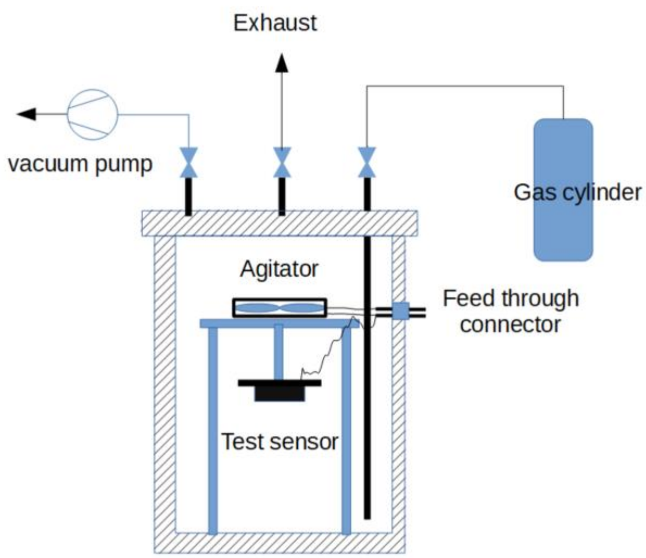



**Figure 2-3. Modified Gas Injection Test Facility for 100% Refrigerant Test**

After the initial performance check, the test sample should be kept in clean air with the power on for at least 15 minutes. For volatile test fluids or those in the gas-phase other than the 100% refrigerant test, the "gas injection" method described in Section 2.2.2 is recommended to perform the harshness test. Since the objective of these tests is to check the resistance to the test fluids, the injected gas should be one of the fluids listed in Table 2-2. The method for obtaining the test gas concentration is the same as for the accuracy evaluation described in Section 2.2.2. For the 100% refrigerant test, the gas injection facility should be set up to the configuration shown in Figure 2-3. The test chamber should be initially vacuumed without the test sensor installed. Next, add pure refrigerant to the vacuumed chamber until atmospheric pressure is reached, then open the exhaust valve and keep adding refrigerant to maintain the pressure in the test chamber slightly higher than atmosphere. Open the test chamber, quickly install the test sensor, re-seal the test chamber, and close the refrigerant supply and exhaust valves. The exposure time starts counting when test chamber is sealed. For liquid-phase fluids, it is recommended to use the "liquid spray" method described in Section 2.3.2.1.

The duration of the exposure should be no less than 2 hours when using the "gas injection" method and no less than 30 minutes when using the "liquid spray" method. The sensor output should be continually measured for the whole period of the exposure. No alarm or initiation of the output signal which is designed to activate the alarm should be observed for all of the test fluids other than 2000ppm and 100% refrigerant. After exposure, the test sample should be put into the clean air for at least 20 minutes to perform the response time and accuracy check under standard condition. The change in response time and accuracy of the test sample caused by each test fluid should be specified in the test report.

#### 2.3.2.1 Liquid spray test method (except oil)

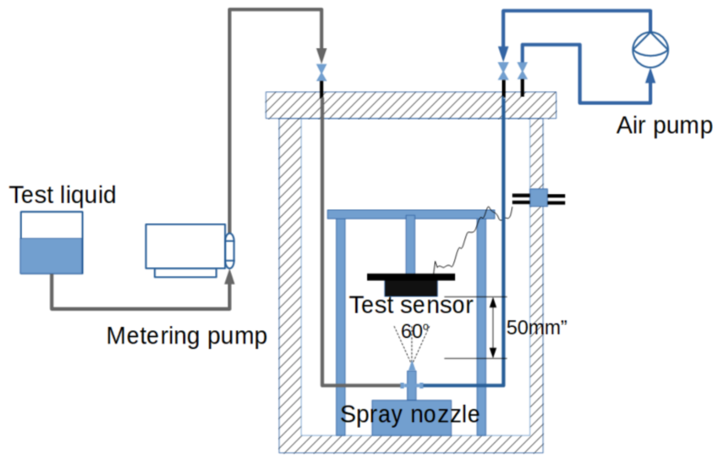



**Figure 2-4. Liquid Spray Test Setup**

A spray method using an entrainment nozzle with air as the driving gas is recommended to ensure finely dispersed liquid droplets. Figure 2-4 shows a schematic of the liquid spray test setup. A metering pump is used to feed the test liquid to the spray nozzle, the liquid flow rate is measured and controlled to 10±5% ml/min as listed in Table 2-2. Air is circulated by an air pump to generate the spray without changing the pressure of the test chamber. The air flow rate should be kept within the range of 5-7L/min. The spray nozzle should be a full cone nozzle with a spray angle of 60°. The test sensor should be installed 50mm above the nozzle tip, as shown in Figure 2-4. The test procedures are as following:

a) The test chamber should be well ventilated with fresh air before the test
b) Place the test sensor inside the test chamber and allow it to run for 15 minutes in clean air.
c) The sensor should be mounted above the spray nozzle with the sensing window facing down.
d) Seal the test chamber to avoid any air infiltration.
e) Turn on the air pump, liquid pump, and adjust the pump speed to the desired flow rate.
f) Keep the spray active for 30 minutes and continually record the output signal.

The liquid spray method has been demonstrated in Phase 3 for the investigation of the effect of oil on the sensor performance. Based on the test result, an improved oil spray method has been developed and verified in Phase 3 and descried in section 3.2.2.3.

## 2.4 Category B: Extreme storage condition test

The response time and the accuracy of the test sample should be initially evaluated under the standard condition. The extreme storage condition test follows the same test procedure as described in Section 5.4.2 of IEC 60079-29-1 Edition 2.0 [10]. The test procedure is as follows:

The test sample shall be exposed sequentially to the following conditions in clean air only:

a) Under temperature of (–25 ± 3) °C for at least 24 h;
b) Under ambient temperature for at least 24 h;
c) Under temperature of (60 ± 2) °C for at least 24 h;
d) Under ambient temperature for at least 24 h.

At each temperature, the humidity of the clean air shall be such that condensation does not occur. Alternatively, a suitable desiccator may be used to keep the test sample from exposure to condensation when under ambient temperature conditions. After exposure, check the sensor response time and the accuracy at the standard condition and specify any change in the test report.

## 2.5 Category C: Operation condition tests

Table 2-3 summarizes the test conditions, required test facility, and the failure metric for Category C. Section 2.5.1 to Section 2.5.6 describe methods of each stress test. Refer to Section 3.4.6 for additional recommendations based on the findings of Category C test examples in Phase 3.

**Table 2-3. Test Matrix for Category C**

<table>
<tr><th>Stress</th><th colspan="2">Test facility</th><th colspan="2">Condition</th><th>Failure metric</th></tr>
<tr><td rowspan="4">Temperature</td><td rowspan="4">Push-through Facility</td><td rowspan="4">Environmental chamber</td><td colspan="2">40±1°C 30-70% RH</td><td rowspan="4">Response time and accuracy</td></tr>
<tr><td colspan="2">55±1°C 30-70% RH*</td></tr>
<tr><td colspan="2">-20±1°C 30-70% RH</td></tr>
<tr><td colspan="2">-10±1°C 30-70% RH</td></tr>
<tr><td>High temperature survival test</td><td>Push-through Facility</td><td>Lab oven</td><td colspan="2">105°C (221°F) or specified by sensor manufacturer or user</td><td>Response time and accuracy</td></tr>
<tr><td rowspan="3">Humidity</td><td rowspan="3">Push-through Facility</td><td rowspan="3">Environmental chamber</td><td colspan="2">40±1°C 20±5%RH,</td><td rowspan="3">Response time and accuracy</td></tr>
<tr><td colspan="2">10±1°C 90±5%RH</td></tr>
<tr><td colspan="2">Condensation</td></tr>
<tr><td rowspan="2">Pressure</td><td colspan="2" rowspan="2">Gas Injection Facility</td><td colspan="2">73±1kPa, standard condition</td><td rowspan="2">Accuracy</td></tr>
<tr><td colspan="2">101±1kPa, standard condition</td></tr>
<tr><td rowspan="10">Air velocity</td><td colspan="2" rowspan="10">Gas Injection Facility</td><td>Velocity</td><td>Air flow angle</td><td rowspan="10">Accuracy</td></tr>
<tr><td rowspan="3">non-forced</td><td>0±5°</td></tr>
<tr><td>90±5°</td></tr>
<tr><td>180±5°</td></tr>
<tr><td rowspan="3">3±0.3 m/s</td><td>0±5°</td></tr>
<tr><td>90±5°</td></tr>
<tr><td>180±5°</td></tr>
<tr><td rowspan="3">6±0.6 m/s</td><td>0±5°</td></tr>
<tr><td>90±5°</td></tr>
<tr><td>180±5°</td></tr>
<tr><td rowspan="3">Orientation</td><td colspan="2" rowspan="3">Push-through Facility</td><td colspan="2">Vertical</td><td rowspan="3">Response time and accuracy</td></tr>
<tr><td colspan="2">45±5°</td></tr>
<tr><td colspan="2">Horizontal</td></tr>
<tr><td>Power supply variation</td><td colspan="2">Push-through Facility</td><td colspan="2">-20%±2% of rated voltage<br>20%±2% of rated voltage</td><td>Response time and accuracy</td></tr>
</table>

*: The application of sensors for systems with furnace may require a higher temperature which has not been considered in this project phase. If any adjustment is needed, a revised version will be included with the Phase 3 report.

### 2.5.1 Method for temperature and humidity tests

The response time and the accuracy of the test sample should be initially checked under the standard condition. An environmental chamber with controlled temperature and humidity is required to perform the temperature and humidity tests. The response time and the accuracy of the sensor should be checked again under the conditions listed in Table 2-3 and the difference in response time and the accuracy caused by the operating environment is to be specified in the test report.

Figure 2-5 schematically shows the setup of the test facility. The response time and accuracy evaluation facility (Push-through Facility) is located in an environmental chamber and isolated with a secondary box to avoid any test gas contamination of the "clean air" in the environmental chamber. The "step-change" procedure is used to evaluate the response time of the test sample as follows:

a) Sensor warm-up

The test sensor is kept in the clean air compartment of the test facility to prevent test sample contact with any test gas before the test. The clean air compartment is connected to a blower placed outside of the secondary box. The blower blows conditioned air from the environmental chamber to the clean air compartment which provides clean air and cooling (or heating) capacity to the entire secondary box as well.

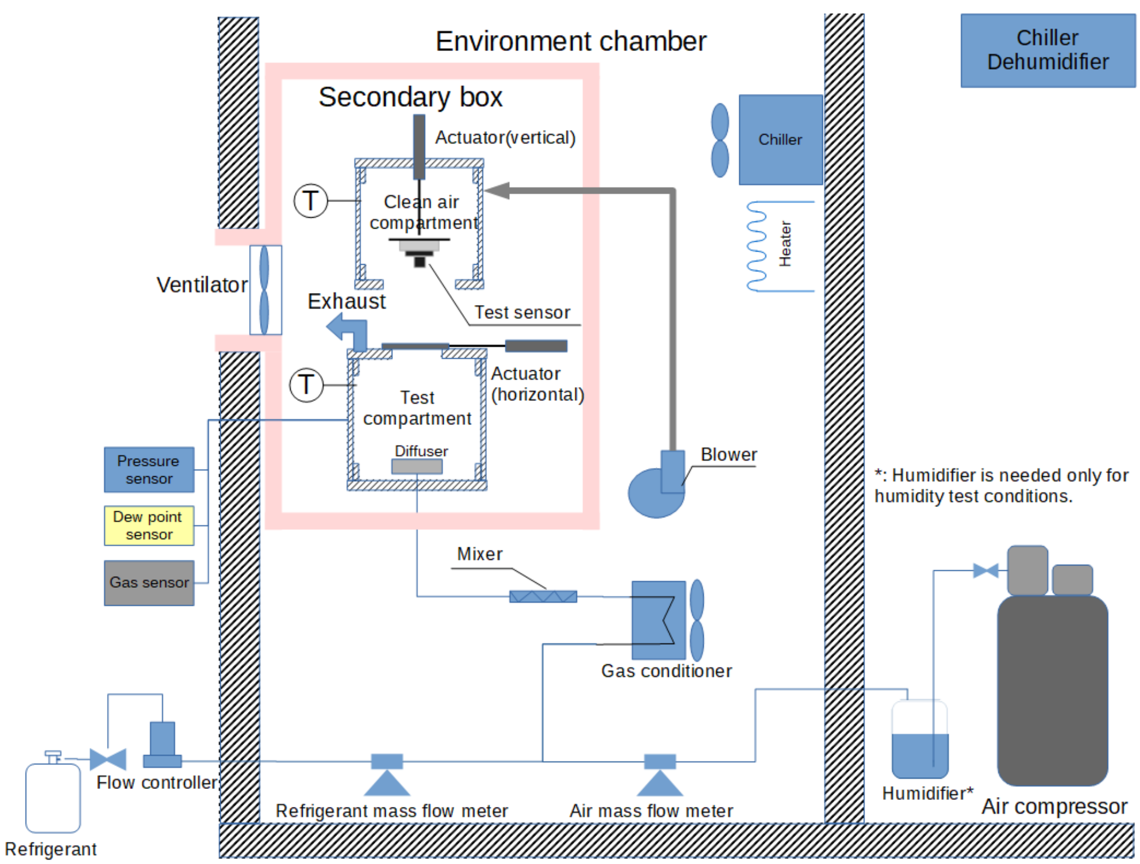



**Figure 2-5. Chamber Setup for Temperature and Humidity Tests**

b) Test gas preparation

The test gas is obtained by mixing the compressed air with the refrigerant. The compressed air is provided by an oil-less air compressor located outside the test chamber to avoid the recirculation of the test gas. For the low-temperature condition test, the compressed air should be dehumidified before being sent to the gas conditioner to avoid frost in the air line. For the humidity test conditions, the humidity of the air stream needs to be adjusted after leaving the air compressor. The mass flow rate of the air stream is measured by a mass flow meter and kept at a constant value. The refrigerant is directly taken from a refrigerant tank, the mass flow is adjusted by a flow controller according to the desired test gas concentration, and the mass flow rate is measured by a mass flow meter as well. After mixing, the test gas is sent to a gas conditioner which is comprised of an air heat exchanger. The gas conditioner has sufficient heat transfer area to cool down (or heat up) the test gas to be very close to the environmental chamber temperature. A static mixer and a diffuser are installed downstream of the gas conditioner to improve the homogeneity of the test gas in the test compartment.

c) Push-through test

After stabilization of the test condition, push down the test sample from the clean air compartment to the test compartment to perform the “step-change” of the test gas concentration. The test procedures for determining the response time and accuracy of the test sample were described in Section 2.2.

The test gas continually exhausts from the test compartment to the secondary box and is vented out by a ventilating fan to the outside of the environmental chamber. The ventilating fan should have sufficient capacity to avoid the test gas leaking into the environmental chamber. The temperature, pressure, humidity, and concentration of the test gas in the test compartment should be monitored during the test to confirm the test conditions.

A high temperature survival test was added to this Category while investigating the effect of temperature on the sensor reliability in Phase 3. The test method is described in section 3.4.1.3.

### 2.5.2 Condensation test

The response time and the accuracy of the test sample should be initially evaluated under the standard condition. The procedure of the condensation test is as follows:

a) The test sample should be kept in an isothermal chamber at -25±2$^{o}$C with the power on until the surface temperature reaches lower than -20$^{o}$C.
b) Place the test sample in an environment with a temperature of 25±5$^{o}$C and relative humidity of 60±5% until condensation occurs on the surface but no shorter than 3 minutes.
c) Repeat the two steps described above 36 times for the test samples with the water proof level rating equal or higher than IPX3 and 1000 times for others.
d) Remove the moisture on the sample surface, then place the test sample under the standard condition for at least 20 minutes.
e) Run the accuracy and response time evaluation tests and specify the change before and after the condensation tests.

f) For all the steps described above, the sensor should be installed in a manufacturer-allowed orientation which is how the sensor will be installed in the real application.

### 2.5.3 Pressure test

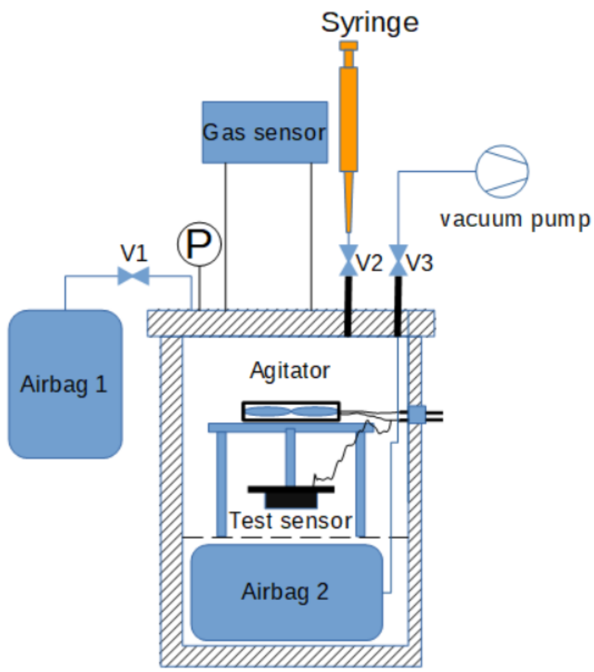



**Figure 2-6. Pressure Test Setup**

The objective of the pressure test is to simulate the sensor application in different elevations from sea level to 8700 ft. Therefore, the accuracy of the sensor is specified to be checked under the pressure of 101±1kPa and 73±1kPa. Figure 2-6 shows a schematic of the pressure test setup. A closed vessel with known inner volume is used as the test chamber for the pressure test, the vessel should be leak-tight at ±30kPag. Similar to the gas injection method, a syringe is used to adjust the test gas concentration in the test chamber. An airbag (Airbag 1) is connected to the test chamber to compensate for the pressure change when adding the test gas. Another inflatable airbag is placed in the test chamber and connected to a vacuum pump. This airbag should be isolated from the test chamber, which means no infiltration is allowed between this airbag and the test chamber. The procedures for the low pressure (73±1kPa) test are as following:

a) The sensor should warm up in clean air for at least 15 minutes before performing the test.
b) Place the sensor in the test chamber with the power on, inflate Airbag 2 with air and close valve V3, keep Airbag 1 flattened, seal the test chamber, and make sure no air infiltration occurs.
c) Calculate the volume of the test gas based on the known volume of the test chamber and the desired test gas concentration.
d) Fill in the necessary amount of test gas through valve V2 to achieve a concentration of 70% to 80% of the lower accuracy limitation and prefill the syringe with sufficient test gas. The

test concentration should be measured by a gas sensor with proven reliability at the test pressure.

e) Close valve V1 and V2, open valve V3, and use a vacuum pump to flatten Airbag 2 to reduce the pressure of the test chamber to the target pressure then close valve V3 to keep the pressure stable.
f) Open valve V2, add a small volume of test gas to increase the test gas concentration to the lower accuracy limitation value. The pressure change before and after adding the test gas should be less than 1kPa.
g) Close valve V2, keep the condition for enough time to let the sensor achieve a stabilized output.
h) Open valve V2, add the necessary amount of test gas to increase the test gas concentration to the higher accuracy limitation value. The pressure change before and after adding test gas should less than 1kPa.
i) Close valve V2, keep the condition for enough time to let the sensor achieve a stabilized output.

Follow the definitions of the lower and higher accuracy limitations as well as the criteria for the accuracy evaluation which were described in Section 2.2.

### 2.5.4 Air velocity test

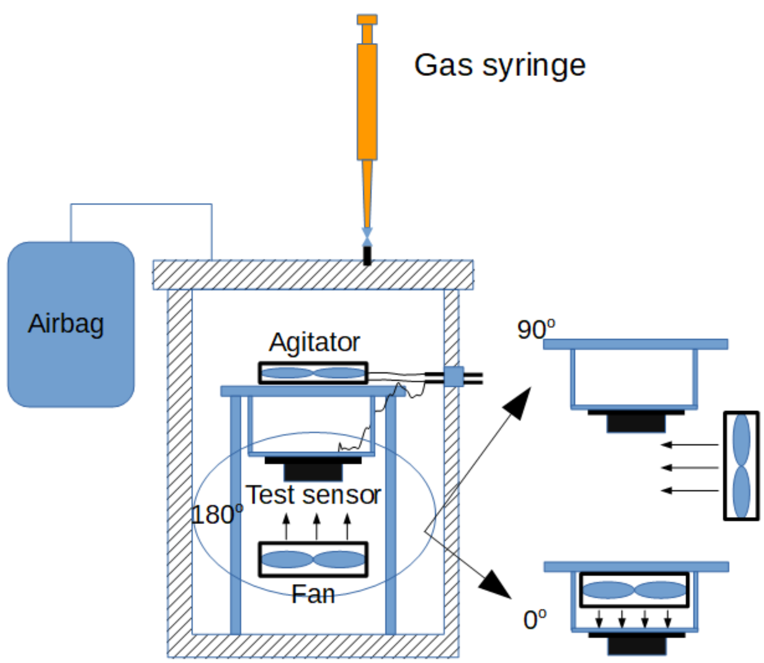



**Figure 2-7. Air Velocity Test Facility**

Figure 2-7 shows the schematic of the recommended setup of the air velocity test facility. A closed vessel with known inner volume is used as the test chamber to perform the air velocity tests. An adjustable fan is used to blow the test gas from different directions with different

velocities. An airbag is connected to the test chamber to compensate for the volume change after test gas injection and avoid pressure change. An agitator is recommended to improve the uniformity of the test gas concentration in the test chamber. Three different airflow directions and three air velocities are specified to be tested. Table 2-4 shows the 3 x 3 test matrix.
The accuracy of the test sample shall be evaluated under each condition. The test procedure is as follows:

a) The test chamber should be completely vented by clean air before a test.
b) The test sample should be kept in the test chamber with power on for at least 15 minutes.
c) Place the adjustable fan at the position for the airflow directions as shown by Figure 2-7.
d) Adjust the fan speed to get the desired air velocity as listed in Table 2-4.
e) Perform the accuracy evaluation test as described in Section 2.2, use the syringe to inject a certain amount of test gas to obtain the desired concentration.
f) The output of the test sample should be continually recorded.

**Table 2-4. Air Velocity Test Conditions (3x3)**

| Air direction | Air flow rate |
|---|---|
| 0±5° | non-forced |
| 90±5° | 3±0.3m/s |
| 180±5° | 6±0.6m/s |

### 2.5.5 Sensor orientation test

Sensor orientation tests should be performed using the Push-through Facility with an additional fixture to adjust the sensor orientation. Three different orientations including vertical (sensing window face down), horizontal (sensing window facing horizontal), and 45 degrees inclined are specified to be tested. Both the response time and the accuracy shall be evaluated at different orientations using the test procedures described in Section 2.2.

### 2.5.6 Power supply variation test

Power supply variation tests should be performed using the Push-through Facility with an adjustable power supply to power the test sample. Both the response time and the accuracy shall be evaluated at the rated input voltage of the test sample, 20%±2% above the rated input voltage, and 20%±2% below the rated input voltage. Follow the response time and accuracy test procedures which were described in Section 2.2.

## 2.6 Category D: Vibration and drop test

Before performing the vibration and drop tests, the test sample performance should be initially evaluated to obtain the response time and the accuracy as the baseline.
The vibration test follows the procedure described in Section 5.4.12 of IEC 60079-29-1 [10]. The required vibration parameters are listed in Table 2-5.

**Table 2-5. Vibration Test Parameters**

| Parameter | Requirements |
|---|---|
| Duration | For a period of at least 1 h for each direction |
| Direction | Three mutually perpendicular planes |
| Sweep rate | Change exponentially with time. The rate of change of frequency shall be one octave per minute |
| Frequency and intensity | • 10 Hz to 31.5 Hz, 0.5 mm displacement amplitude (1.0 mm peak-peak total excursion)<br>• 31.5 Hz to 100 Hz (150 Hz for remote sensors), 19.6 $m/s^2$ acceleration amplitude |

For the drop tests, the test procedure described in Section 5.4.13 of IEC 60079-29-1 [10] for the transportable type is recommended. The release height of the drop test depends on the mass of the sensor. For those with the mass less than 5kg, the drop height should be 0.3m and for others, the drop height is 0.2m. The test sample should be tested while not operating. Each test sample should be dropped three separate times with the normal transport direction. The test sample should be tested with the full in-field setup. If the interface board is supposed to be installed with the sensor in the detecting location, the interface board should be part of the test sample.
After performing the vibration or drop tests, the functionality of the sensor should be checked. The response time and the accuracy of the test sample are required to be evaluated again. The change in response time and accuracy shall be specified in the test report. Refer to Section 3.5 (Phase 3) for findings of Category D test examples.

## 2.7 Category E: Repeatability test

Per the requirements of JRA 4068T-2016 [6] and IEC 60079-29-1 [10], both short-term stability and long-term stability are specified to be evaluated by checking the repeatability of the sensor response to the test gas. The Push-through test facility is to be used for both the short term and the long-term stability tests. The repeatability of the response time of the test sample shall be evaluated as follows:

For short term repeatability, the test sample shall be exposed to six applications of the standard test gas (25%LFL R32) for 3 minutes followed by exposure to clean air for 7 minutes. The sensor response time shall be recorded at each exposure to the standard test gas.

For long term repeatability, the equipment shall be operated in clean air for a period of 64 ± 0 days. Every eighth day, the equipment shall be exposed to 100% LFL refrigerant for a 480 +10/-0 minute period. The accuracy and response time of the test sample shall be evaluated at the end of each subsequent day period.

Refer to Section 3.6.3 for additional recommendations based on the findings of Category E test examples in Phase 3.

Note: 100%LFL refrigerant is selected as the test gas for the long term repeatability test and is based on the following understanding: a refrigerant sensor is not reasonably expected to be repeatedly exposed to 100% refrigerant during the equipment lifetime (8 times for a 64 day test). This would represent a refrigerating system that lost its entire refrigerant charge 8 times due to some component failure, and after each failure the system would have to be repaired and re-charged. If that happened so many times it seems reasonable that the refrigerant sensor would be tested or diagnosed and likely replaced (i.e. not expected or required to survive). The shorter period exposure to 100% refrigerant is covered by the Category A test for fluid resistance, as it simulates a one-time event for a refrigerating system to rapidly lose the entire system charge and expose the sensor to nearly pure refrigerant for the duration of the release event and some period after the release stops.

# Phase 3

## 3.1 Introduction

As the shift towards low-GWP working fluids becomes more prevalent, the HVAC&R industry is opening up to the usage of flammable refrigerants. Safety codes require sensors to be installed in the refrigeration system when using these flammable refrigerants to mitigate the potential fire hazards. Because the sensors are required for safety purposes, reliability becomes an essential characteristic, requiring careful assessment.

Therefore, the test methods for the sensor reliability and robustness assessment have been developed and documented in Phase 2 of this project. As the continuation of Phase 2, the harshness tests have been conducted during this phase. The main objective is to verify, improve, and demonstrate the test methods developed in Phase 2. The test results also provided useful information regarding the future suitability of commercially available and developmental sensor technologies to meet the safety standard requirements.

Following the structure defined in Phase 2, five categories of harshness tests have been investigated. They are:

- Category A: Fluid resistance and poisoning test
- Category B: Extreme storage condition test
- Category C: Operation condition test
- Category D: Vibration and drop test
- Category E: Repeatability test

Six sensors from different manufacturers have been obtained, which covered five different major sensing principles. Sensors were chosen based on availability prior to the start of testing, and some may be further developed by the manufacturers. A letter code of A through F has been assigned to the sensor samples, as shown in Table 3-1. It needs to be noted, the letter codes used in this phase are different from Phase 1. Figure 3-1 shows the picture of the sensor samples used in this phase.

Since the main objective of this phase is to demonstrate the test methods and due to the limited schedule and resources, similar and middle conditions in the test matrix developed in Phase 2 were not demonstration tested as part of Phase 3. Table 3-2 shows the reduced test matrix for Phase 3 to be conducted.

**Figure 3-1. Picture of the Six Sensors for Experimental Assessment**

**Table 3-1. Sensors Participating in the Experimental Assessment**

| Sensor Letter Code[i] | Sensor Principle | Function | |
|---|---|---|---|
| | | Measuring | Indicating |
| A | MMM[ii] | ● | |
| B | TC[iii] | ● | |
| C | NDIR[iv] | ● | ● |
| D | MOS[v] | | ● |
| E | NDIR[iv] | ● | ● |
| F | SS[vi] | ● | ● |

[i] Sequence of sensor letter code in Phase 3 is different from Phase 1.
[ii] MMM: Micro Machined Membrane
[iii] TC: Thermal Conductivity
[iv] NDIR: Nondispersive Infrared
[v] MOS: Metal-Oxide Semiconductor
[vi] SS: Speed of sound

**Table 3-2. Test Matrix**

| Category | Item | Condition |
|---|---|---|
| A | Carbon dioxide | 5000ppmv |
| | Carbon monoxide | 35ppmv |
| | D4 | 100ppmv |
| | Ethanol | 200ppmv |
| | Refrigerant (R32) | 100% vol |
| | POE oil | 10±5% ml/min 30min |
| B | Storage test | |
| C | Temperature | -20°C RH30-70% |
| | | 55°C RH30-70% |
| | | 85°C survival test |
| | Humidity | 40°C 20±5%RH |
| | | Condensation |
| | Pressure | 73kPa |
| | Air velocity | 0 °, 3±0.3m/s |
| | | 90 °, 3±0.3m/s |
| | | 180 °, 3±0.3m/s |
| | | 0 °, 6±0.6m/s |
| | | 90 ° , 6±0.6m/s |
| | | 180 °, 6±0.6m/s |
| | Sensor orientation | Horizontal |
| | | Vertical |
| | | 45° inclined |
| D | Drop test | |
| E | Short term stability | |

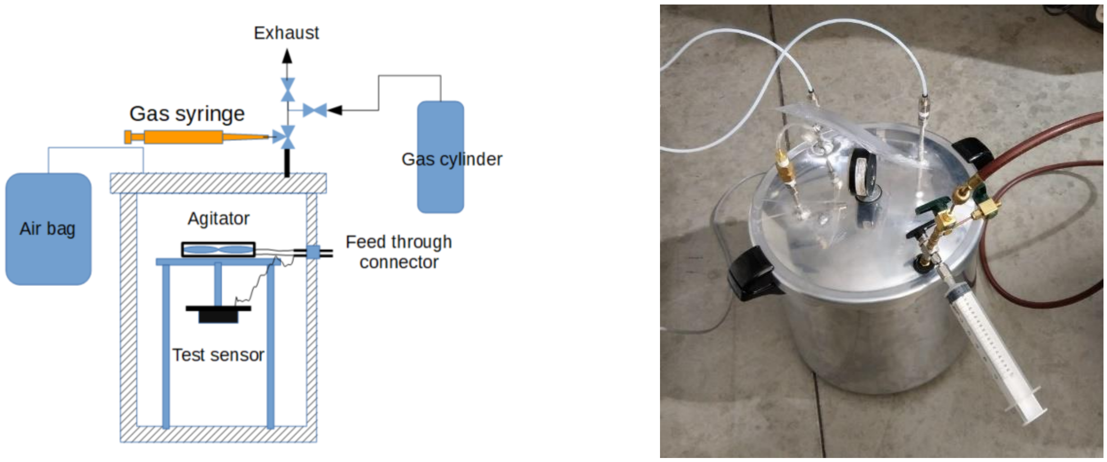
For the assessment of the sensor reliability, two approaches have been adopted in this project. The first approach is to compare the sensor performance before and after exposure to the harshnesses. Here, sensor performance is strictly analyzed by sensor response time and accuracy. The method for evaluating the sensor performance has been described in Phase 2. The second approach for the assessment is by checking the sensor performance when exposed to the harshnesses. The criteria of assessment used in the second approach are determined by the type of stress. This assessment will help to uncover the effect of stress. The specific criteria used are discussed in further sections.

## 3.2 Category A: Fluid resistance and poisoning test

### 3.2.1 Test methods

The recommended test procedure for the fluid resistance and poisoning test was described in Section 2.3 (Phase 2).

For the gas phase fluids, like CO and $CO_2$, the "gas injection" method was used to perform the harshness tests. Figure 3-2 shows the schematic and picture of the "gas injection" test setup. The test gas concentration was determined by the ratio of injected fluid volume to the test chamber volume. To have better accuracy of test concentration control, a calibration process was conducted before the test.




(a) Schematic (b) Picture

**Figure 3-2. Gas Injection Test Facility**

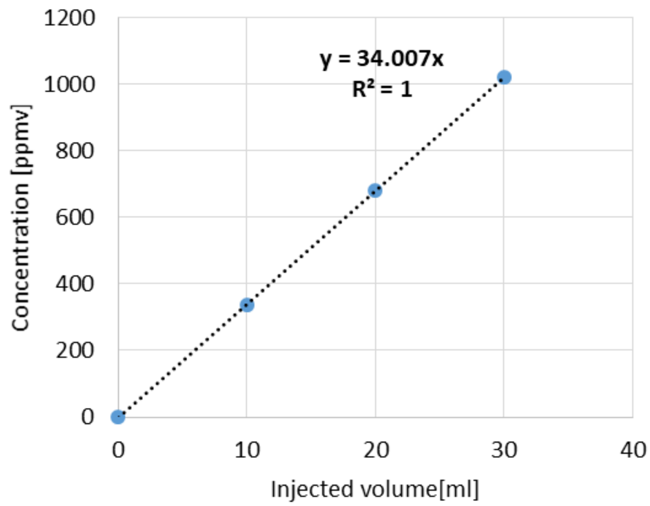
**Figure 3-3. Photoacoustic Sensor Used for Calibration**

As shown in Figure 3-3, a high-accuracy photoacoustic sensor was used to measure the test concentration in the test chamber after gas injection. The calibration was done under room temperature (20±5°C), consisting of two steps: first, as shown by Figure 3-4 (a), a correlation between the injection gas volume and the test gas concentration was obtained by varying the injection gas volume from 10 to 30ml and measuring the test gas concentrations correspondingly; second, the gas injection was performed with different injection volumes 24 times and compared with the calculated concentration by using the correlation obtained during the first step with the measured values. Figure 3-4 (b1) and (b2) show the calibration result. The deviation between the calculated concentration and the measured value was within ±5%. Based on the result of the calibration, Equation (7) was used to determine the test gas concentration for this category.

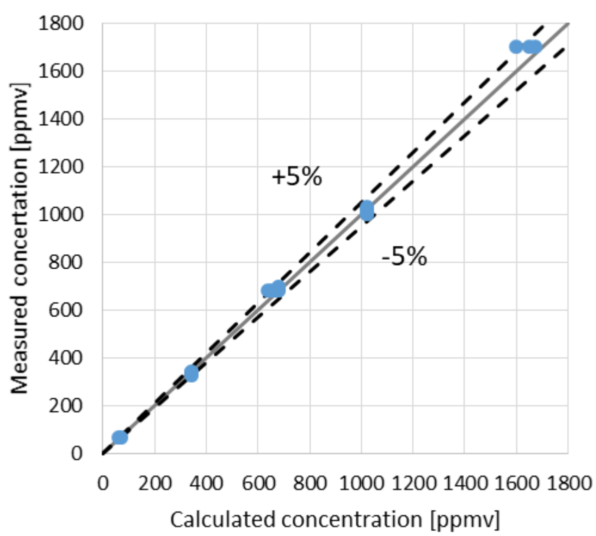
$$Conc_{test} = 34.007 V_{in,gas} \quad (7)$$

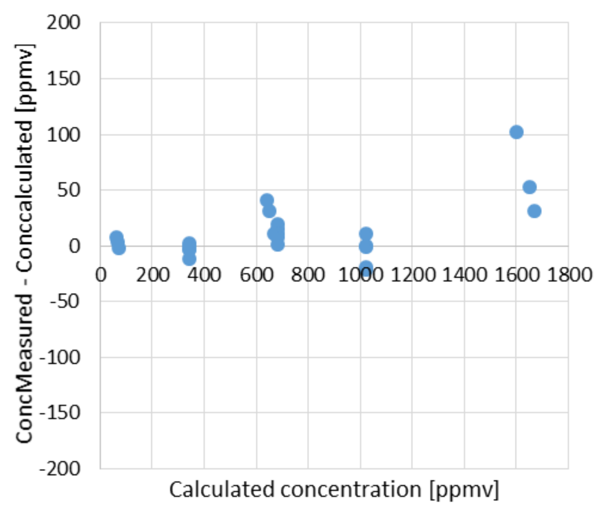
Where: $Conc_{test}$ is the test gas concentration, ppmv

$V_{in,gas}$ is the gas injection volume, ml




(a) Step 1




(b1) Step 2

(b2) Step 2

**Figure 3-4. Gas Injection Calibration**

For volatile fluids, like octamethylcyclotetrasiloxane (D4) and ethanol, the test gas concentration was determined by the volume fraction of the gas mixture after vaporization, while the fluids were initially injected in the liquid phase. To determine the test gas concentration the correlation obtained through the calibration described in Equation (7) was modified by using the equivalent gas injection volume calculated by Equation (8).

$$V_{in,gas} = 22400 \frac{V_{in,liquid} \times Rho_{liquid}}{M} \tag{8}$$

Where: $V_{in,gas}$ is the equivalent gas injection volume, ml

$V_{in,liquid}$ is the liquid injection volume, ml

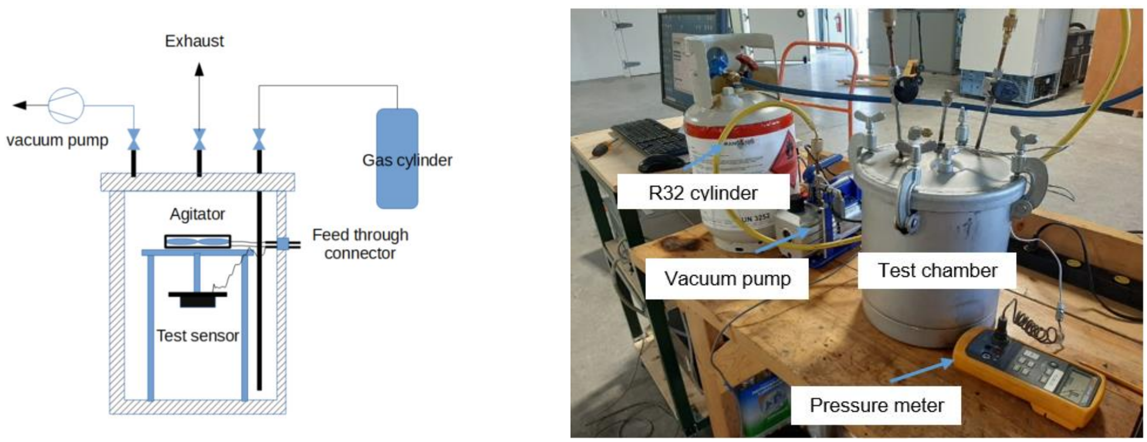
$Rho_{liquid}$ is the liquid density of the fluid, g/ml

$M$ is the molar mass of the injected fluid, g/mol

**The coefficient 22400 is the standard gas molar volume with the unit of ml/mol*

<u>Because Phase 2 did not discuss the calibration procedure and how to modify the "gas injection" method for volatile fluids, it is recommended that they should be annotated in the test protocols for Category A.</u>

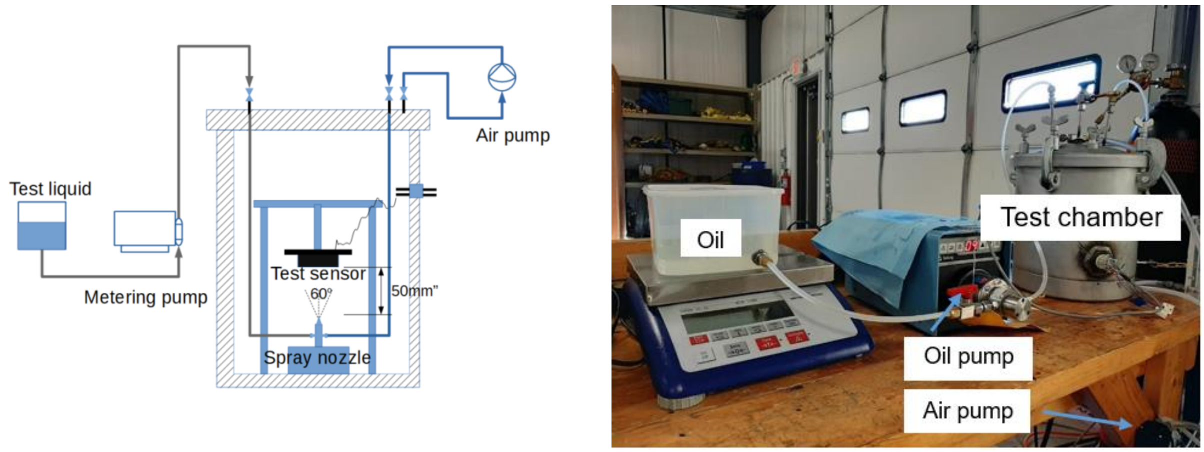
For the 100% R32 test, the modified gas injection facility as recommended in Phase 2 was used. Figure 3-5 shows the schematic and the picture of the test facility. An absolute pressure meter was added to the test setup to have better pressure control during the test. As recommended by Section 2.3.2 (Phase 2), the pressure in the test chamber should be slightly higher than the atmospheric pressure before opening the test chamber for the test sensor installation.




(a) Schematic (b) Picture

**Figure 3-5. Modified Gas Injection Test Facility for 100% R32 Test**

For nonvolatile fluids, like oil, the liquid spray test method is recommended in the Phase 2 section. Figure 3-6 shows the schematic and picture of the test facility. Following the instructions in the Phase 2 section, test sensors were installed 51 mm above the spray nozzle tip with the normal operation orientation as shown in Figure 3-7.




(a) Schematic (b) Picture

**Figure 3-6. Liquid Spray Test Facility for Oil Test**

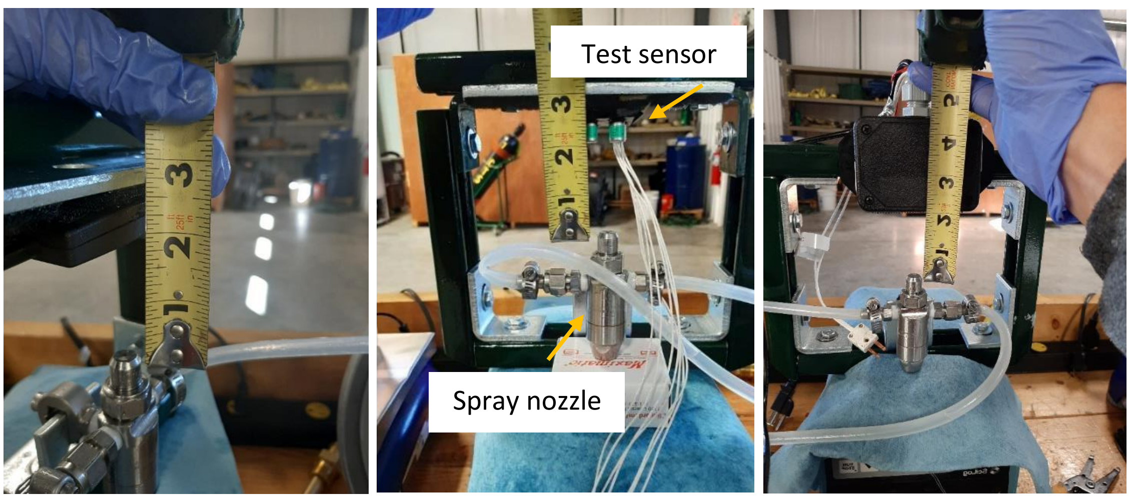



**Figure 3-7. Spray Nozzle and Sensor Installation Position**

### 3.2.2 Test results and observations

The criteria of reliability assessment for Category A tests are:

- No alarm or initiation of the output signal which is designed to activate the alarm should be observed for all of the test fluids other than 2000ppm and 100% refrigerant;
- The change in response time and accuracy of the test sample caused by each test fluid should be specified in the test report.

Therefore, the sensor output signals were recorded when exposed to the test fluids. The response time and accuracy of the tested sensors were checked after exposure to the fluids and compared with the initial performance data, which was done before exposure to the fluids.

#### 3.2.2.1 Effect of CO, $CO_2$, D4, and Ethanol

During the 2 hours of exposure to CO, $CO_2$, D4, and ethanol, none of the sensors were triggered. However, the presence of $CO_2$ affected the concentration outputs of Sensor B and Sensor F. As shown in Figure 3-8, the output of Sensor B and F increased by 3%LFL and 2%LFL respectively immediately after $CO_2$ injection.

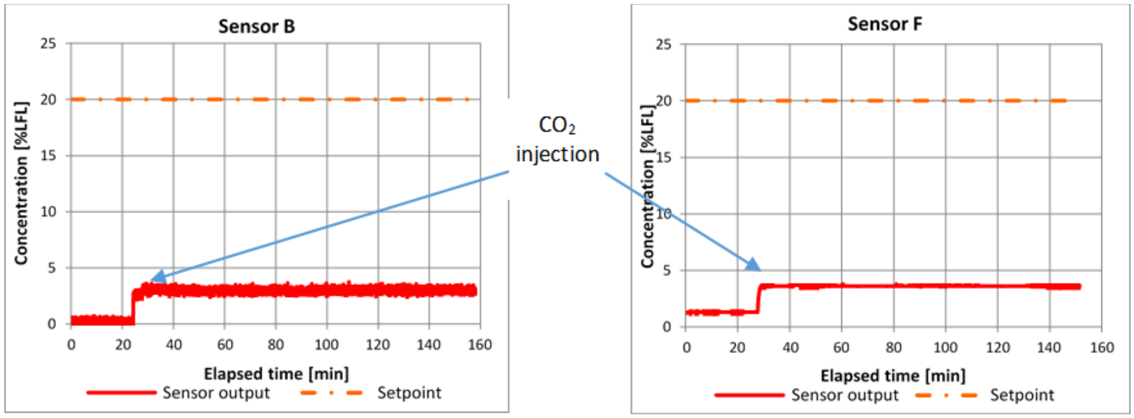



**Figure 3-8. Two-hour Output Data of Sensor B and F to 5000ppm $CO_2$**

One of the possible explanations is Sensor B uses thermal conductivity as its sensing principle. The thermal conductivity of pure $CO_2$ at standard temperature and pressure is very close to that of R32. The thermal conductivity of 3%LFL R32 and 5000 ppm $CO_2$ in dry air were calculated and bolded in Table 3-3. It can be seen that 3%LFL of R32 has almost the same thermal conductivity as 5000ppmv $CO_2$ causing the sensor measurement to increase by 3%LFL. A similar explanation can also be used for Sensor F, which uses the speed of sound as the sensing principle. The sound speed of $CO_2$, R32, dry air, and their mixtures are also listed in Table 3-3.

**Table 3-3. Thermal Conductivity and Sound Speed Comparison for R32 and $CO_2$**

| Property [1,2] | Dry Air | R32 [100%] | $CO_2$ [100%] | R32+dry air[4] [2%LFL] | R32+dry air[4] [3%LFL] | $CO_2$+ dry air[4] [5000ppmv] |
|---|---|---|---|---|---|---|
| TC[2]. [$10^{-3}$W/mK] | 25.88 | 13.96 | 16.22 | 25.84 | **25.83** | **25.83** |
| SS[3]. [m/s] | 343.3 | 239.3 | 266.6 | **343.0** | 342.9 | **343.0** |

1. Properties of pure fluid were determined at the condition of 20°C, 101.3kPa by using EES V10.7 (Engineering Equation Solver)
2. TC. Thermal Conductivity
3. SS. Sound Speed
4. The concentration of the mixtures are volume-based and use dry air as the background gas

After 2-hour exposure to CO, $CO_2$, D4, and ethanol, the tested sensor was put in clean air and powered up for more than 15min to recover. The performance of the sensor including response time and accuracy was checked again afterward. Compared with the initial performance data for all six tested sensors, no obvious difference in response time or accuracy was observed.

Depending on the application, the miscellaneous gases may exist in the environment where the sensors are installed. Considering two of the tested sensors have shown a noticeable output increase when exposed to 5000ppmv $CO_2$, the sensors' response time or accuracy may be affected when used in an environment with a concentration of $CO_2$ in the background. Sensors tested in this project were only exposed to one test substance at any given time, i.e. the sensors were not simultaneously exposed to test gas (R32) and a background gas (e.g. $CO_2$). It is recommended to further improve the test method for the fluid resistance test. The sensor response time and accuracy need to be tested when sensors are exposed to a certain type of fluid.

#### 3.2.2.2 Effect of 100% R32

During the 2 hours of exposure to the 100% R32 test, the sensors' output and alarm signal were continually recorded. Figure 3-9 shows the output data of Sensor A, B, C, E, and F. Sensor D, which is the MOS type, is designed to be irreversibly malfunctional after exposure to a concentration higher than the setpoint for more than 7min. Therefore, Sensor D was not used for the 2 hour 100% R32 test.

For all five tested sensors, the output signals reached their higher limit of the working concentration range. For Sensors C, E, and F, the alarm signals were activated and stayed triggered for the entire period. After the post-exposure performance check, all five sensors showed no poisoning, malfunction, or performance degradation.

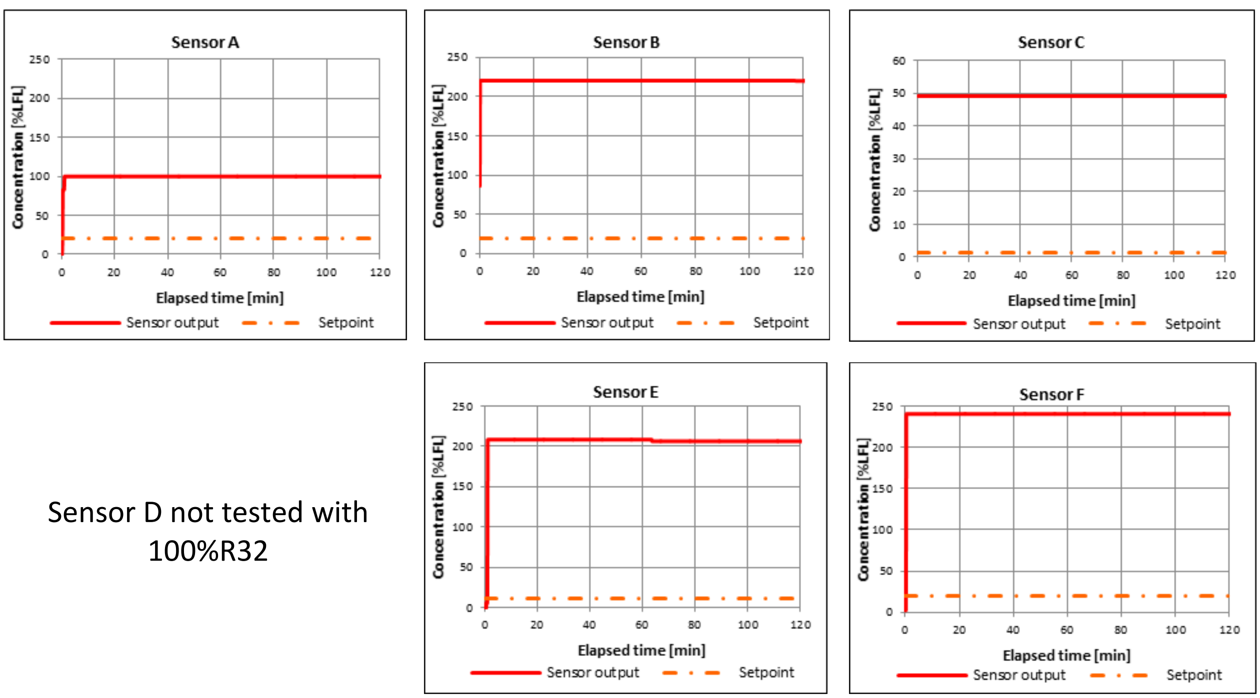



**Figure 3-9. Two-hour Output Data of Sensor A, B, C, E, and F Resistance to 100% R32 Test**

#### 3.2.2.3 Effect of oil spray

When catastrophic leakage happens, depending on where the leak point is, a large amount of the lubricant could be sprayed out by the refrigerant and make contact with the sensor installed nearby. Therefore, the oil spray test was initially designed with a fairly high oil flow rate (10ml/min) and long spray duration (30min) to investigate the effect of the oil during and after a severe leakage. As recommended by the Phase 2 section, to ensure finely dispersed liquid droplets, an entrainment nozzle with air as the driving gas is used in this test. The sensor outputs have been recorded during the oil spray period and the sensor performances were evaluated after oil spray.

Figure 3-10 shows the sensor reading during the 30min of oil spray. Sensor A showed no response; Sensor B's output signal jumped up to about 10%LFL initially and stayed at around 0.6%LFL for the whole spray period; Sensor C also showed a relatively larger output signal at the beginning and then slowly reduced to about 0.4%LFL; for Sensor D, which is the indication type, no alarm signal has been initiated during the spray period; Sensor E's reading stayed at zero for the first 4 minutes before increasing to 8%LFL; Sensor F showed occasionally enormous (more than 200%LFL) readings.

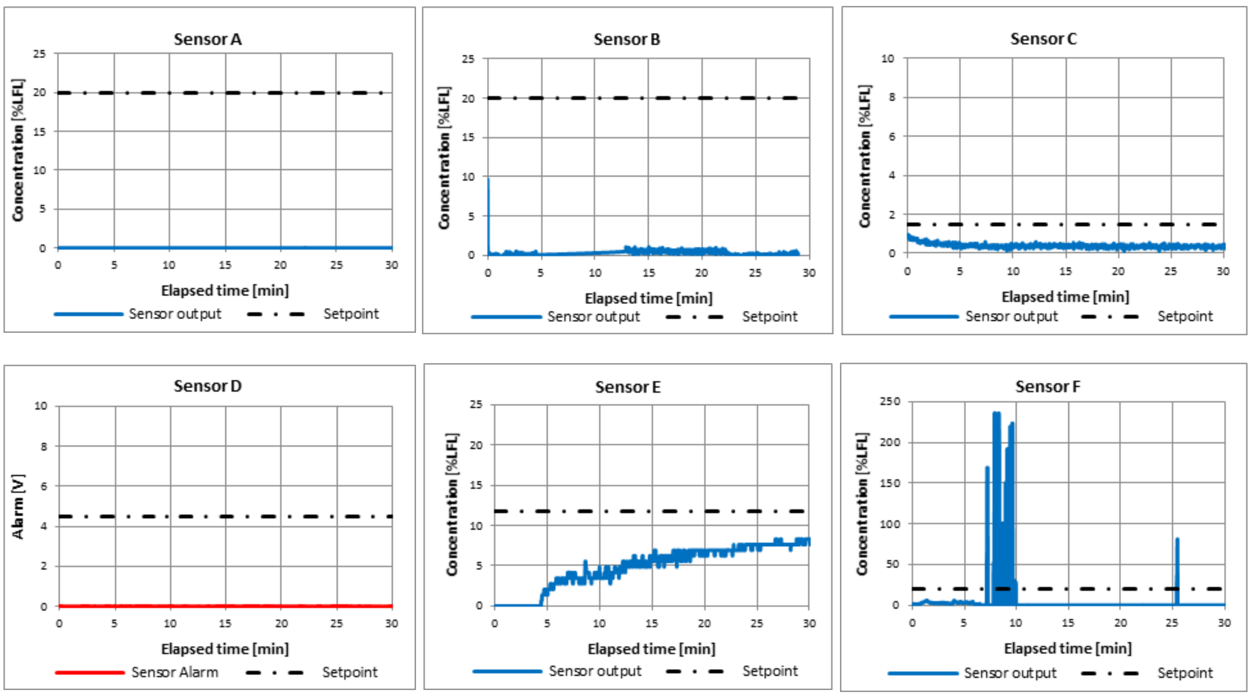



**Figure 3-10. Sensor Reading during 30min Oil Spray Test**

After the 30-minute oil spray test, sensor response time and accuracy tests were performed again. Figure 3-11 compares the sensor response time test results before and after the oil spray. As shown by the blue curves in the charts, after oil spray, Sensors A, C, and F did not respond to the test gas with 25%LFL of R32 at all. Sensors B, C, E responded significantly slower and did not reach their setpoints in 60 seconds.

Based on the test results, it is clear that after a severe leakage and when the sensor potentially made contact with the lubricant, a sensor performance check or replacement is needed. In reality, the chance of having such a catastrophic leakage is small. Therefore, the currently used oil spray test method seems to be too harsh to cover real-world leak scenarios. Additionally, as uncovered by the test results, sensor response can fully degrade to the test gas after contact with oil. It is possible sensors may not be able to catch a leakage when oil and refrigerant are present simultaneously. Therefore, changes to further improve the oil spray test method should include:

(i) reduction of the oil flow rate and the duration of spray to be more realistic, and (ii) spray oil with refrigerant instead of air.

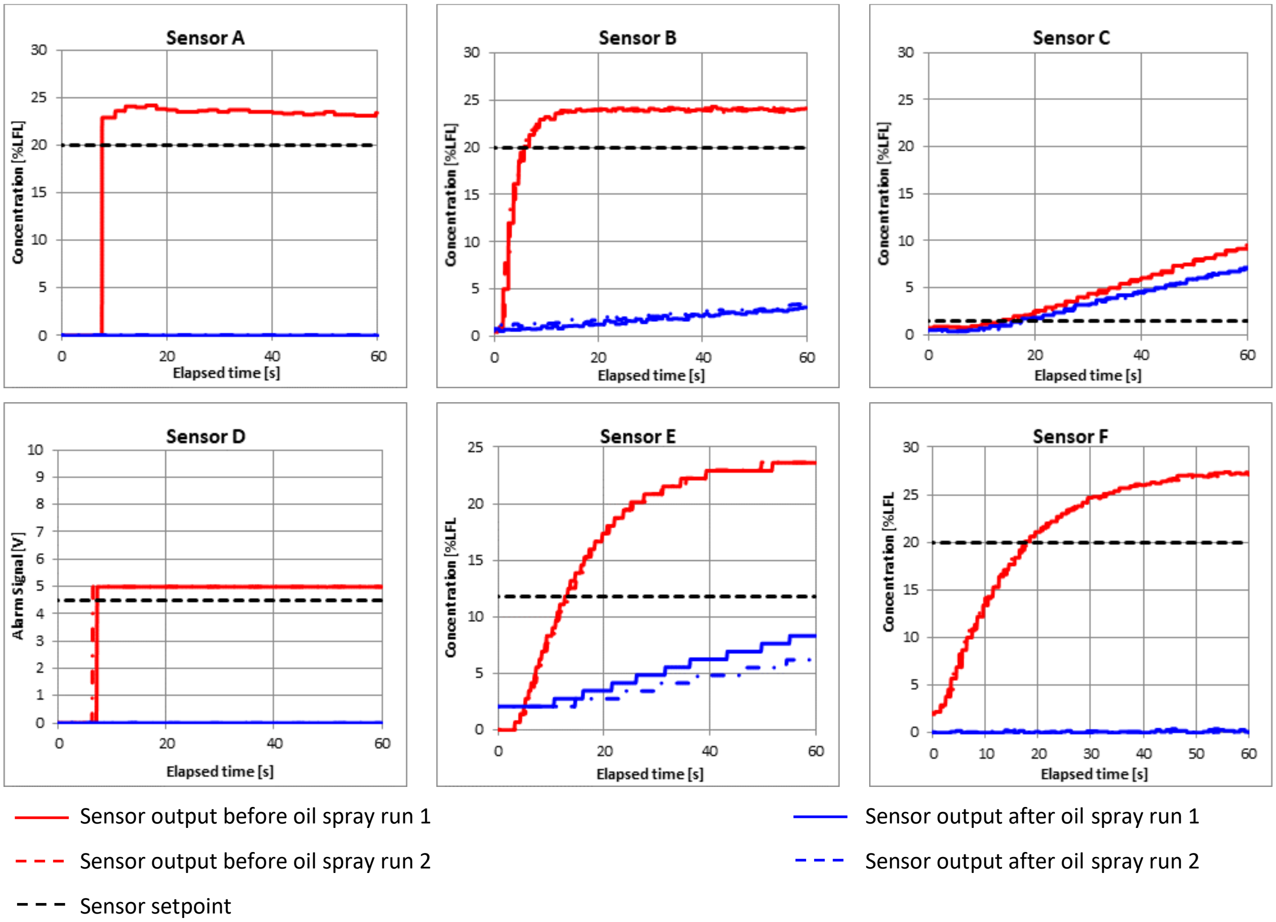



**Figure 3-11. Sensor Response Time Comparison Before and After Oil Spray**

An improved oil spray test method has been developed to simulate more realistic leakage of a conventional HVAC unit. The recommended conditions for the oil spray test are as following:

- Driving fluid: Refrigerant
- Oil type: Miscible with refrigerant
- OCR (Oil Circulation Ratio): 1.5%m
- Leak rate: 2.3 kg ± 0.2 kg in 4 minutes
- Two different spray heights: 0.3 m and 0.6 m

Figure 3-12 shows the schematic of the revised oil spray test setup. In the leak test container, test sensors are placed on an elevated mesh-based stage surrounded by a cylindrical wall. The design reduces circulating flows which may reach again the surface of the test sensor. Sensor windows are (i) facing upward, (ii) elevated to the same height, and (iii) 76 mm apart from each other. The spray height is 0.3 m or 0.6 m above sensor surfaces. The spray fluid is supplied by the refrigerant/oil mixture tank in a temperature controlled box. The method used for preparing the mixture is as follows:

1. The refrigerant tank has been cleaned, evacuated, and initially scaled for the weight;
2. Add a certain amount of oil to the evacuated tank;
3. Vacuum the tank again after adding oil (no air in the tank);
4. Scale the weight of the tank again after adding oil to determine the mass of oil added to the tank;
5. Calculate the required mass of refrigerant based on the desired oil concentration;
6. Add refrigerant to the tank;
7. Scale the weight of the tank to determine the added mass of refrigerant and calculate the oil concentration;
8. May need to repeat step 6 and 7 several times until reaching the desired oil concentration;
9. After charging both fluids sufficiently shake the tank.

The mixture is considered homogeneous in the liquid phase because the oil is miscible with the refrigerant in this test.

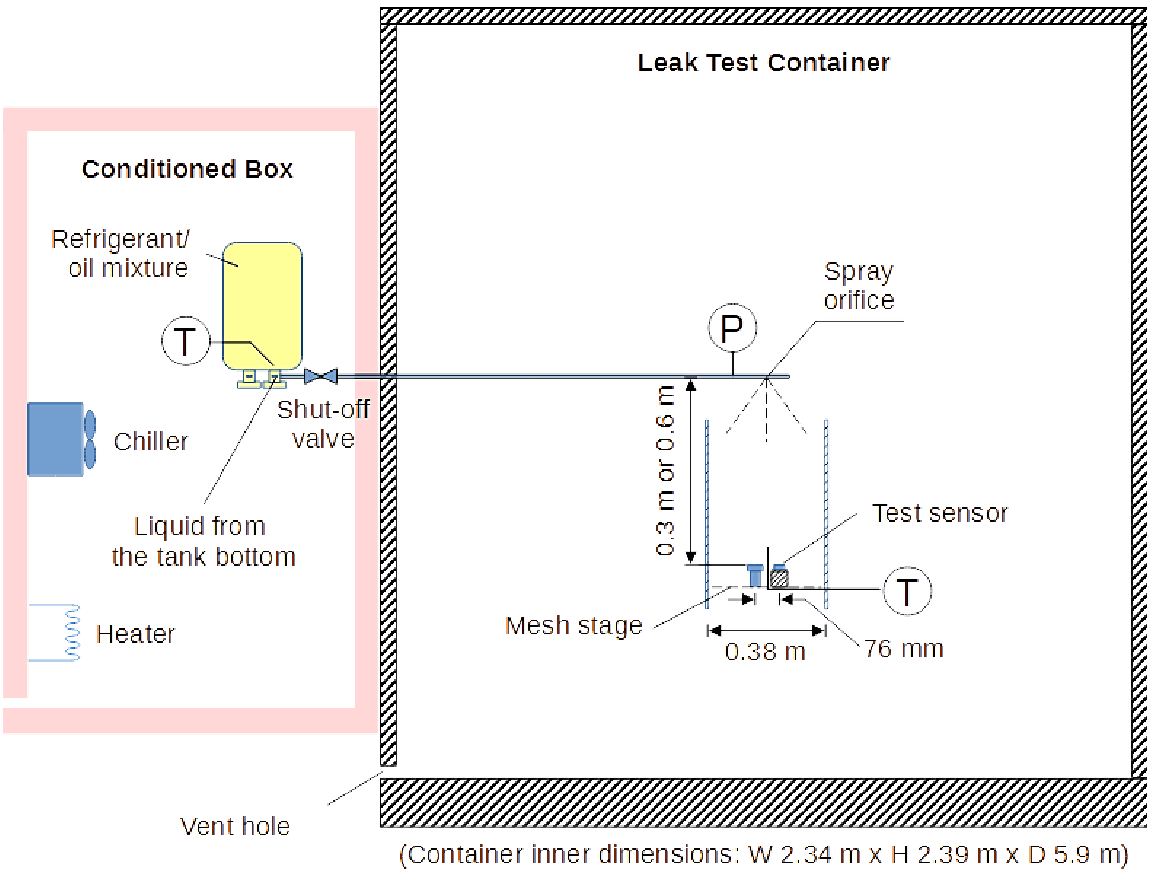



**Figure 3-12. Test Conditions of the Improved Oil Spray Test**

The test method has been demonstrated in this phase, as shown in Figure 3-13. The specified test conditions were achieved by the following setup:

- Driving fluid: R32
- Oil type: CPI NXG 5020 oil, miscible with R32 at the test temperature
- Spray nozzle: A close-ended tube with an orifice made by a 0.78 mm nominal size drill bit
- The pressure upstream of the orifice: 1450 ± 100 kPa (or tank temperature of 20-22°C)
- Spray duration: 220s (between open/close of the shut-off valve) + 20s (pressure ramp down)

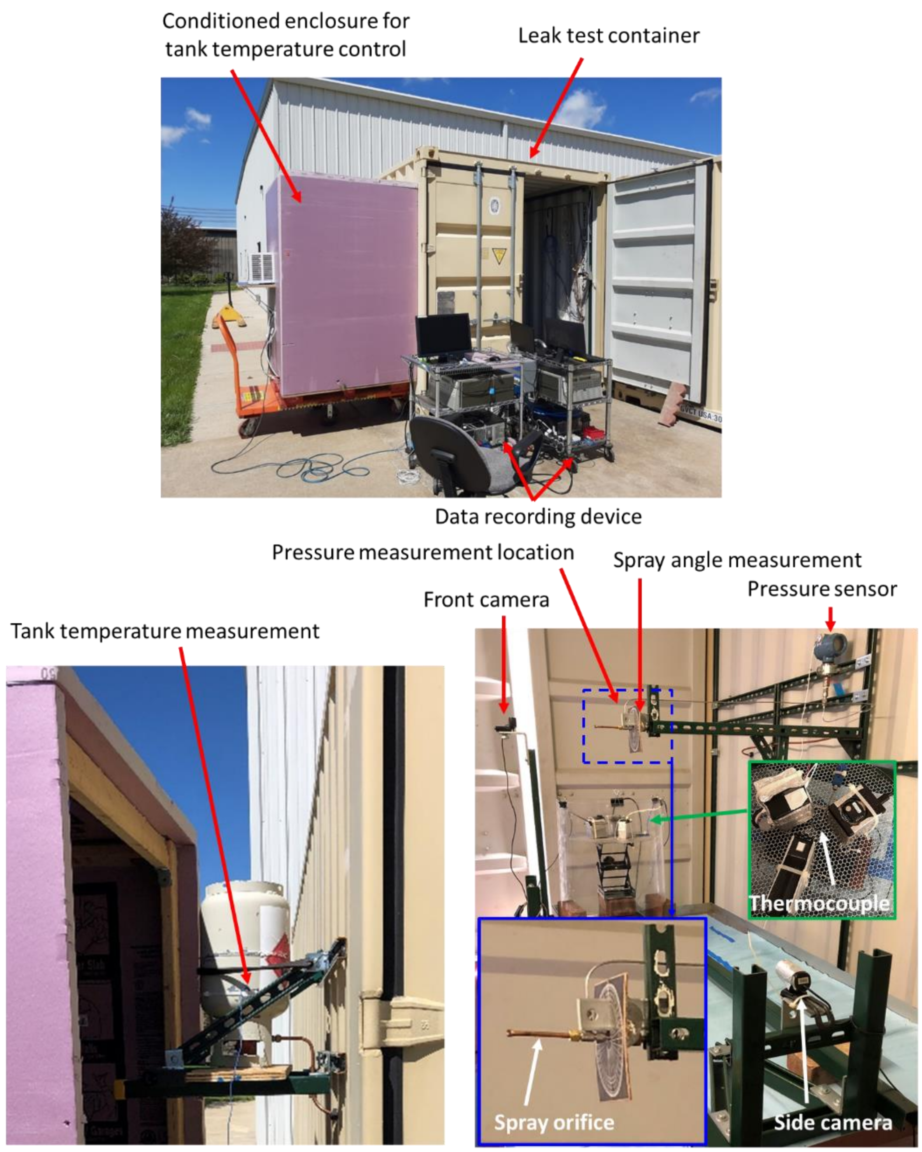



**Figure 3-13. Facility of the Revised Oil Spray Test**

Figure 3-14 shows the pictures of the spray during the test. The spray angle was 75°, which fully and uniformly covered the sensor stage. It can be clearly seen that after 4 minutes of spray the test chamber is filled with oil mist. After the oil spray test, all sensor surfaces have oil coverage in the form of film and/or droplet, as shown in Figure 3-15.

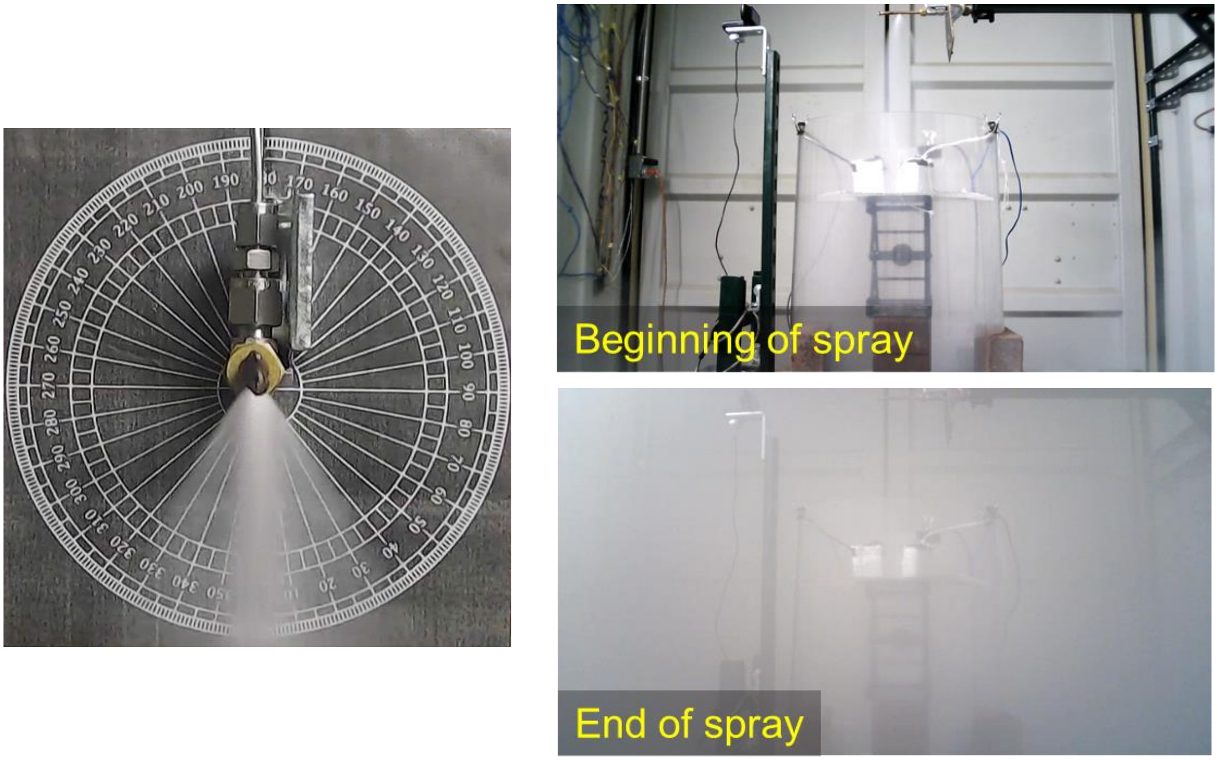



**Figure 3-14. Test Visualization during the Spray Test**

Data during oil spray tests are presented in Figure 3-16 (Sensors A-C) and Figure 3-17 (Sensors D-F). Results showed that the change of spray pressure in the 4 minutes spray period was within 200 kPa; the temperature at sensor location dropped to approximately 0°C with 0.6 m spray height and approximately -20°C with 0.3 m spray height. This indicates that the test sensor is exposed to much more refrigerant and oil at a shorter spray distance. From the sensor output curves, it was also observed that all sensors were able to trigger the alarm in both 0.6 m and 0.3 m spray tests. The measured concentration of Sensor B reached more than 100%LFL, higher than the other sensors in the 0.3 m spray tests. Sensor E showed unsteady readings. Sensor F showed signal spikes.


**Figure 3-15. Post-spray Sensor Appearance**

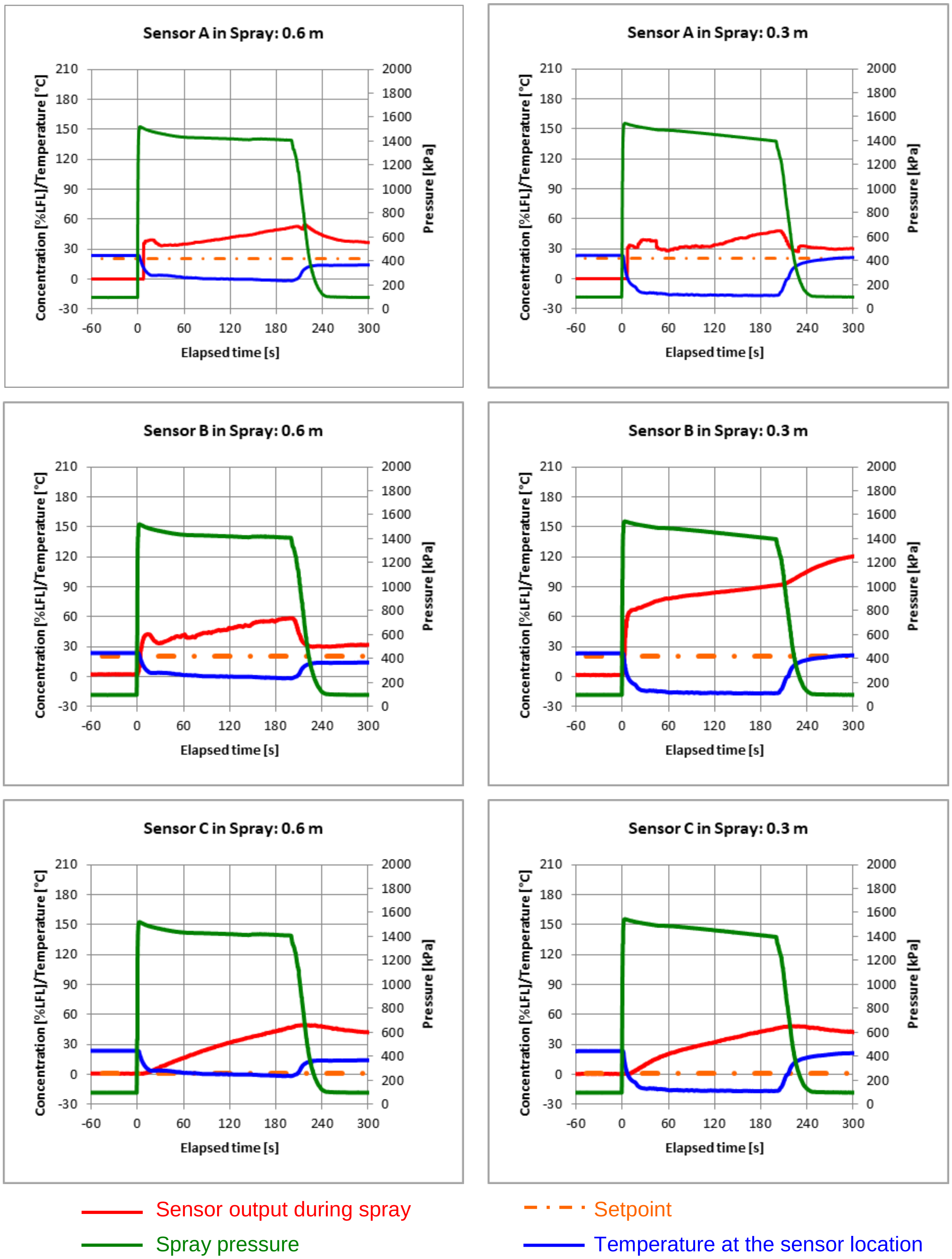



**Figure 3-16. Sensor Output in the Oil Spray Test: Sensor A, Sensor B, Sensor C**

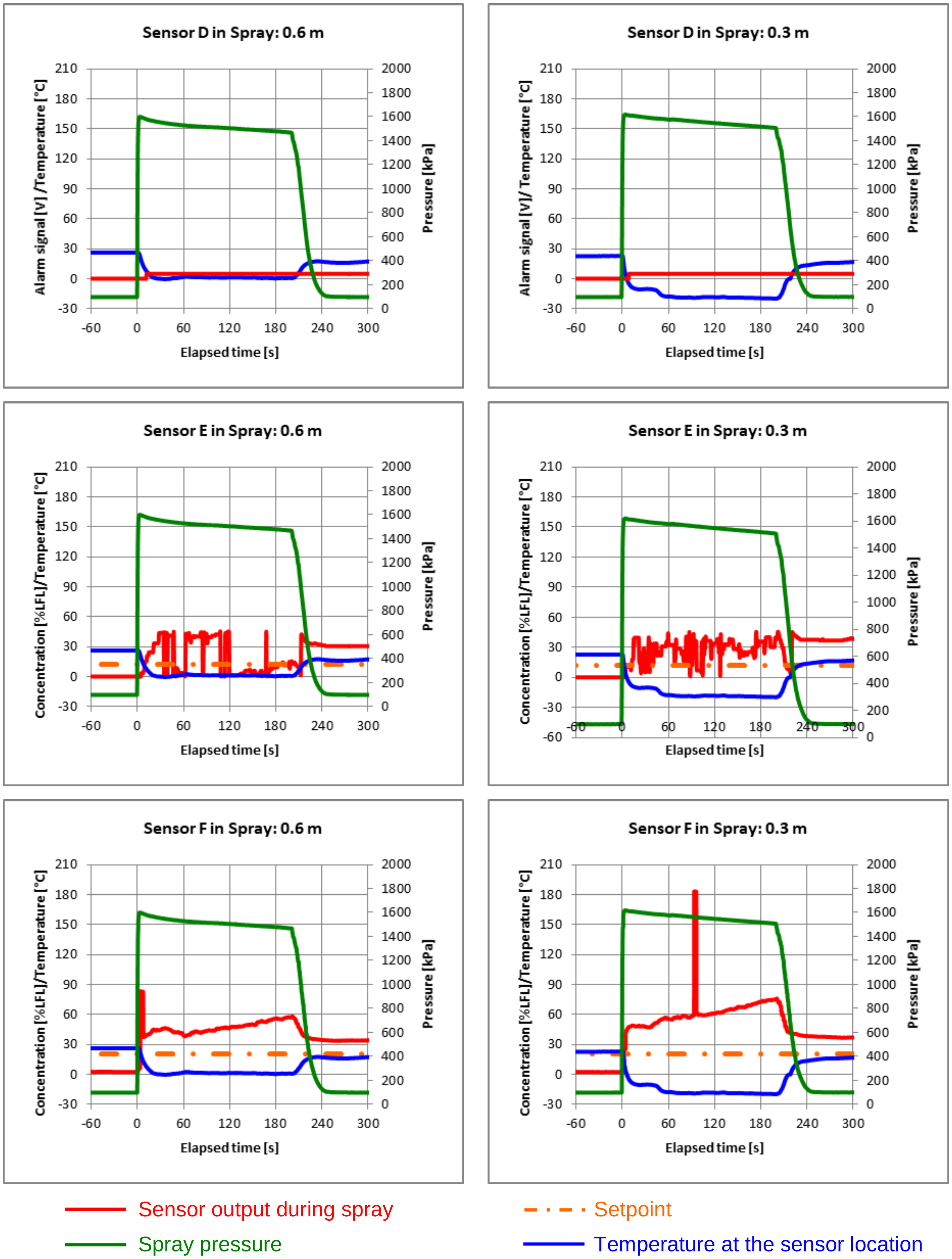



**Figure 3-17. Sensor Output in the Oil Spray Test: Sensor D, Sensor E, Sensor F**

Test data comparing sensor response before and after the oil spray are presented in Figure 3-18 (Sensors A-C), Figure 3-19 (Sensors D-F), and summarized in Table 3-4. Test data comparing sensor accuracy before and after the oil spray are presented in Figure 3-20 (Sensors A-C), Figure 3-21 (Sensors D-F), and summarized in Table 3-5. Observed outcomes after the oil spray are as follows:

- Sensor A showed much slower responses after the spray tests.
- Sensor B showed no obvious effect after the 0.6 m spray but a much slower response after the 0.3 m spray.
- Sensor C showed 2-3s slower responses after both 0.3 m and 0.6 m spray tests.
- Sensor D showed malfunction signal, possibly due to more than 7 minutes exposure to the test gas with higher concentration than the sensor setpoint is designed for.
- Sensor E showed 2s faster response after the 0.6 m spray and 2-3s slower response after the 0.3 m spray.
- Sensor F showed slightly slower response after the 0.6 m spray, and slightly faster response after the 0.3 m spray.

**Table 3-4. Sensor Response before/after the Spray Test**

<table>
<tr><th rowspan="3">Sensor[i]</th><th colspan="3">0.6 m</th><th colspan="2">0.3 m</th></tr>
<tr><th>Before Spray</th><th colspan="2">After Spray</th><th>Before Spray</th><th>After Spray</th></tr>
<tr><td>Response time [s]</td><td colspan="2">Response time [s]</td><td>Response time [s]</td><td>Response time [s]</td></tr>
<tr><td>A</td><td>7.6</td><td colspan="2">49.4</td><td>8.6</td><td>-</td></tr>
<tr><td>B</td><td>5.9</td><td colspan="2">5.7</td><td>4.7</td><td>-</td></tr>
<tr><td>C</td><td>12.5</td><td colspan="2">14.2</td><td>15.2</td><td>18.5</td></tr>
<tr><td>D</td><td>9.0</td><td colspan="2">-</td><td>8.9</td><td>-</td></tr>
<tr><td>E</td><td>10.5</td><td>8.3</td><td>8.6[ii]</td><td>9.4</td><td>12.0</td></tr>
<tr><td>F</td><td>14.1</td><td colspan="2">15.3</td><td>14.8</td><td>13.8</td></tr>
</table>

[i] Sequence of sensor letter code in Phase 3 is different from Phase 1.
[ii] Repeated test for confirmation

**Table 3-5. Sensor Accuracy before/after the Spray Test**

| Sensor [i] | 0.6 m | | | | 0.3 m | | | |
|---|---|---|---|---|---|---|---|---|
| | Before Spray | | After Spray | | Before Spray | | After Spray | |
| | Alarm at l.a[ii] | Alarm at h.a[ii] | Alarm at l.a[ii] | Alarm at h.a[ii] | Alarm at l.a[ii] | Alarm at h.a[ii] | Alarm at l.a[ii] | Alarm at h.a[ii] |
| A | N | Y | N | Y | N | Y | N | N |
| B | N | Y | N | Y | N | Y | N | N |
| C | N | Y | N | Y | N | Y | N | Y |
| D | N | Y | M[iii] | | N | Y | M[iii] | |
| E | N | Y | N | Y | N | Y | N | Y |
| F | N | Y | N | Y | N | Y | N | Y |

[i] Sequence of sensor letter code in Phase 3 is different from Phase 1.
[ii] l.a = low %LFL accuracy limit; h.a = high %LFL accuracy limit
[iii] M = malfunction signal

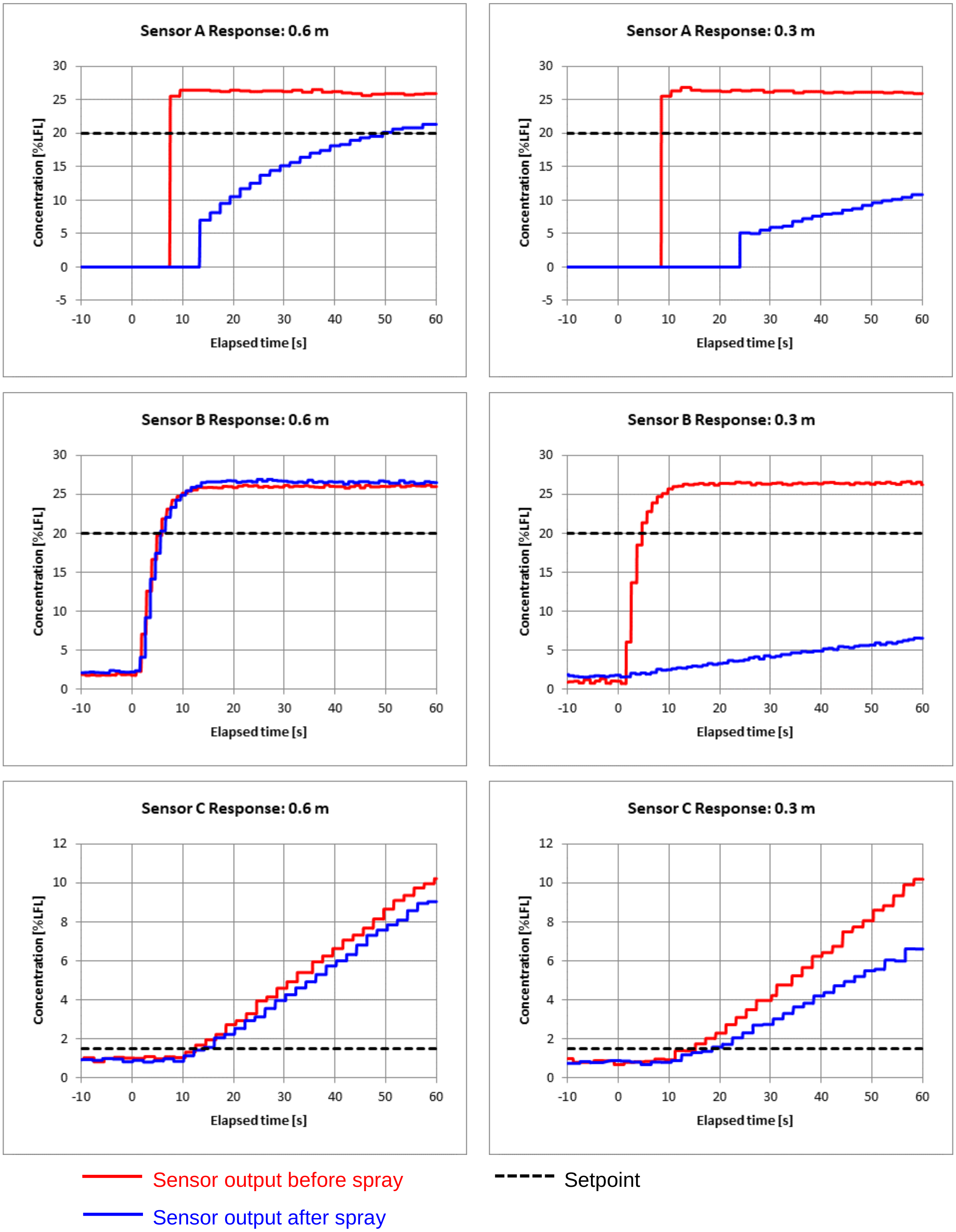



**Figure 3-18. Sensor Response before/after the Oil Spray Test: Sensor A, Sensor B, Sensor C**

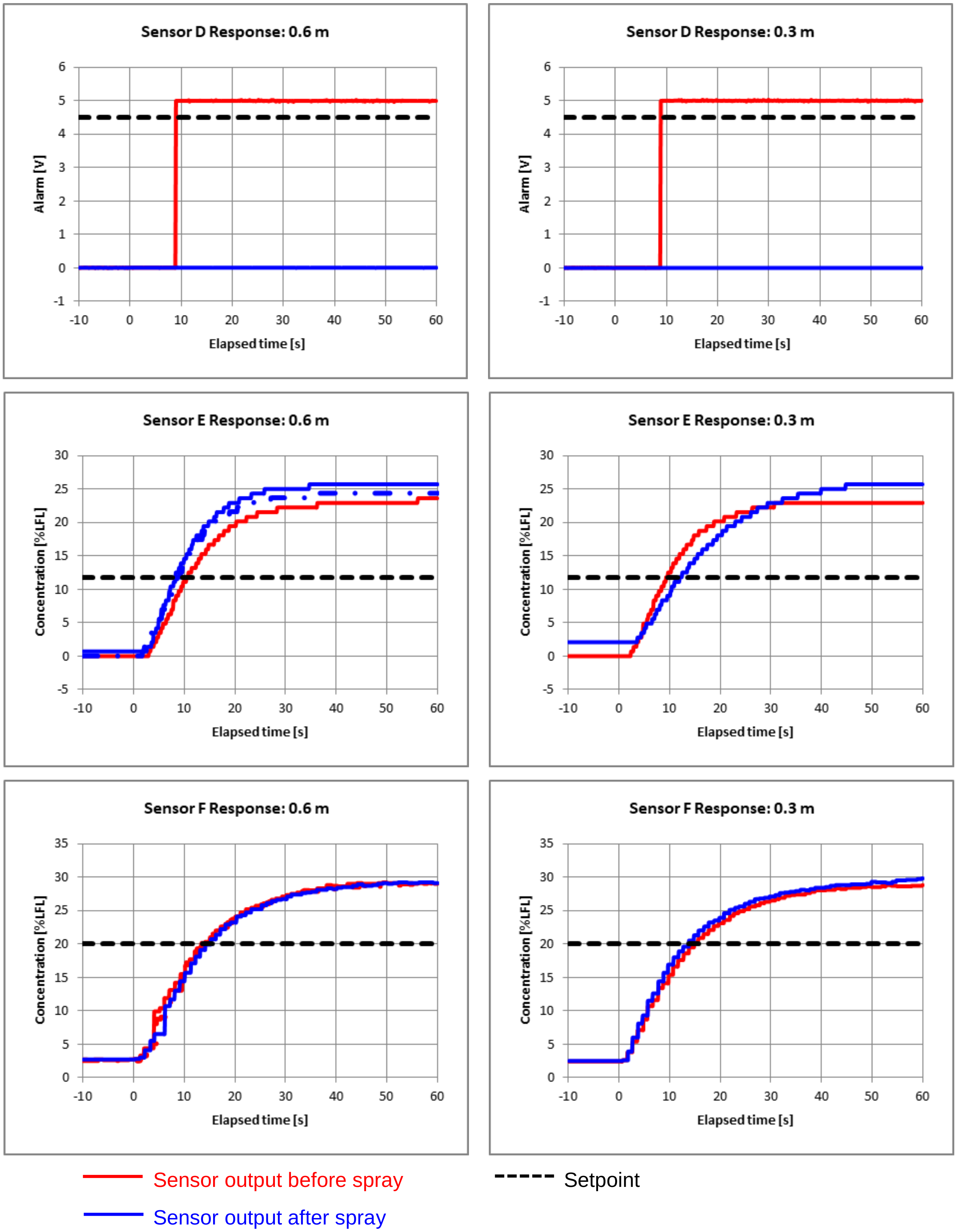



**Figure 3-19. Sensor Response before/after the Oil Spray Test: Sensor D, Sensor E, Sensor F**

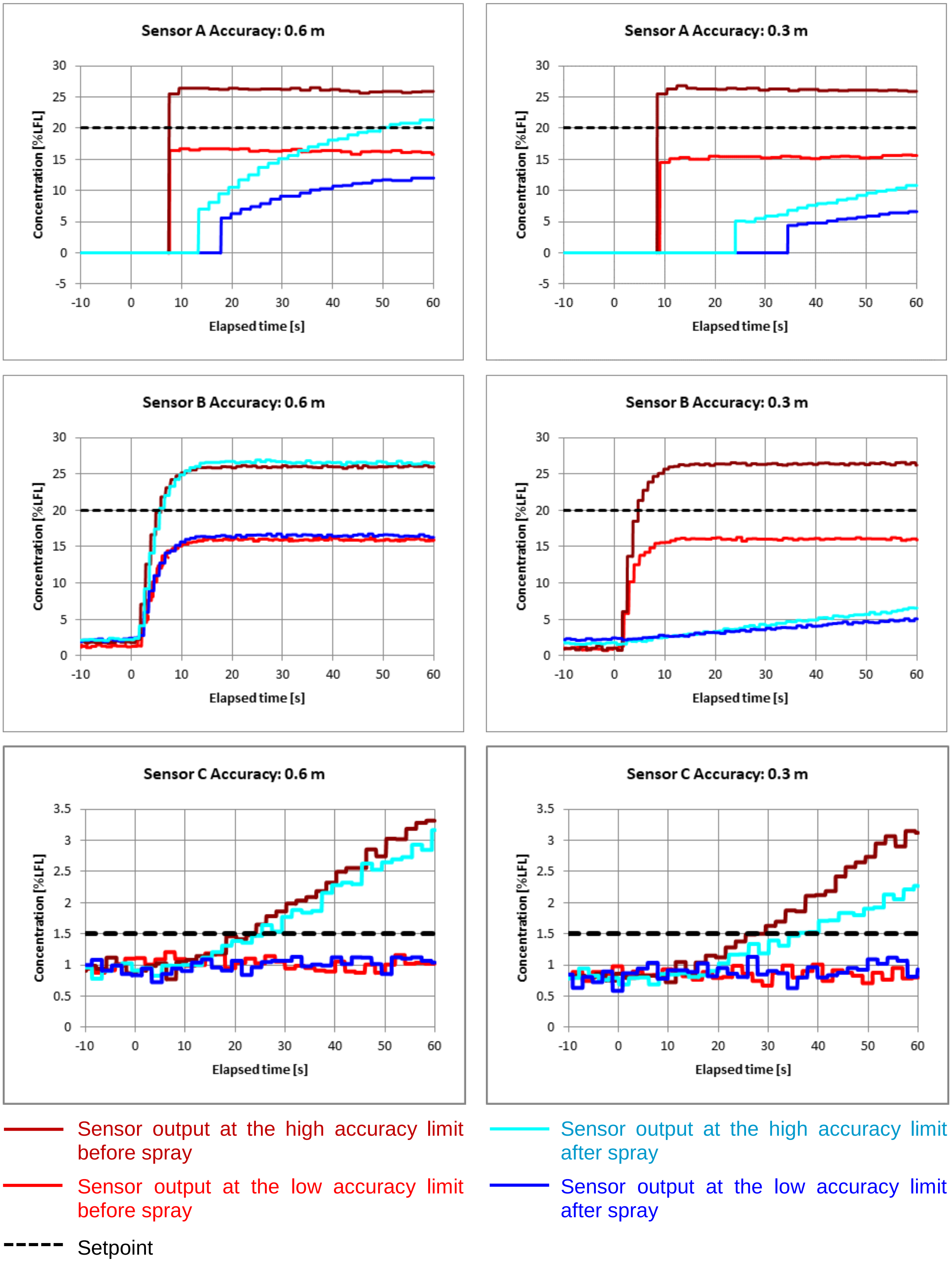



**Figure 3-20. Sensor Accuracy before/after the Spray Test: Sensor A, Sensor B, Sensor C**

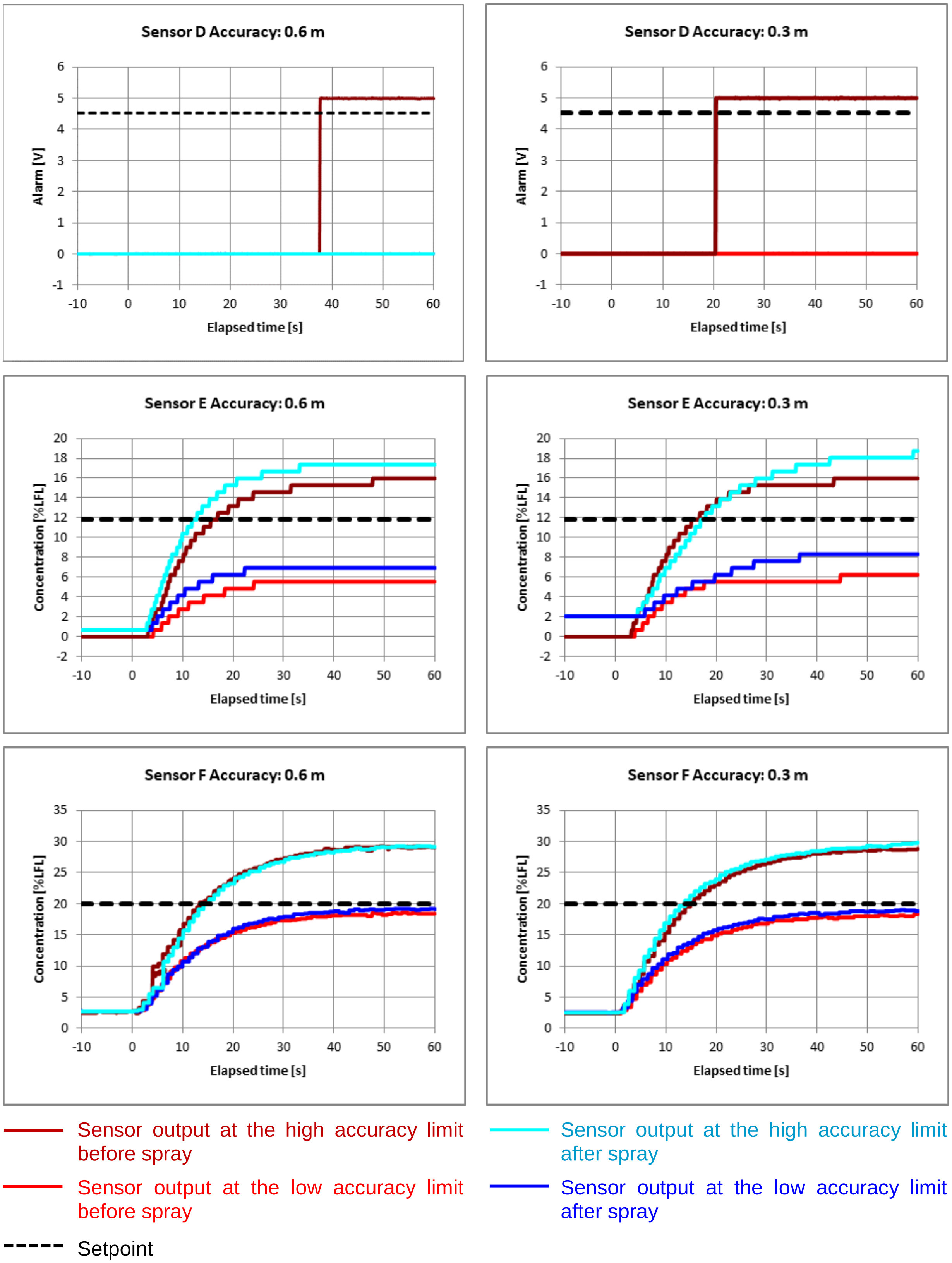



**Figure 3-21. Sensor Accuracy before/after the Spray Test: Sensor D, Sensor E, Sensor F**

### 3.2.3 Summary

Test methods for the Fluid Resistance and Poisoning test including the Gas Injection test method and Liquid Spray test method have been performed on six sensors for the test method verification, demonstration, and improvement.

The gas injection test method has been used for the tests of CO, $CO_2$, D4, and ethanol. With a slight modification of the configuration and procedure, it was also used for the 100% R32 test. During the 2 hours of exposure to the test fluids, all six tested sensors showed no response to CO, D4, Ethanol and the five tested sensors showed a saturated reading to 100% R32 as expected. Two of the tested sensors showed a noticeable output increment (2 and 3%LFL respectively) immediately after the injection of 5000ppmv $CO_2$. Comparing the sensors' initial and post-performance data, it shows all tested fluids have no obvious effect on the sensors’ performance.

The liquid spray test method was used for the oil resistance test. After spraying 10ml/min of oil for 30 minutes, three of the tested sensors showed no response to the test gas, and three of them showed a significantly slowed response to the test gas. A more realistic leak scenario-based method with a reduced oil flow rate and spray duration has been developed and experimentally demonstrated. R32 is used to replace the air as the driving fluid for the spray. Test results showed that the oil spray can affect a sensor’s performance at different levels. It is worth pointing out that the revised oil spray test method introduced three features of harshness: (i) oil deposition, (ii) high concentration of refrigerant, and (iii) low temperature. For the sensors used in this oil spray test, five of them have been proven no permanent effect by the 100% R32 and all six sensors have been proven no permanent effect by low temperature. It is reasonable to conclude that the observed performance change of the sensors in the spray test is due to the impact of oil. However, Sensor D is designed to output a malfunction signal after long exposure to high test gas concentration. The effect of oil on Sensor D performance could therefore not be determined.

Based on the observations and test results, the following recommendations have been made for the future improvement of the test method:

- To determine the volume of the test chamber for a better concentration control of the test gas used in the gas injection method, a calibration procedure is recommended;
- To uncover the effect of the possible background miscellaneous gases on the sensor performance, the response time and accuracy evaluation during the exposure to miscellaneous gases is recommended to be added to the test for the fluid resistance test;
- Due to the nature of multiple harshnesses in the revised oil spray test, the 100% R32 test and low-temperature test are required to be performed before the oil spray test, to properly study the oil effect on sensor performance.

## 3.3 Category B: Extreme storage condition test

### 3.3.1 Test procedure and results

Following the test procedure described in Section 2.5 (Phase 2), the response times and accuracy of the test sensors were initially evaluated under the standard condition before performing the storage test. Here the standard condition is defined as a temperature of 20±5°C and humidity of 50±10%. After keeping the sensors in clean air for 12 hours, the storage test was conducted in four stages:

- Stage 1: Low temperature storage

As shown in Figure 3-22, a low temperature freezer was used for this stage. To ensure no frosting or condensation occurs on the sensor surface during the test, a dry keeper (as shown in Figure 3-22) with a desiccant inside was used. Six test sensors with power off were kept in the dry keeper and put in the freezer for 24 hours under the temperature of -25 ± 2 °C. Figure 3-23 shows the temperature profile of the freezer and sensor during the 24-hour low temperature test stage. Sensor surrounding air temperature was measured in the dry keeper at the location close to sensors surface. After that, the dry keeper with the sensors inside was taken out from the freezer. It was observed that the surface of the dry keeper was instantly covered with a layer of frost when the cold surface touched the room air which had relatively higher humidity, as shown by Figure 3-24. The dry keeper was kept sealed until the sensor temperature reached room temperature. Thus, for the entire low temperature test stage, the sensors were kept dry and clean.

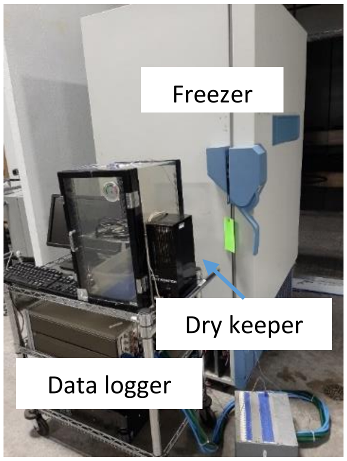



**Figure 3-22. Test Setup for Low Temperature Storage**

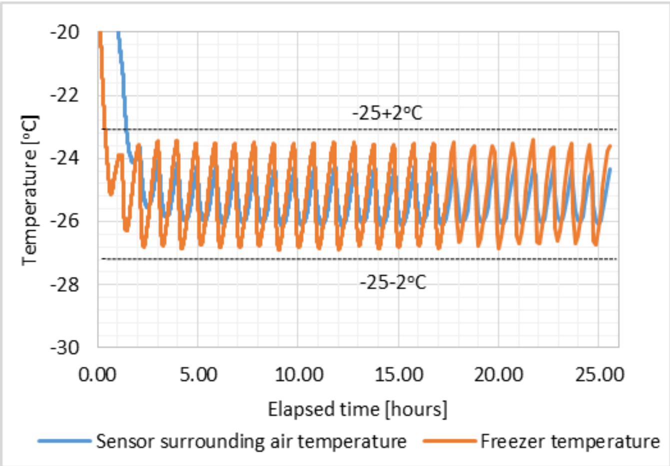



**Figure 3-23. Freezer and Sensor Surrounding Air Temperature for Low Temperature Stage**

**Figure 3-24. Dry Keeper with Sensors When Taken Out From the Freezer**

- Stage 2: Room temperature storage

After being removed from the freezer, the sensors were kept at room temperature with clean air for another 24 hours with power off.

- Stage 3: High temperature storage

After staying at room temperature for 24 hours, the test sensors were then moved into an oven with a temperature of 60 ±2°C for 24 hours. Figure 3-25 shows the picture for the setup used in this stage. Oven and sensor surrounding air temperatures were recorded by a data logger for 24 hours and are shown in Figure 3-26.

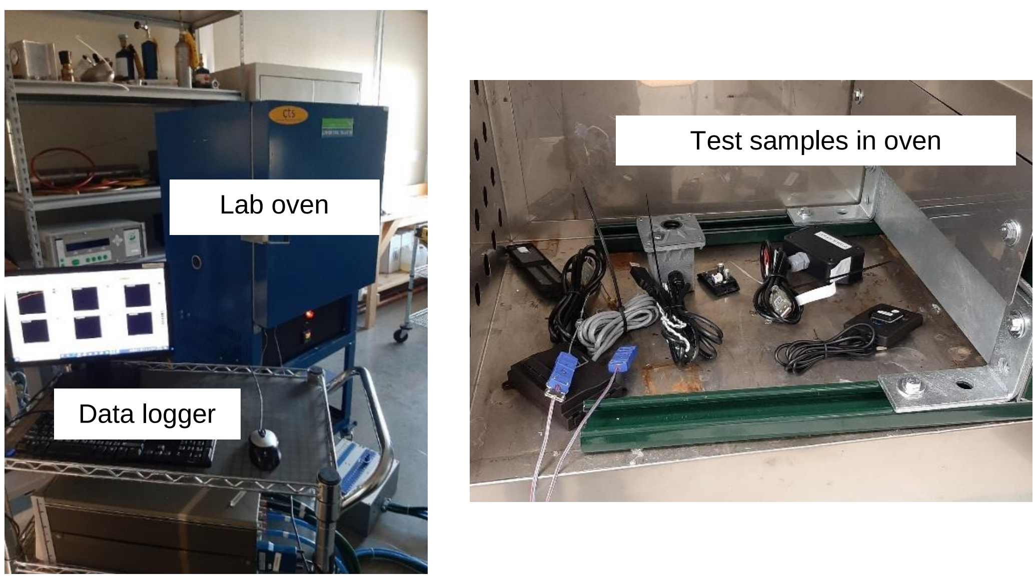



**Figure 3-25. Test Setup for High Temperature Storage**

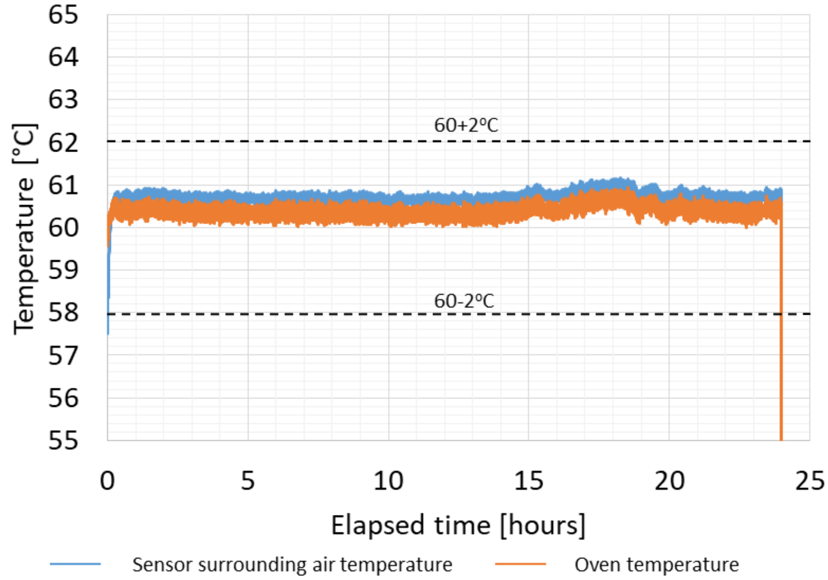



**Figure 3-26. 24-Hour Oven and Sensor Surrounding Air Temperature**

- Stage 4: Room temperature storage

After that, test sensors were taken out from the oven and stayed at room temperature for another 24 hours with power off.

After completing the four-stage storage test, the response time and accuracy of all the tested sensors were recorded and compared with initial performance check results. No obvious effect from extreme condition storage was observed.

### 3.3.2 Summary

The extreme storage condition test method developed in Phase 2 has been conducted and demonstrated in this section. By using a dry keeper as the "suitable desiccator" recommended in the Phase 2 section, no condensate or frost has been observed on the sensor surface during the entire test period. The test method has been proven feasible.

The test results showed extreme storage condition has no obvious effect on any of the six tested sensors.

## 3.4 Category C: Operation condition tests

For the operation condition tests, six stresses including temperature, humidity, pressure, air velocity, and sensor orientation are covered in this category. Table 3-6 summarizes the test conditions, required test facilities, and the failure metric for Category C.

**Table 3-6. Selected Operation Test Conditions**

<table>
<tr><th>Stress</th><th colspan="2">Test facility</th><th colspan="2">Condition</th><th>Failure metric</th></tr>
<tr><td rowspan="3">Temperature</td><td rowspan="3">Push-through Facility</td><td rowspan="2">Environmental chamber</td><td colspan="2">55±1°C 30-70% RH</td><td rowspan="3">Response time and accuracy</td></tr>
<tr><td colspan="2">-20±1°C 30-70% RH</td></tr>
<tr><td>Oven</td><td colspan="2">85±2°C cycling</td></tr>
<tr><td rowspan="2">Humidity</td><td rowspan="2">Push-through Facility</td><td rowspan="2">Environmental chamber</td><td colspan="2">40±1°C 20±5%RH</td><td rowspan="2">Response time and accuracy</td></tr>
<tr><td colspan="2">Condensation</td></tr>
<tr><td>Pressure</td><td colspan="2">Gas Injection Facility</td><td colspan="2">73 ±1kPa, standard condition</td><td>Accuracy</td></tr>
<tr><td rowspan="7">Air velocity</td><td colspan="2" rowspan="7">Gas Injection Facility</td><td>Velocity</td><td>Airflow angle</td><td rowspan="7">Accuracy</td></tr>
<tr><td rowspan="3">3±0.3 m/s</td><td>0±5°</td></tr>
<tr><td>90±5°</td></tr>
<tr><td>180±5°</td></tr>
<tr><td rowspan="3">6±0.6 m/s</td><td>0±5°</td></tr>
<tr><td>90±5°</td></tr>
<tr><td>180±5°</td></tr>
<tr><td rowspan="3">Orientation</td><td colspan="2" rowspan="3">Push-through Facility</td><td colspan="2">Vertical</td><td rowspan="3">Response time and accuracy</td></tr>
<tr><td colspan="2">45±5°</td></tr>
<tr><td colspan="2">Horizontal</td></tr>
</table>

### 3.4.1 Operation temperature test

The test facility for both the low and high operation temperature test is shown in Figure 3-27. The detailed information for both the facility design and test procedures can be found in Section 2.5.1 (Phase 2).

The test facility has been built and used in this phase for the sensor performance evaluation under 55°C and -20°C conditions. Figure 3-28 shows the picture of the test facility.

After testing, several points have been made to improve the test quality:

- The blower in the schematic is designed to draw clean and conditioned air from the environmental chamber to the clean air compartment in the secondary box where the sensor sits before contact with the test gas. The released refrigerant and air mixture from the test compartment was vented by a ventilator to the outside of the chamber. Therefore, a good sealing between the secondary box and the environmental chamber is required to avoid the released test gas contaminating the clean air compartment by recirculation.

- As shown by the schematic in Figure 3-27, a humidifier was used to control the humidity of the test gas by humidifying the compressed air, which was used as the background gas for the test. While the environmental chamber was conditioned to the desired temperature, the humidity of the air in the environmental chamber may not be the same as the humidity of the test gas. When the sensor is pushed down from the clean air compartment to the test compartment, it may go through a sudden humidity change which is not desired for the test. <u>Therefore, a humidifier is also needed to control the humidity of the air in the environmental chamber to be the same as the humidity of the test gas.</u>

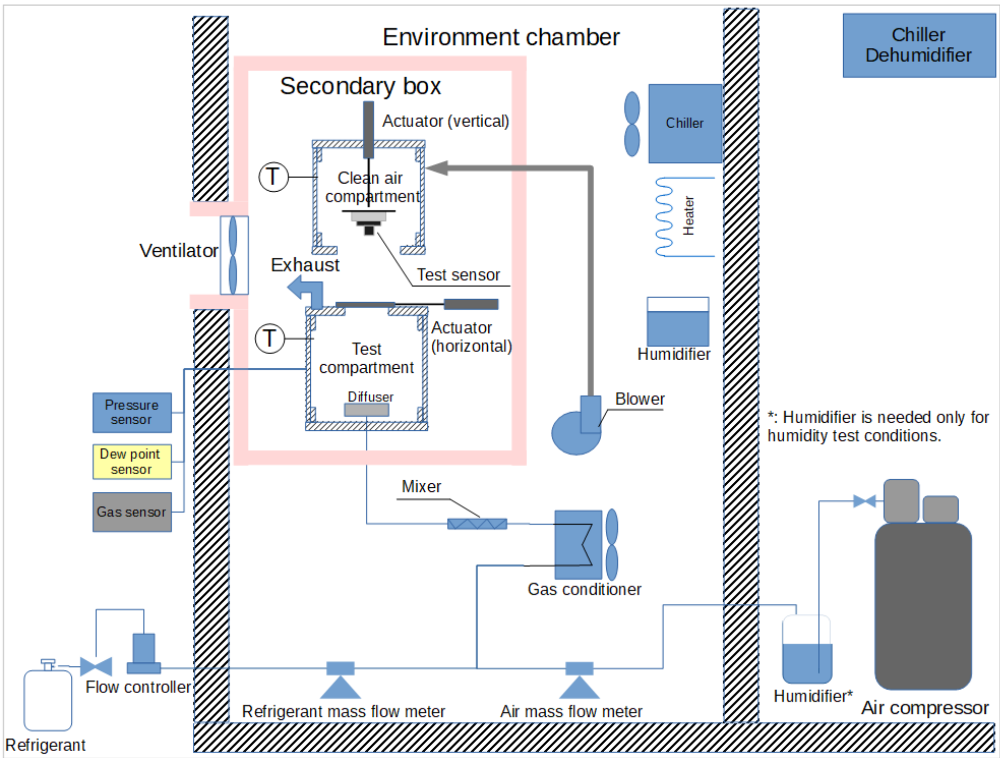



**Figure 3-27. Environmental Chamber Setup for Temperature Tests**


**Figure 3-28. Picture of the Operation Temperature Test Facility**

3.4.1.1 High temperature test result

Sensor response time test results under 55±1°C /30-70% RH condition are shown in Figure 3-29 in blue curves. Compared with the test results at standard condition, which are shown by the red curves in the charts, the following effects have been observed:

- Sensor A showed a slower response and a higher final output at 55°C when exposed to 25%LFL R32;
- Sensor B's final output shifted up by 4%LFL when operated at 55°C, which triggered the alarm about 1.5s earlier;
- Sensor C showed a zero-point shift-up by 1%LFL to 1.5%LFL, which caused the sensor to trigger in the clean air compartment before applying the test gas;
- Sensor D triggered the alarm 3s faster than the standard condition;
- Sensor E's final output shifted up about 2%LFL and triggered the alarm earlier;
- Sensor F showed a shift-down about 2%LFL, but the response time was not affected.

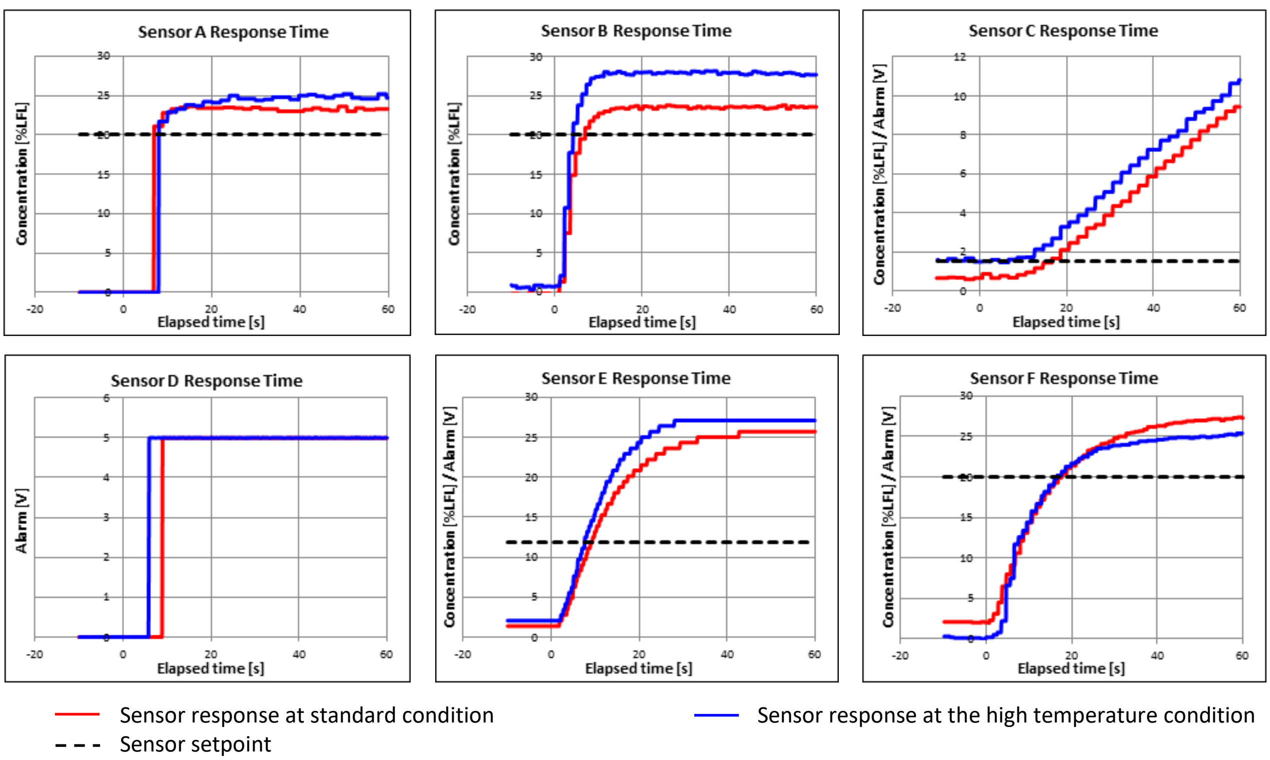



**Figure 3-29. Sensor Response Test Results at 55±1°C 30-70% RH**

Besides the response time tests, the accuracy evaluation tests were also performed at 55±1°C/30-70% RH condition. As described in the Phase 2 section, the criteria for the sensor accuracy are that the sensor should not send an output signal under the concentration of lower accuracy limit and should send an output signal at the concentration of higher accuracy limit. The accuracy limit concentrations are determined by the sensor setpoint (the threshold for activating the alarm). The lower accuracy limit concentration is 5%LFL below the sensor setpoint, but not lower than 1%LFL. The higher accuracy limit concentration is 5%LFL above the sensor setpoint.

Figure 3-30 compares the accuracy check results under the high temperature condition with the standard condition. The observations are:

- Sensor A showed a shift-up of the final output, but no obvious effect on accuracy was observed caused by the high temperature;
- The final output of Sensor B shifted up by 4%LFL for both higher and lower accuracy limit concentrations but did not fail the accuracy requirement;
- Due to the zero-point shift, Sensor C showed an output over the setpoint before exposure to the test gas;
- Sensor D was triggered at the higher accuracy limit concentration 12s earlier than at the standard condition;
- Sensor E's output shifted up about 2%LFL at both higher and lower accuracy limit concentrations but did not fail the accuracy requirement;
- Sensor F's output shifted down about 2%LFL at both higher and lower accuracy limit concentrations but did not fail the accuracy requirement.

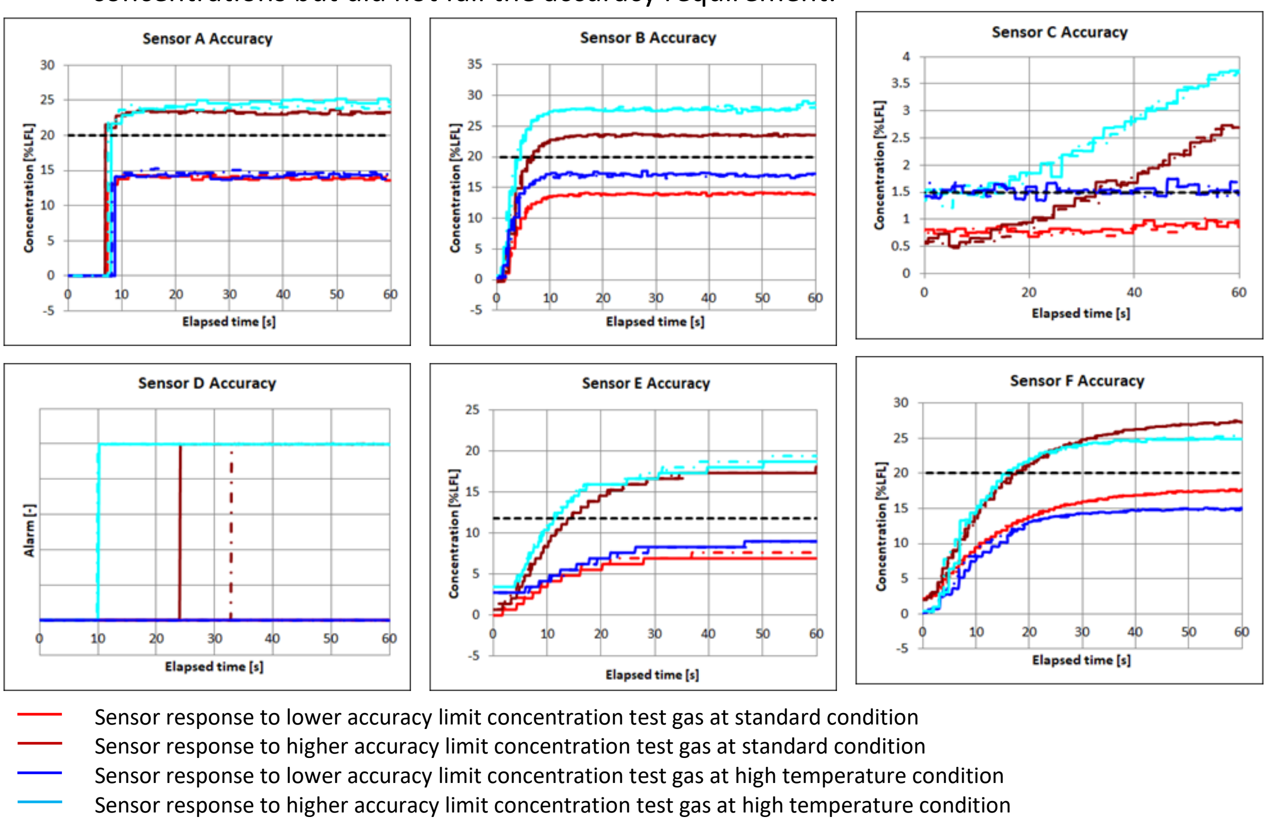



**Figure 3-30. Sensor Accuracy Test Results at 55±1°C, 30-70% RH**

#### 3.4.1.2 Low temperature test result

Figure 3-31 shows the comparison of the response time test results under the low temperature condition with the standard condition. The observations are:

- Sensor A's response time did not shift when exposed to 25%LFL R32;

- Sensor B's final output shifted down about 1.5%LFL at the low temperature condition, which caused the alarm to be delayed about 2s;
- Sensor C showed the zero-point shifted up by 4%LFL. Because the setpoint of this sensor is 1.5%LFL, the alarm was triggered before coming into contact with the test gas;
- Sensor D showed a slower response at the low temperature condition. The alarm was triggered 2s later than the standard condition;
- Sensor E's final output shifted down about 3%LFL, which delayed the response time by 3s;
- Sensor F showed the output shifted up about 7%LFL, which caused the alarm to be triggered 8s earlier.

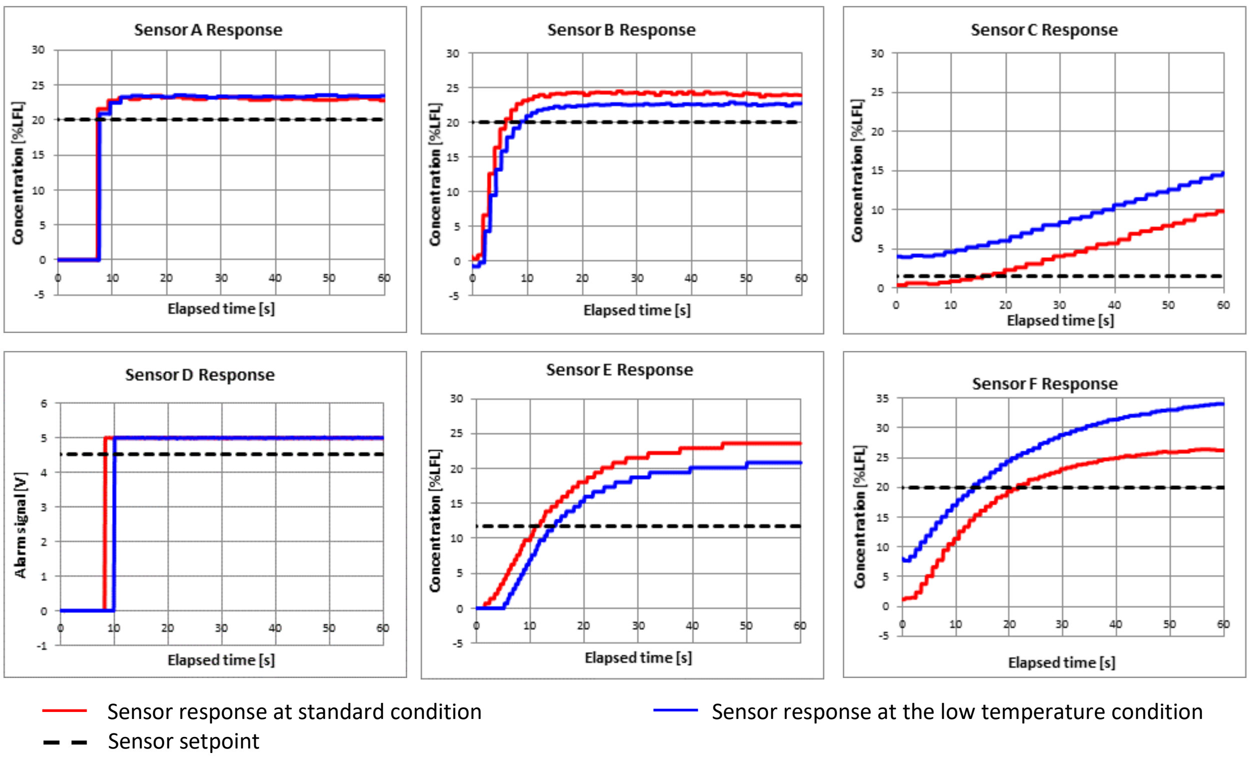



**Figure 3-31. Sensor Response Test Results at -20±1°C, 30-70% RH**

Figure 3-32 shows the accuracy test results at low temperature. The observed effects of the low operation temperature on sensor accuracy are as follows:

- No obvious effect has been observed for Sensor A;
- Sensor B showed the output shifted down about 1.5%LFL when operating at low temperature for both higher and lower accuracy limit concentration tests;
- Sensor C showed the zero-point shift up about 4%LFL which caused the alarm signal to be triggered at both higher and lower accuracy limit concentration tests;
- Sensor D showed good accuracy when operating at the low temperature condition, although the sensor responded slightly slower at the higher accuracy limit concentration test;

- Sensor E's output shifted down about 3%LFL at the low temperature condition for both higher and lower accuracy limit concentration tests;
- Sensor F's output shifted up about 7%LFL which caused the alarm to trigger at the lower accuracy limit concentration test.

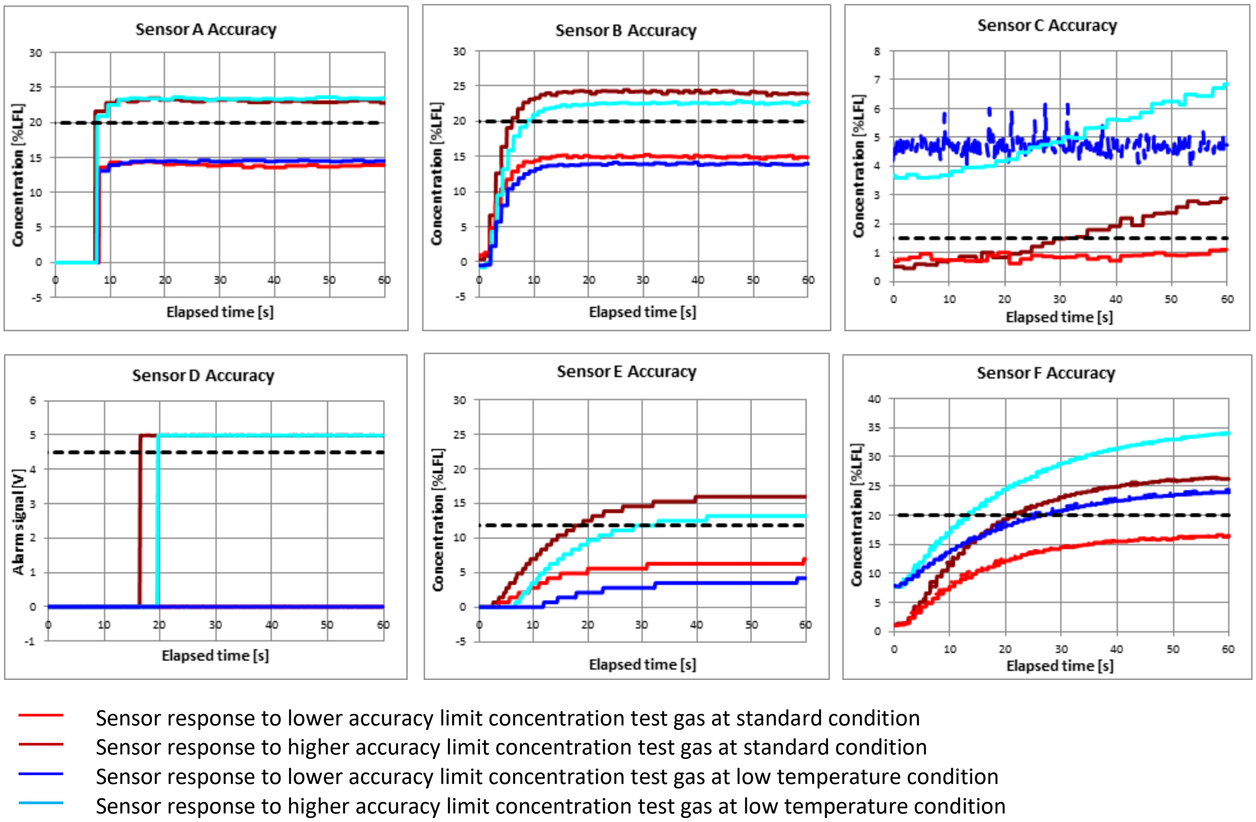



**Figure 3-32. Sensor Accuracy Test Results at -20±1°C, 30-70% RH**

#### 3.4.1.3 High temperature survival test and test result

The tests described in the previous two sections were based on the scenario of extreme operating conditions. This requires the sensor to be fully functional under the conditions when the HVAC&R system is operating properly. However, when taking the malfunction and transition conditions of the HVAC&R system into account, a different test method is required. An example would be a furnace coil application. Assuming a sensor is installed above the furnace in the indoor unit and under extreme conditions when the system is running at heating mode but the blower failed to turn on, by natural convection, the hot air leaving the furnace can hit the sensor and heat it to a much higher temperature than the normal operation condition. Therefore, ANSI Z21.47-2016/CSA 2.3-2016 [12] requires testing of furnaces to 93°C (200°F) and specifies all electronics and wiring to withstand up to 105°C (221°F). During these extreme conditions, sensors are not required to be fully functional. However, some of the systems have an auto-reset function, which requires the sensor to be functional immediately after returning to normal condition.

As recommended by the PMS of this project, a high temperature survival test has been added to this category. The procedure of the test is as follows:

1. Sensor warm-up for no less than 15min under room temperature and clean air
2. Perform initial performance check (response time and accuracy)
3. Keep oven at a designated temperature
4. Keep the sensor powered on with the output recorded
5. Move test sensor to the oven and leave for 20min
6. Remove the sensor from the oven and let it cool down to 20±5°C
7. Repeat steps 5 and 6 for four times (5 cycles total)
8. Run performance test right after the sensor cools back to room temperature

The designated temperature of the oven is allowed to be determined by the user based on the application or specified by the sensor manufacturer. For the test performed in this phase, per the agreement of the PMS and the sample suppliers, the oven temperature was set to 85±2°C. Figure 3-33 shows the test setup for the high temperature survival test used in this phase.

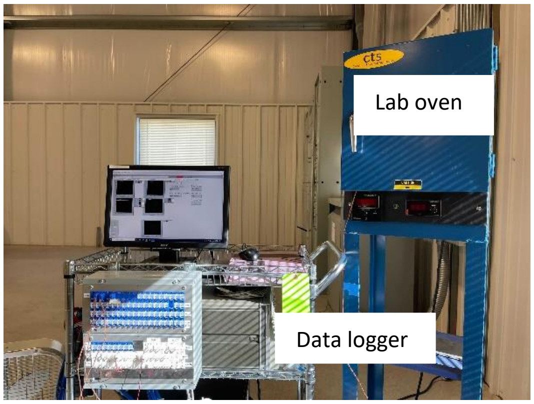



**Figure 3-33. Test Setup for High Temperature Survival Test**

The temperature profiles and the sensor behaviors during the test are shown in Figure 3-34:

- Sensor A showed a concentration above setpoint for the first three cycles, but stayed at zero for the last two;
- Sensor B showed a non-zero concentration for each heating cycle, but the maximum output was below the setpoint;
- Sensor C's output signal was above the setpoint for each cycle;
- Sensor D (indication type) showed no alarm during the test. It was noticed, as shown in Figure 3-34 (D), the sensor surface temperature was even higher than the oven temperature. According to the manufacturer, the MOS sensor has an internal heater with a working temperature of around 300°C, which could heat the sensor surface to be hotter than the surrounding environment temperature;
- Sensor E also showed a non-zero concentration for each cycle but stayed below the setpoint;
- Sensor F has a similar behavior as Sensor E.

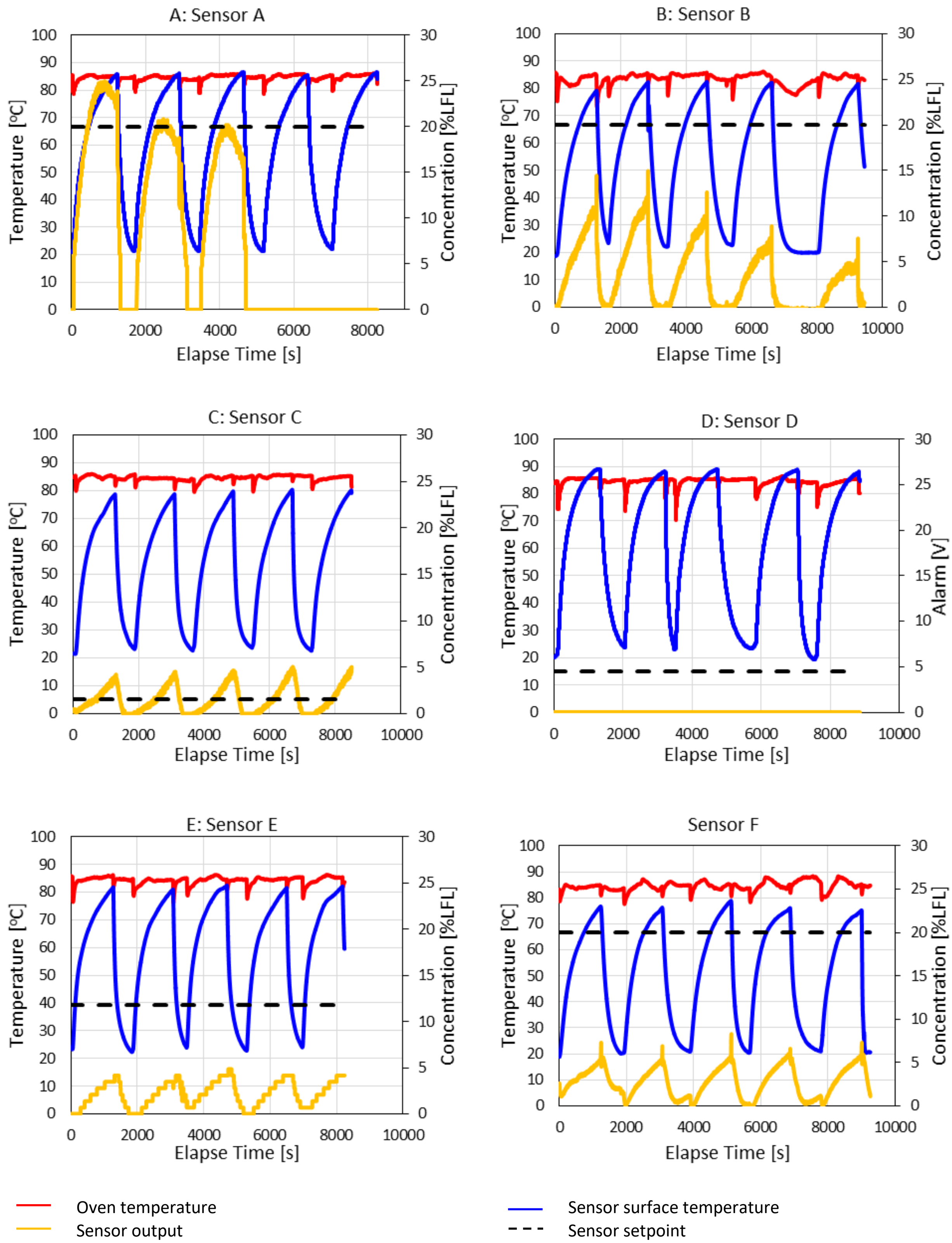



**Figure 3-34. Temperature Profile and Sensor Behavior during High Temperature Survival Test**

After being exposed to high temperatures 5 times, the sensor performances were checked right after the sensor surface temperature returned to room temperature. Figure 3-35 compares the sensor response time test result before and after heating:

- Sensors A, E, and F showed no effect on the sensor performance;
- Sensors B and C showed a slight downward zero-point shift;
- Sensor D responded significantly slower.

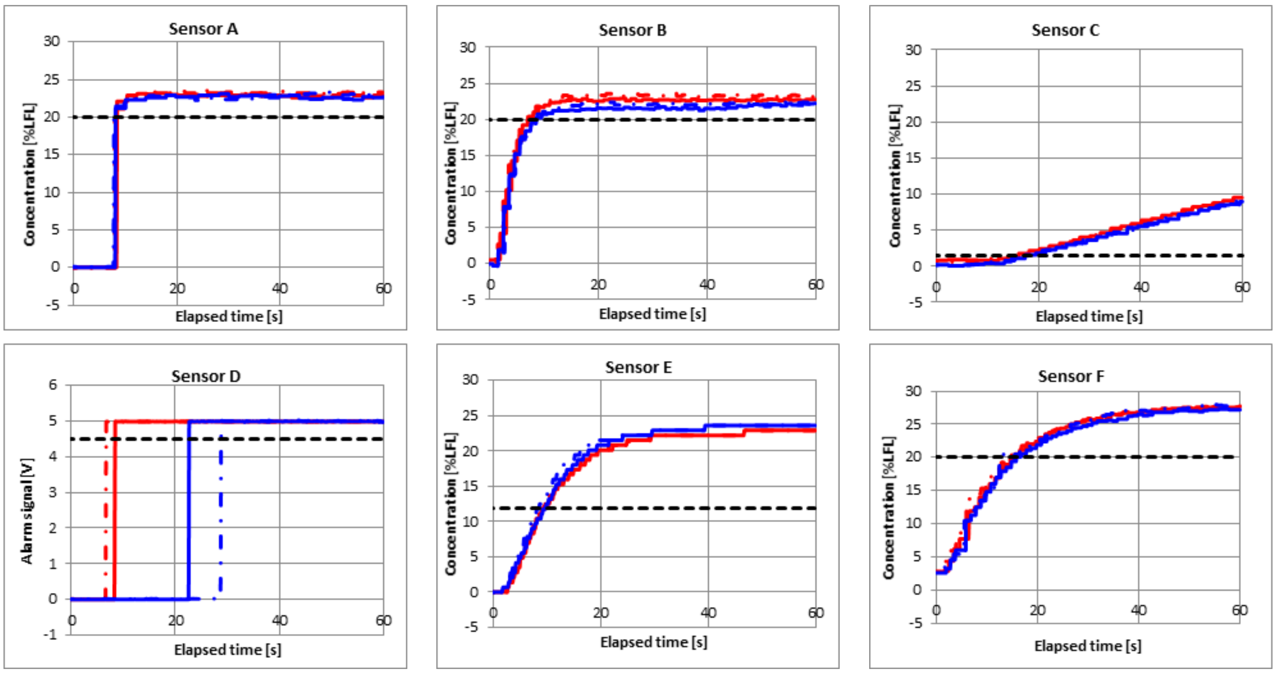



**Figure 3-35. Sensor Response Time Test Result before and after High Temperature Survival Test**

### 3.4.2 Humidity test

3.4.2.1 Dry condition test

The test facilities used for the operation temperature tests were also used for the dry condition test but conditioned to 40±1°C and 20±5% RH as required. The response time and accuracy of the test sample were initially checked under the standard condition, and then checked again under dry condition.

Under the dry condition, no obvious effect was observed for Sensors A, C, D, or F. Sensor B and E showed some effect from dry operation conditions as shown by Figure 3-36. Sensor B showed an upward zero-point shift, which caused the response time to be 3s faster than under standard condition. Sensor E showed a steeper slope of the output curve, which caused the alarm to be triggered 3s faster than standard condition.

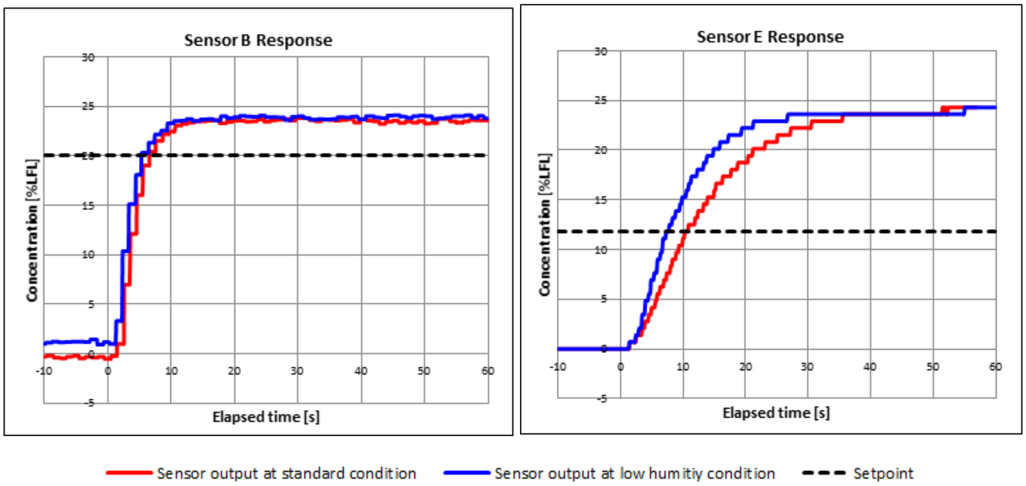


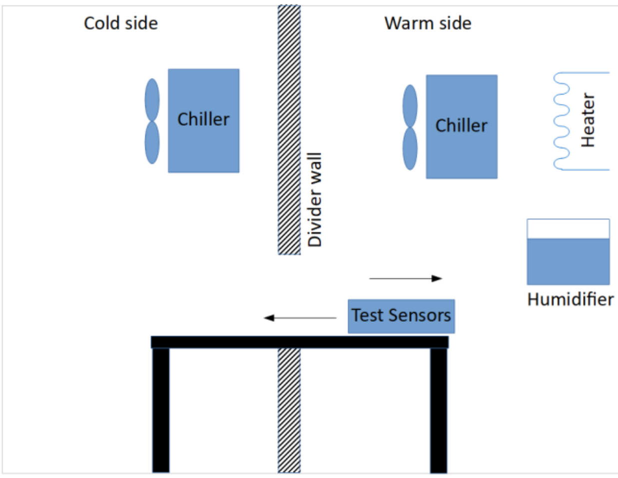

**Figure 3-36. Sensor B and E Response Time Comparison between Dry Condition and Standard Condition**

### 3.4.2.2 Condensation test

As specified in the Phase 2 section, there are two high humidity related operation condition tests. One is the test with the condition of 10±1$^{o}$C, 90±5%RH, and the other is the condensation test. The condensation test was selected to be performed in this phase, because it is relatively harsher than the high humidity condition and should provide a more conservative result for the sensor reliability assessment.

The test procedure was described in the Phase 2 section. An environmental chamber with a warm side and a cold side was used for this test. Figure 3-37 shows the schematic and picture of the test chamber setup. The warm and cold side of the test chamber were conditioned to 25±5$^{o}$C / 60±5%RH and -25±2$^{o}$C, respectively. The sensors were moved between two sides of the chamber to perform the required 36 cool down and warm-up cycles. Figure 3-38 shows the temperature and humidity of the test chamber during the 10-hour test period. The fairly large thermal mass of the chamber and higher cooling and heating capacity provided good stability of the test condition.

Figure 3-39 shows the temperature profiles measured on the surface of each tested sensor and sensor output during the test. It is worth pointing out that some of the tested sensors contained an internal heater to keep the sensor core warm when detecting a low temperature condition. It was observed that when the surface thermocouple was attached very close to the location where the internal heater was installed, the measured sensor surface temperature was never able to drop below the required temperature (-20$^{o}$C). To better represent the actual sensor surface temperature these warm spots should be avoided when installing the temperature detector.



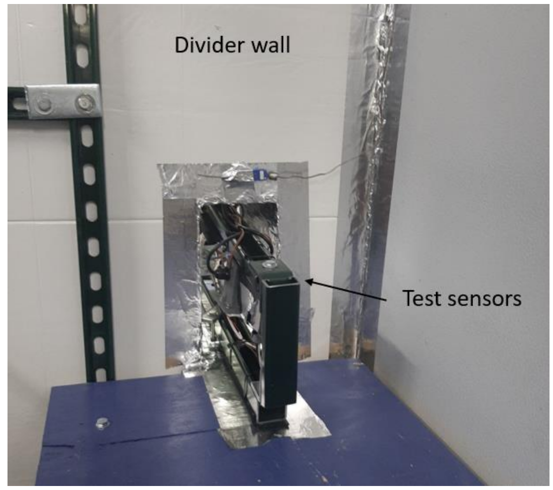




**Figure 3-37. Chamber Setup for Condensation Test**

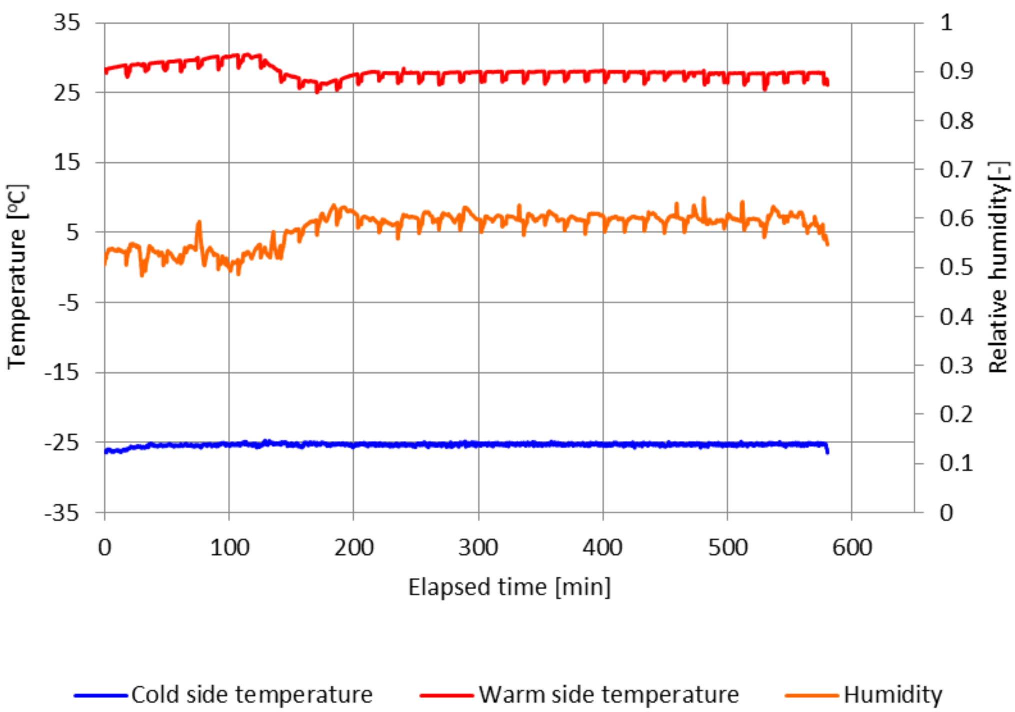



**Figure 3-38. Test Condition for the Condensation Test**

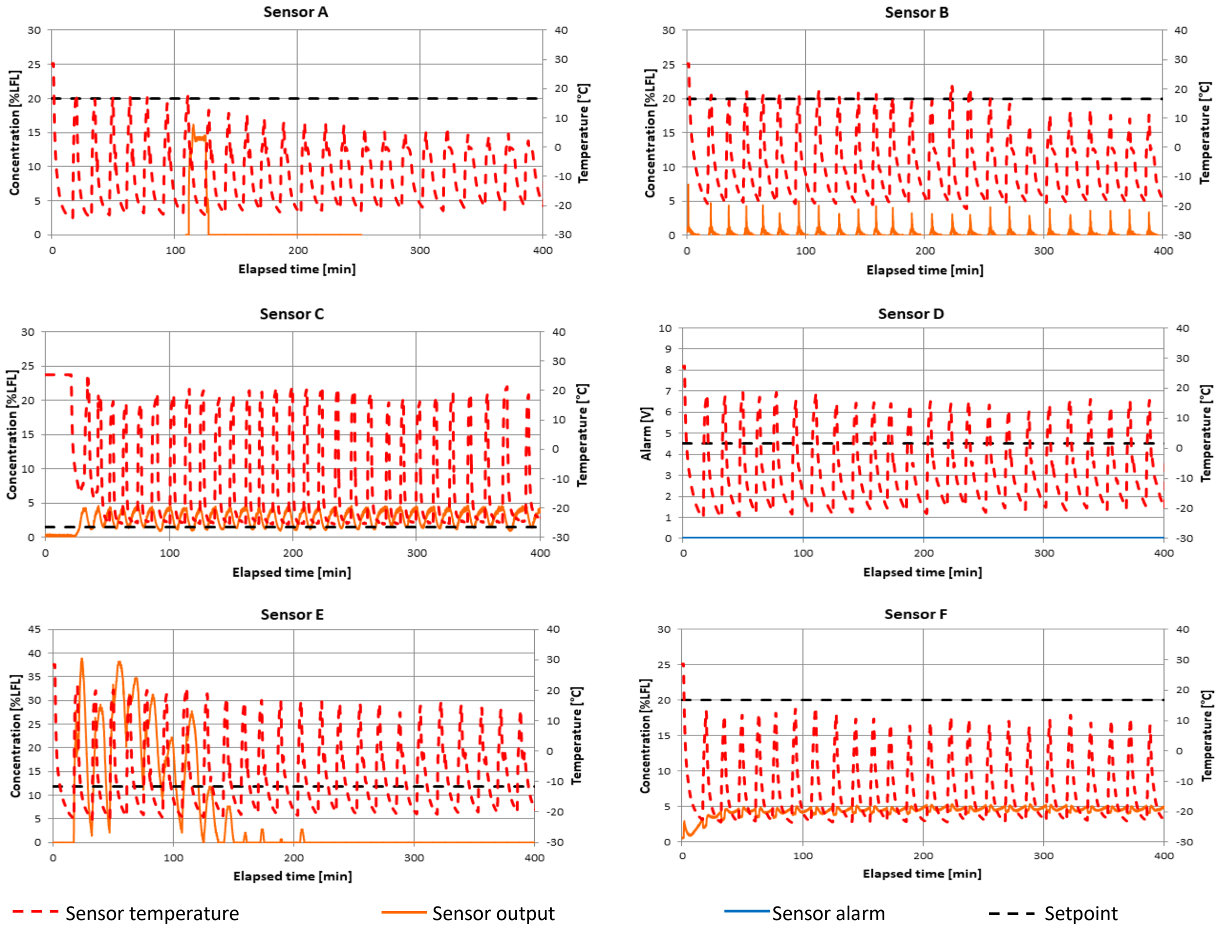



**Figure 3-39. Temperature Profile and Sensor Behavior during the Condensation Test**

The observations of the sensor behavior during the condensation test are as follows:

- Sensor A randomly showed a peak during the condensation test. After several cycles, the sensor lost connection with the IB board. The chart of Sensor A in Figure 3-39 shows only a short period of the sensor output, because the sensor data was lost when data logging software was not closed properly;
- Sensor B showed an output of 2.5%LFL to 7.5%LFL for every cycle;
- Sensor C showed a repeatable output increase from 1 to 4.6%LFL for every cycle. Since the set point of Sensor C was as small as 1.5%LFL, the alarm was triggered for each cycle;
- No alarm signal was observed for Sensor D during the condensation test;
- Sensor E randomly provided an output signal (up to ~40%LFL) and triggered an alarm for the first few cycles;
- Sensor F showed an upward output shift of 4-5%LFL at the beginning of the condensation test.

Figure 3-40 shows a picture of the tested sensors towards the end of these 36 cycles. Frost (or ice) can be seen on the surface of the tested sensors. However, after warm-up and the removal of the condensate on the sensor surface, no obvious performance change was observed for any of the tested sensors.

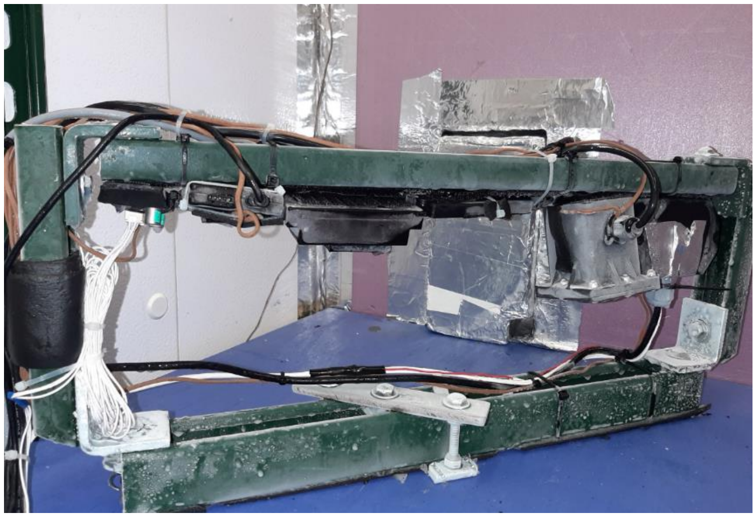


**Figure 3-40. Tested Sensors towards the End of the Condensation Test**

The test method was initially developed by referring to JRA standard 4068T-2016 [6]. According to JRA [13], the test procedure was designed for light commercial refrigeration applications, more specifically, for refrigerated display cases. As described above, it has been observed that five out of six tested sensors showed responses to the sudden temperature and humidity change at a different level during the condensation test, and two of them triggered the alarm. However, the criterion for this test is to check the performance after removal of the condensate. Thus, the sensor's ability to function during normal operation cannot be assessed. Another recommendation that has been made by the PMS of this project is to change the test name of "Condensation test" to "Freeze & Thaw test", since the required cold side temperature of -25°C will turn every droplet on the test sensor surface into frost. Later, these frost particles thaw when moving the sensor back to the warm side.

### 3.4.3 Pressure test

The schematic of the facility used for the pressure test is shown in Figure 3-41. The recommended test procedures were described in the Phase 2 section. It has been found during the verification tests, the prefilling of the test gas to 70-80% of the concentration of the lower accuracy limit can be increased to 100%. The original attempt of reduced prefilling percentage was to ensure no alarm occurs before performing the pressure reduction. Since it is required to check the sensor performance before conducting the pressure test, it should be already confirmed no alarms will be triggered at atmospheric pressure.

For the measuring type sensors (Sensors A, B, C, E, and F), to uncover the effect of the pressure on the sensor output at both concentrations of higher and lower accuracy limit, the same procedures were used for both concentrations. In other words, instead of using the recommended method of increasing the test gas concentration from lower accuracy limit to higher accuracy limit by gas injection, the approach of prefilling the test chamber to the desired concentration before reducing the pressure has been adopted. Thus, the change of sensor output caused by the pressure drop for both concentrations was captured and is shown in Figure 3-42.

For the indication type sensor (Sensor D), the gas injection method as recommended in the Phase 2 section was used in this phase.

The measuring type sensors were kept in the test chamber for 10min after reducing the pressure to let the sensor output have enough time to stabilize. Sensor D is designed to show an irreversible malfunction signal after exposure to the test gas with a concentration higher than the setpoint for more than 7min. Therefore, the exposure time for Sensor D was reduced to 5min.

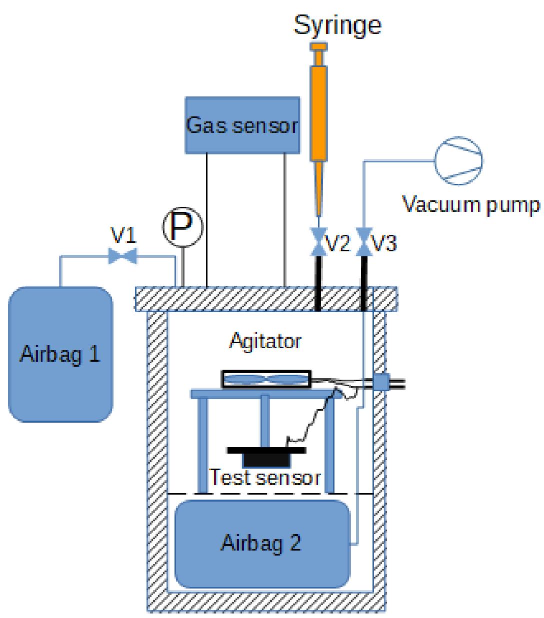
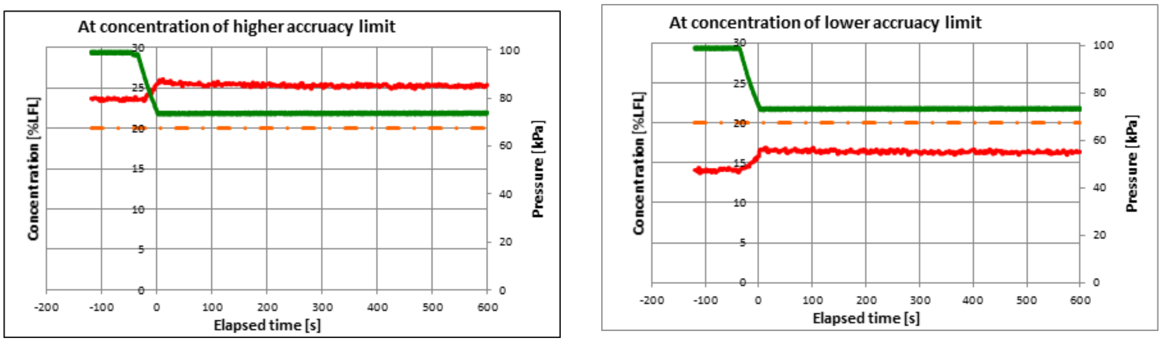


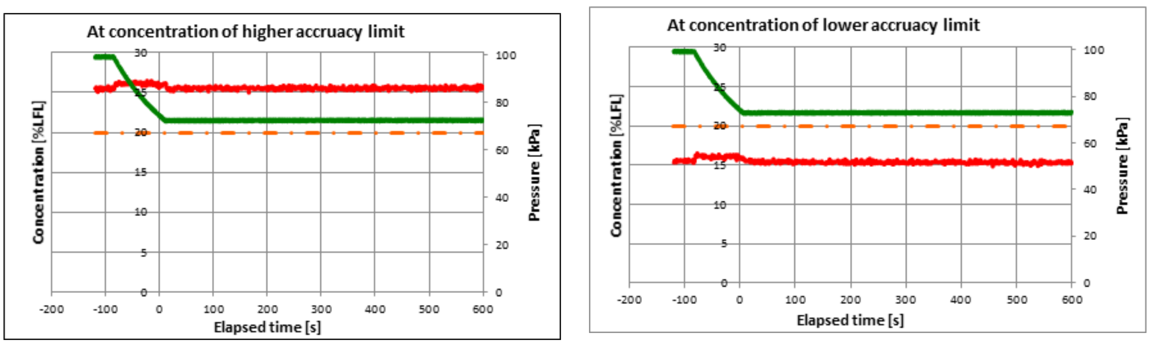

**Figure 3-41. Pressure Test Setup**

The effects of pressure on sensor outputs are shown in Figure 3-42:

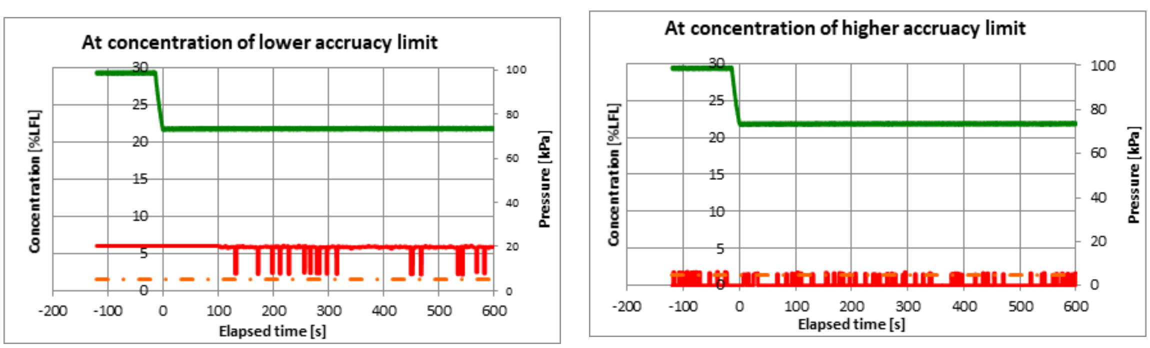
- For Sensor A, as the pressure reduced from atmospheric pressure (100kPa), the output shifted up about 2%LFL on both concentrations of higher and lower accuracy limit;
- For Sensor B, the output shifted up about 1%LFL initially when the pressure dropped from 100kPa to 73kPa but came back to the previous value when the pressure stabilized;
- Sensor C showed a noisy output during the test, especially for the concentration of higher accuracy limit condition;
- No effect of pressure on the alarm signal of sensor D has been observed ;
- For Sensor E, the output reduced by 2-4%LFL after pressure reduction;
- The output of Sensor F slightly increased during pressure reduction, but slowly decreased back to the previous reading after pressure stabilized.



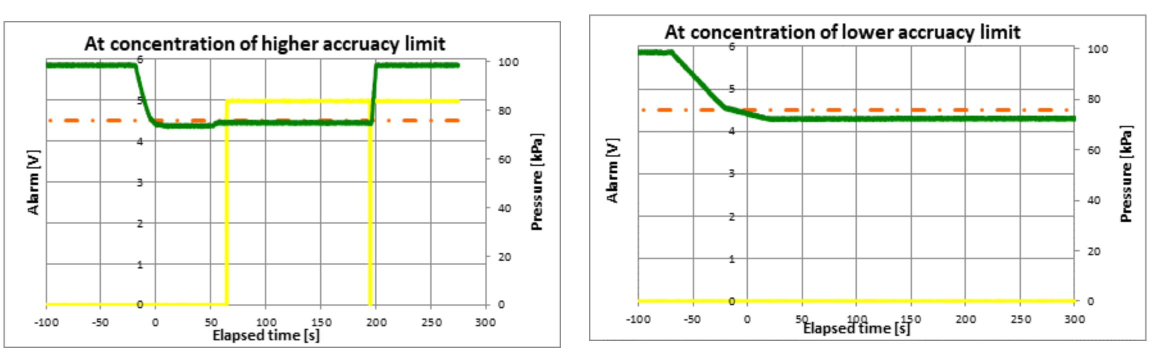

Sensor A



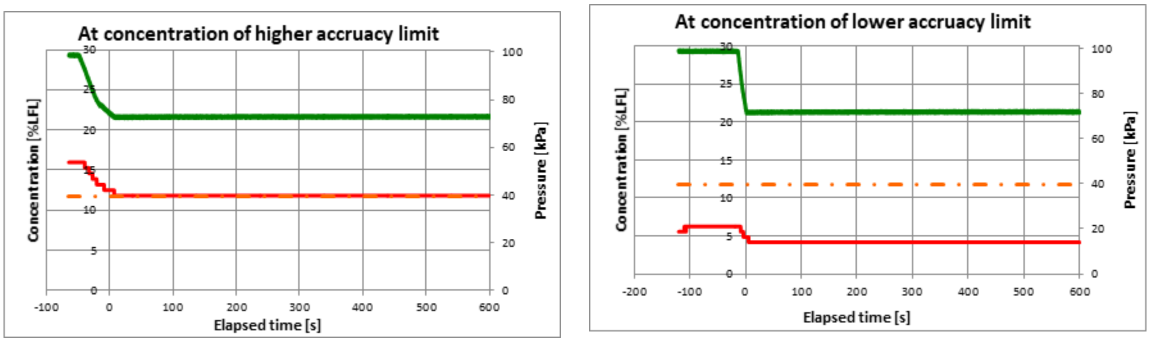

Sensor B



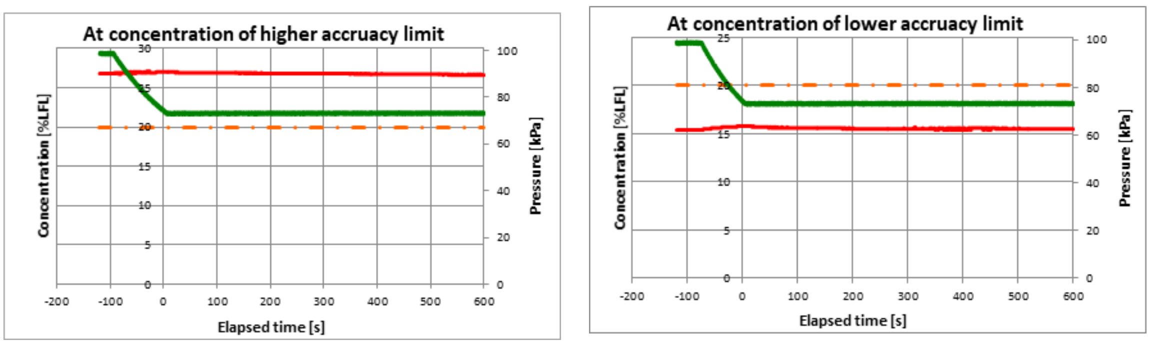

Sensor C




Sensor D




Sensor E




Sensor F

Sensor output — Sensor alarm signal — Setpoint — Pressure

**Figure 3-42. Sensor Performance at 73kPa**

### 3.4.4 Air velocity test

Figure 3-43 shows the schematic and picture of the air velocity test facility. A detailed description can be found in the Phase 2 section. Before performing the test, air velocity in the test chamber at the location where the test sensor was installed was checked and monitored by an anemometer. Figure 3-44 shows the setup in the test chamber for 0°, 90°, and 180° conditions. Air velocity was adjusted by regulating the fan speed. Table 3-7 shows the test matrix for the air velocity test. No obvious effect of the air velocity was observed for any of the six tested sensors.

**Table 3-7. Air Velocity Test Conditions (3x3)**

| Air direction | Air velocity | |
|---|---|---|
| 0±5° | 3±0.3m/s | 6±0.6m/s |
| 90±5° | 3±0.3m/s | 6±0.6m/s |
| 180±5° | 3±0.3m/s | 6±0.6m/s |

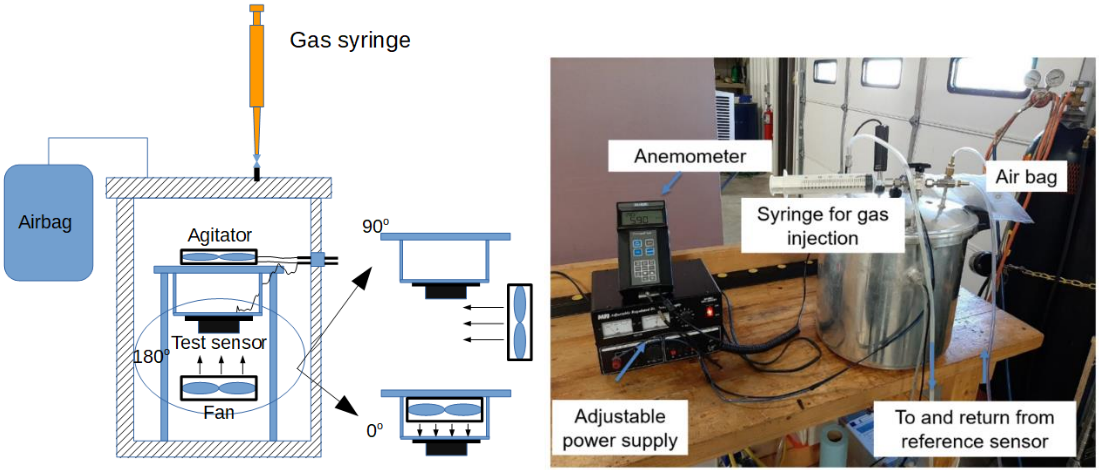



**Figure 3-43. Air Velocity Test Facility**

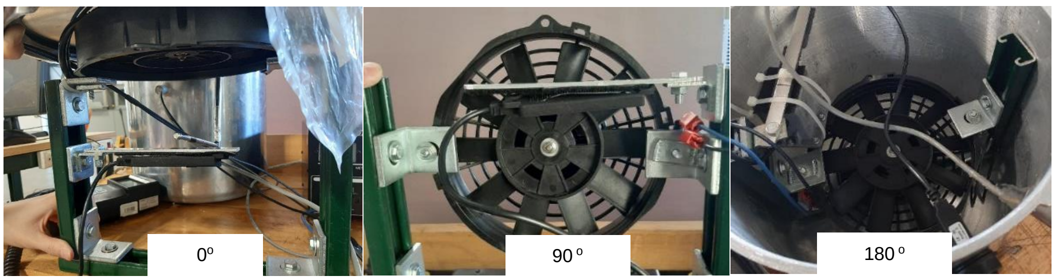



**Figure 3-44. Test Setup inside the Test Chamber**

### 3.4.5 Sensor orientation test

Sensor orientation tests were performed using the Push-through Facility with an additional fixture to adjust the sensor orientation. Three different orientations including vertical, horizontal, and a 45° incline were tested. Both the response time and accuracy were evaluated at different orientations. Figure 3-45 shows the setup of the six tested sensors for three different orientations.

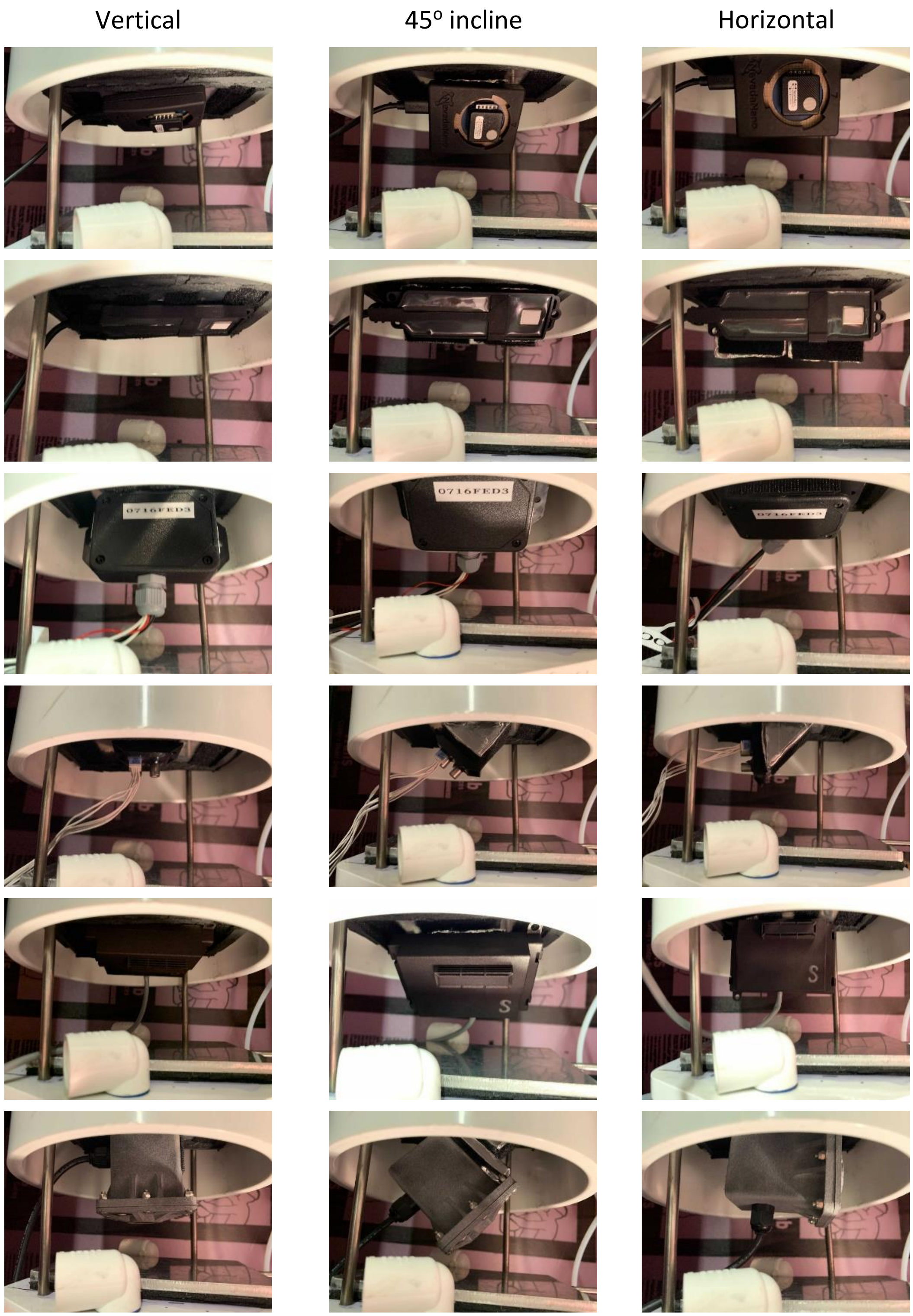



**Figure 3-45. Test Setup for the Sensor Orientation Test***

* Sensor designations have been omitted intentionally to keep supplier names confidential.

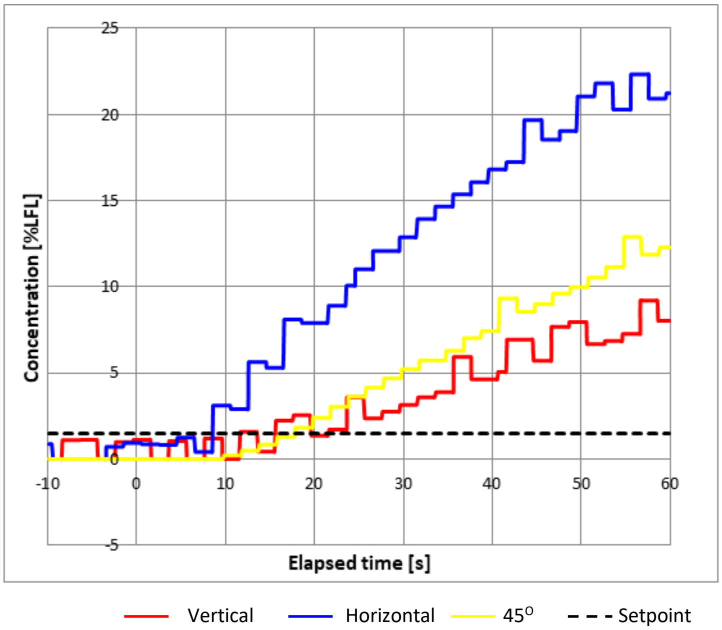



**Figure 3-46. Sensor Orientation Test Results for Sensor C**

As shown by the test results, no obvious effect of sensor orientation has been observed for any of the tested sensors except Sensor C. Figure 3-46 shows the output curve for Sensor C at three different orientations. The fastest response of this sensor was found at the horizontal orientation.

### 3.4.6 Summary

The impact of the working condition factors including temperature, humidity, condensation (frost), pressure (elevation), air velocity, and sensor orientation on the sensor performance were investigated in this category.

The test facility and method used for the operating temperature and low humidity tests were demonstrated and proven to be feasible. To ensure the reliability of the test result, two recommendations have been made to be denoted in the test protocol for these tests:

- A good sealing between the secondary box and the chamber is required to avoid possible recirculation of the released test gas;
- The clean air compartment of the Push-through Facility needs to be conditioned identically as the test compartment to avoid an undesired sudden change of the test conditions.

The test result shows most of the test sensors were impacted by the operation temperature and humidity, but the influence was relatively small.

Based on the scenarios of possible malfunction and transition conditions of a furnace system, a high temperature survival test has been developed and demonstrated in this section. The test result showed no effect on any of the sensors except Sensor D. The response of this MOS sensor became much slower after being heated to 85°C with a very short recovery time.

The condensation test was conducted in this section by using the method recommended by JRA standard 4068T-2016 [6]. Frost and thaw on the sensor surface were observed. Most of the test sensors showed an impact from sudden temperature and humidity change on the sensor reading during the test, but no degradation of performance has been found afterward.

The pressure test developed in Phase 2 has also been conducted in this section for demonstration. The test results showed the pressure change can cause the concentration reading of Sensor A and Sensor E to be shifted by 2-4%LFL.

The air velocity test has shown that both the air direction and velocity have no impact on the sensor performance of any of the tested sensors.

Among the six tested sensors, Sensor C is the only one that showed different response times at different sensor orientations.

## 3.5 Category D: Drop test

As recommended by the Phase 2 section, the test procedure described in Section 5.4.13 of IEC 60079-29-1 [10] for the transportable-type sensor was used for the drop test. The release height of the drop test was 0.3m and was determined based on the mass of the sensors. Figure 3-47 shows the picture of six sensors before and after drop test.

**Figure 3-47. Drop Test**

Before performing the drop, the response time and the accuracy of the tested sensors were initially evaluated at standard condition. Identical tests were repeated after being dropped three times. No effect of the drop test on the tested sensors' response time and accuracy was observed.

## 3.6 Category E: Short term stability test

### 3.6.1 Test method

The short-term stability tests were also performed on the Push-through test facility. The repeatability of the sensor response time was evaluated by these tests. As described in the Phase 2 section, the test sample was exposed six times to the test gas (R32 and air mix) with a concentration of 25%LFL. The duration for each exposure was 3min. Between each exposure, the test sample was kept in clean air for another 7min. The time length of the sensor kept in clean air between each exposure to test gas is called the "Clean Air Interval".

### 3.6.2 Test result

Figure 3-48 uses Sensor A as an example to show the test results. Test gas concentration was measured by another sensor (the reference sensor as described in the Phase 2 section) and confirmed by converting the measured mass flow ratio of R32 to air to a volume fraction. The "Push down signal" uses a voltage signal (5V or 0V) to indicate whether the sensor is exposed to the test gas. Higher voltage means the sensor is exposed to the test gas while lower voltage means the sensor stays in the clean air. The response time for each sensor and each repetition was calculated and compared in Figure 3-49. Sensors A, B, C, E, and F showed good repeatability of response time for the tested six repetitions. The deviation between each exposure was less than 1.5s. However, Sensor D showed a trend that the response time became faster for each repetition. Based on the observation, a hypothesis has been made that 7min of the Clean Air Interval may not be enough to eliminate the effect of the previous exposure on the response time.

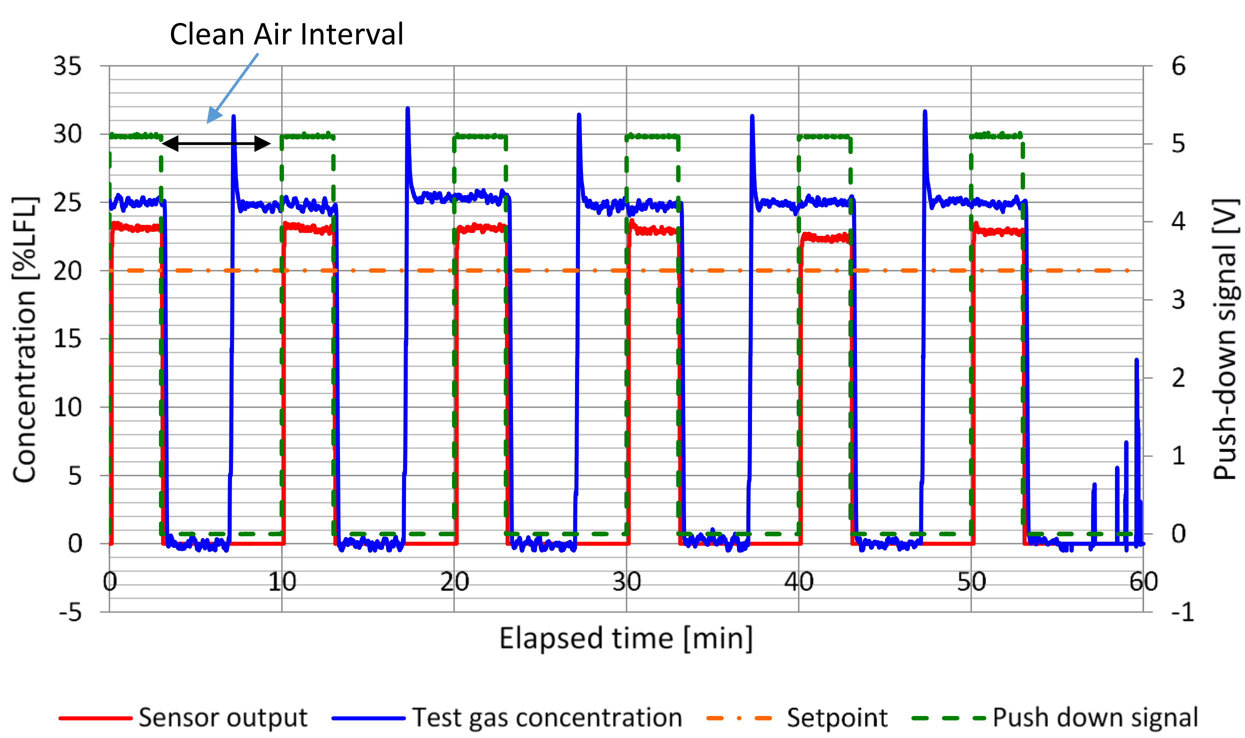



**Figure 3-48. Short Term Stability Test Result for Sensor A**

To verify the hypothesis, verification tests with a longer Clean Air Interval have been performed on Sensor D. A comparison of the response time with different Clean Air Intervals is shown in Figure 3-50.

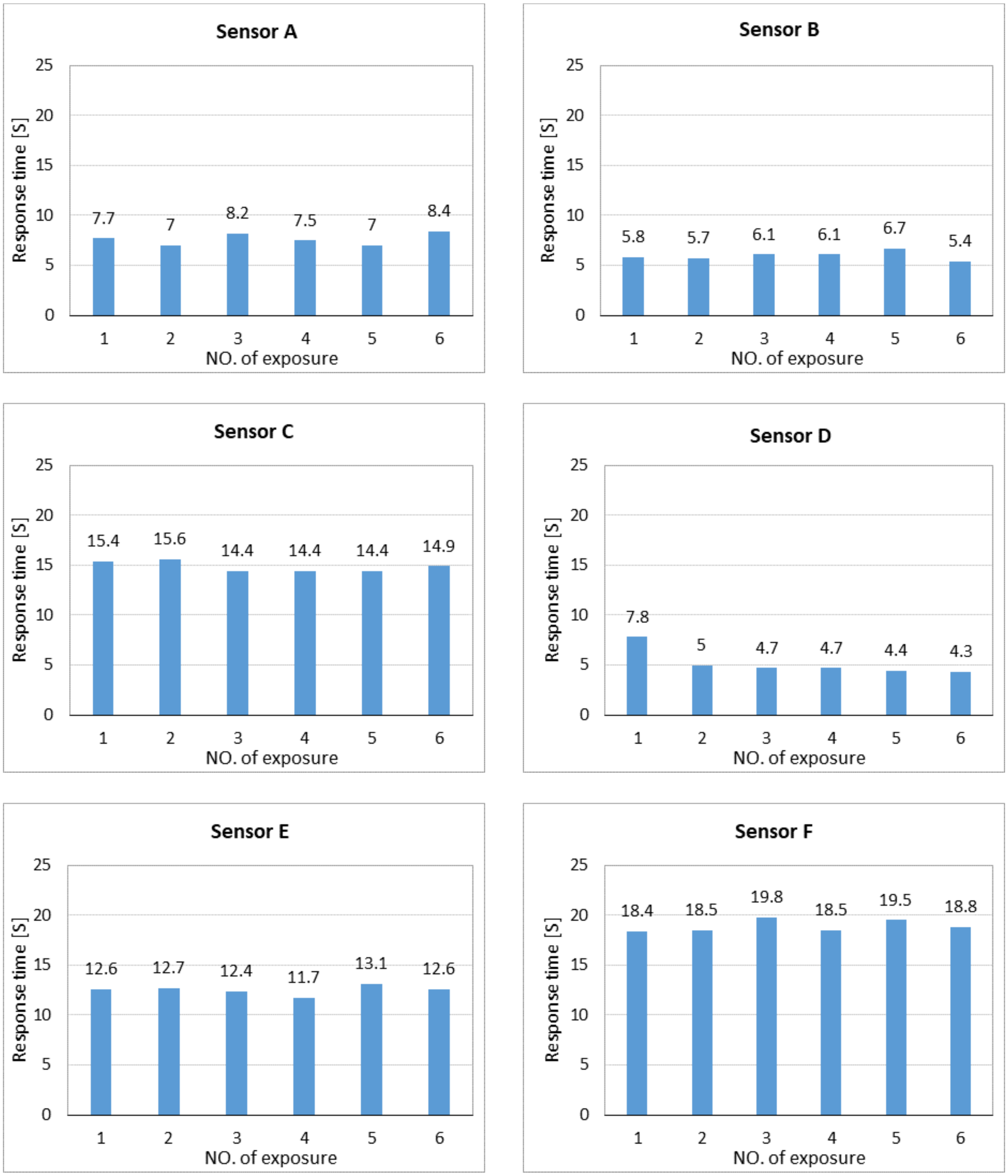



**Figure 3-49. Repeatability of the Response Time for the Tested Sensors with Clean Air Interval of 7min**

The response times of the sensor for all the exposures after the initial one became longer as the Clean Air Interval increased, and the deviation between each exposure became smaller. This indicates, for different sensing principles, the minimum required rest time after triggering the alarm could be different, and it can be determined by the test procedure demonstrated above. The minimum required rest time should be specified by the sensor manufacturer or be determined by the sensor user based on the application.

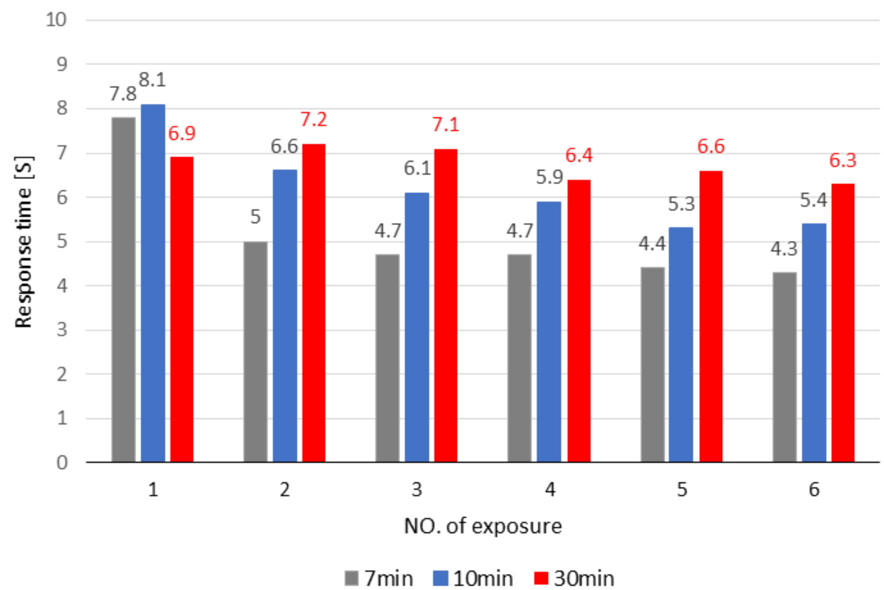



**Figure 3-50. Response Time Comparison with Different Clean Air Intervals of Sensor D**

### 3.6.3 Summary

The test method for assessment of the sensors' short-term stability (repeatability) was demonstrated in this section. The test was initially performed with a Clean Air Interval of 7min. Five of the six tested sensors showed good repeatability during the initial test. To investigate the effect of the Clean Air Interval on sensor response time, an additional test with three different Clean Air Intervals was conducted. The test result showed the length of the Clean Air Interval could affect the repeatability of a sensor's response time. It is recommended, in the test protocol, the length of Clean Air Interval should be specified by the sensor manufacturer based on the minimum required reset time or required by the user based on the application.

## 3.7 Conclusions

To verify, improve, and demonstrate the test methods developed in Phase 2 of this project, sensor reliability assessment tests were conducted on six different sensor samples. Five major sensing principles including: Micro Machined Membrane, Thermal Conductivity, Nondispersive Infrared, Metal-Oxide Semiconductor, and Speed of Sound were covered in the tests. The effects of five categories of harshness tests including Fluid Resistance and Poisoning, Extreme Storage Condition, Operation Condition, Vibration & Drop, and Short-term Stability on the sensor reliability were investigated.

Based on the observation and the results of the tests, the following recommendations have been made to be denoted in the test protocol for future improvement of the test method:

- For the Fluid resistance and poisoning test:
    - To determine the volume of the test chamber for a better concentration control of the test gas used in the gas injection method, a calibration procedure is recommended;
    - To uncover the effect of the possible background miscellaneous gases on the sensor performance, the response time and accuracy evaluation during the exposure to miscellaneous gases is recommended to be added to the test method for the fluid resistance test;
    - Due to the nature of multiple harshnesses in the revised oil spray test, the 100% R32 test and low-temperature test are required to be performed before the oil spray test, to properly study the oil effect on sensor performance.
- For the Operation condition test
    - A good sealing between the secondary box and the chamber is required to avoid possible recirculation of the released test gas;
    - The clean air compartment of the Push-through Facility needs to be conditioned identically as the test compartment to avoid an undesired sudden change of the test conditions.
- For the Short-term stability test
    - The effect of Clean Air Interval should be taken into account when assessing the sensor repeatability. It is suggested that the Clean Air Interval should be specified by the sensor manufacturer based on the minimum required reset time or by the user based on the application.

The tests conducted in this phase not only demonstrated the test methods, but also provided useful information regarding the future suitability of commercially available and developmental sensor technologies to meet the safety standard requirements:

- For the Fluid resistance and poisoning test:
    - During the 2 hours of exposure to the test fluids, all six tested sensors showed no response to CO, D4, Ethanol and the five tested sensors showed a saturated reading to 100% R32 as expected;
    - Two of the tested sensors showed a noticeable output increment (2 and 3%LFL respectively) immediately after the injection of 5000ppmv $CO_2$;

  - By comparing the sensors' initial and post-performance data, it shows all tested fluids have no obvious effect on the sensor's performance;
  - After spraying 10ml/min of oil for 30 minutes, three of the tested sensors showed no response to the test gas, and three of them showed a significantly slowed response to the test gas. As a revised version, a more realistic leak scenario-based method with a reduced oil flow rate and spray duration has been developed and experimentally demonstrated. R32 was used as the driving gas for the spray. All sensors triggered the alarm during the tests. Post-spray results showed that the oil spray can affect a sensor's performance, at different levels. The revised oil spray test method introduced three features of harshness: (i) oil deposition, (ii) high concentration of refrigerant, and (iii) low temperature.
- For the extreme storage condition test:
  - No obvious effect from extreme condition storage was observed.
- For the Operation condition tests:
  - Most of the test sensors were impacted by the operation temperature and humidity, but the influence was relatively small;
  - Uncovered by the High temperature survival tests, the response of the MOS sensor became much slower after being heated to 85°C with a very short recovery time;
  - Most of the test sensors showed an impact from sudden temperature and humidity change on the sensor readings during the condensation test, but no degradation of performance has been found afterward;
  - The results of the pressure test showed reduced pressure from 100kPa to 73kPa can cause the concentration reading of the Sensor A and E to be shifted 2-4%LFL;
  - The air velocity test has shown that both the air direction and velocity have no impact on the sensor performance of all the tested sensors;
  - Among the six tested sensors, Sensor C is the only one that showed different response times at different sensor orientations.
- For the drop test:
  - No obvious effect from being dropped 3 times was observed.
- For the Short-term stability test:
  - The test on Sensor D showed that the length of the Clean Air Interval has an impact on the sensor repeatability.

# References

[1] IEC 60335-2-40:2018, Edition 6.0. Household and similar electrical appliances – Safety – Part 2-40: Particular requirements for electrical heat pumps, air-conditioners and dehumidifiers. International Electrotechnical Commission, Geneva, Switzerland, January, 2018.

[2] UL 60335-2-40: 2019, Edition 3. Standard for safety Household and Similar Electrical Appliance – Safety – Part 2-40: Particular Requirements for Electrical Heat Pumps, Air-Conditioners and Dehumidifiers. Underwriters Laboratories, Inc., Northbrook, IL, 2019.

[3] CAN/CSA-C22.2 No. 60335-2-40-19, Household and Similar Electrical Appliances - Safety- Part 2-40: Particular Requirements for Electrical Heat Pumps, Air Conditioners and Dehumidifiers. CSA Group, Toronto, Canada, 2019.

[4] ASHRAE Standard 15-2019. Safety Standard for Refrigeration Systems. ASHRAE, Atlanta, GA, 2019.

[5] ASHRAE, Proposed Standard 15.2 (Advisory Public Review Draft). ASHRAE, Atlanta, GA, 2018.

[6] JRA 4068T:2016R, Requirements of refrigerant leak detector and alarm for air conditioning and refrigeration equipment. Standard of The Japan Refrigeration and Air Conditioning Industry Association (English translation). Published 23-May-2016, amended 26-Sep-2016.

[7] Chemical and energy process engineering. Sigurd Skogestad, CRC Press, 2009.

[8] AHRTI. Pravinray Gandhi, George Hunter, Randall Haseman, and Brian Rodgers. AHRTI Report 9007-01, Benchmarking Risk by Whole Room Scale Leaks and Ignitions Testing of A2L Refrigerants, June 2017.

[9] ASHRAE Standard 34-2019. Designation and Safety Classification of Refrigerants. ASHRAE, Atlanta, GA, 2019.

[10] IEC 60079-29-1:2016-07, Edition 2.0. Explosive atmospheres – Part 29-1: Gas detectors – Performance requirements of detectors for flammable gases. International Electrotechnical Commission, Geneva, Switzerland, 2016.

[11] National Primary and Secondary Ambient Air Quality Standards, 40 CFR Part 50 (http:// https://www.law.cornell.edu/cfr/text/40/part-50).

[12] ANSI Z21.47-2016/CSA 2.3-2016, Seventh Edition. Gas-Fired Central Furnaces. American National Standards Institute. New York, United States, 2016.

[13] Koji YAMASHITA. Standards of refrigerant leak detector and alarm for air conditioning and refrigeration equipment. JRAIA International Symposium, 2016.

# Appendices

## Appendix A: Summary of the refrigerant detector (sensor) requirements from safety standards

| Requirement | Priority | Standards | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | IEC 60335-2-40 Edition 6.0 (Jan-2018) | | UL/CSA 60335-2-40 edition 3 | | ASHRAE 15-2019 direct systems | | ASHRAE 15-2019 machinery rooms | | ASHRAE 15.2P (proposed) small residential direct systems | | JRA 4068T: 2016R | |
| Capable of sensing presence of refrigerant | primary | 3.1.38 | yes/no | LL.1DV | yes/no | 3.1 | yes/no | 3.1/8.13.9 a | yes/no | 4.0 | yes/no | 3.5/4.3 | yes/no |
| Capable to be installed "within the unit" when required | secondary | 22.121 | yes/no | 22.121DV | yes/no | 7.6.5 c 2 | yes/no | | | 13.1.6 | yes/no | 9 | yes/no |
| Capable to be installed "remote from unit" when permitted | secondary | 22.121 | yes/no | 22.121DV | yes/no | 7.6.5 c 2 | yes/no | 8.11.5 | yes/no | 13.1.6 | yes/no | 9 | yes/no |
| Capable to be installed "indoor coil cased assembly" when required | secondary | | | 22.121DV | yes/no | | | | | | | | |
| Capable to be installed "in air supply duct work" when permitted | secondary | | | | | | | | | 13.1.6 | yes/no | | |
| Does sensor fulfill listing requirement of ASHRAE 15-2019, i.e. has sensor been evaluated by test lab? | secondary | | | | | 7.6.5 a | yes/no | | | | | | |
| Does the sensor work when the voltage applied is varied by ±10% rated voltage? | | | | | | | | | | | | 5.2.5/5.3.5 | yes/no |
| Can the sensor produce repeatable, accurate outputs (stability test JRA 10.7)? | | | | | | | | | | | | 5.2.6 | yes/no |
| Comply with Annex LL (itemized below) | primary | 22.122 | yes/no | 22.122 | yes/no | | | | | | | | |
| Capable of number of cycles of operation (300 for self-resetting, | primary | 24.1.4 | yes/no | 24.1.4 | yes/no | | | | | | | | |

| Requirement | Priority | Standards | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | IEC 60335-2-40 Edition 6.0 (Jan-2018) | | UL/CSA 60335-2-40 edition 3 | | ASHRAE 15-2019 direct systems | | ASHRAE 15-2019 machinery rooms | | ASHRAE 15.2P (proposed) small residential direct systems | | JRA 4068T: 2016R | |
| 30 for non-self-resetting) | | | | | | | | | | | | | |
| Is the sensor a multiport-type device | primary | | | | | | | 8.13.8 | yes/no | | | | |
| When multiple signals are received, alarms from all locations should sound and the location in which the refrigerant is detected shall be identified | | | | | | | | | | | | 7.6 | yes/no |
| Capable of using a setpoint less than 25% of LFL | primary | GG.4 | yes/no | GG.4 | yes/no | | | 8.13.9d | yes/no | 13.12 | yes/no | 7.2 | yes/no |
| Capable of using a setpoint not greater than OEL | primary | | | | | | | 8.11.5/8.13.9c | yes/no | | | | |
| Includes audible alarm | secondary | GG.13.1, GG.13.2.1 | yes/no | GG.13.1, GG.13.2.1 | yes/no | | | 8.11.5/8.13.10.1 | yes/no | | | 7.3 | yes/no |
| Includes visual alarm | secondary | GG.13.1, GG.13.2.1 | yes/no | GG.13.1, GG.13.2.1 | yes/no | | | 8.11.5/8.13.10.1 | yes/no | | | 7.3 | yes/no |
| Alarm 70dbA at distance of 1 meter | | | | | | | | | | | | 7.4 | yes/no |
| Does the device have an output to indicate the presence of a refrigerant concentration exceeding the setpoint | primary | | | LL.5DV | yes/no | | | | | | | 5.1/7.5 | yes/no |
| Capable of setpoint less than 25% of LFL | primary | LL.1, LL.2 | yes/no | LL.1, LL.2 | yes/no | | | 8.13.9d | yes/no | 13.1 | yes/no | 7.2 | yes/no |
| Setpoint is preset (e.g. factory set) | secondary | LL.1, LL.2 | yes/no | LL.1, LL.2 | yes/no | | | | | 13.1.3 | yes/no | | |
| Is pre-set level setpoint adjustable | secondary | | | LL.4DV | yes/no | | | | | | | | |
| Complies with the requirements IEC 60079-29-1 for Group II equipment | primary | | | LL.1DV | yes/no | | | | | | | | |
| Is sensor still functional after 100% | primary | | | LL.4DV | yes/no | | | | | | | | |

| Requirement | Priority | Standards | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | IEC 60335-2-40 Edition 6.0 (Jan-2018) | | UL/CSA 60335-2-40 edition 3 | | ASHRAE 15-2019 direct systems | | ASHRAE 15-2019 machinery rooms | | ASHRAE 15.2P (proposed) small residential direct systems | | JRA 4068T: 2016R | |
| refrigerant exposure for 480-490min (used for long term stability Group II test) | | | | | | | | | | | | | |
| Does the sensor show false or nuisance trips or does it show poisoning after being subjected to the gas and vapor types specified by Table LL.4A.1DV | primary | | | LL.4ADV | yes/no | | | | | | | 5.2.2/5.3.2/ 5.2.7.1/5.3.6.1 | Ethyl Alcohol (1,000 ppm), Hydrogen (500 ppm), Methane(10000-12500ppm) |
| Capable of meeting response time requirement | primary | LL.3 | Shall make output according to the applicable clauses of Annex GG of this standard within 30 s when the sensor is put into refrigerant concentration of 25 % of LFL or lower | LL.3DV | Shall provide an output according to applicable clauses of Annex GG of this standard within 10 s or less when the sensor is put into refrigerant concentration of 100 % of LFL or lower. | 7.6.5 b | Shall activate the functions required by Section 7.6.2.4 within a time not to exceed 15 seconds when the refrigerant concentration reaches 25% of the LFL. | 8.13.9 b | Shall activate responses within a time not to exceed a limit specified in Sections 8.13.10 and 8.13.11 after exposure to refrigerant concentration exceeding a limit value specified in Sections 8.13.10 and 8.13.11. | 13.1.2 | shall activate within 10 seconds when the detector is put into refrigerant concentration of 25 % of LFL or lower | 5.2.4/5.3.4 | Performance Criteria 1&2 - 30sec, Performance Criteria 3 - 60sec |
| Can meet response time requirement throughout temperature range, (pressure range?), and humidity range of the installed environment | primary | LL.3 | see Annex AA | LL.3 | see Annex 101.DVA | | | | | | | 4.2 5.2.3/5.3.3/ 5.2.7/5.3.6 | yes/no |
| "Within the unit" | | | yes/no | | yes/no | | | | | | | | |
| "Remote from unit" | | | yes/no | | yes/no | | | | | | | | |
| Can the sensor resist condensation (JRA 10.9) | | | | | | | | | | | | 5.2.8/5.3.7 | yes/no |

| **Requirement** | **Priority** | **Standards** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **IEC 60335-2-40 Edition 6.0 (Jan-2018)** | | **UL/CSA 60335-2-40 edition 3** | | **ASHRAE 15-2019 direct systems** | | **ASHRAE 15-2019 machinery rooms** | | **ASHRAE 15.2P (proposed) small residential direct systems** | | **JRA 4068T: 2016R** | |
| Accuracy of setpoint | primary | LL.4 | accuracy ±20% of setpoint | LL.4 | accuracy ±20% of setpoint | | | | | | | 5.2.1 | Performance Criteria 1 & 2: ±25% |
| Includes output for signal or trigger of mitigation and ventilation | primary | LL.5 | yes/no | | | 7.6.2.4 | | 8.11.5 | yes/no | | | 7.5/7.7 | |
| Resistance to vibration, can pass required vibration test | primary | LL.6 | two samples each vibrated for 1 hour each in 3 planes; after shall be tested to verify they still sense refrigerant at 25 % of LFL or lower | | | | | | | | | | |
| Includes means for self-testing? | primary | LL.7 | yes/no | LL.7/LL.7DV | yes/no | 7.6.5 d | yes/no | 8.13.9e | yes/no | 13.1.5 | yes/no | 7.8 | yes/no |
| Self-tests include open circuit, shorted circuit and output out of range | primary | | | LL.7DV | yes/no | | | | | | | | |
| Self-test at least every hour | primary | LL.7 | yes/no | LL.7/LL.7DV | yes/no | | | | | 13.1.5 | yes/no | | |
| Active trouble alarm if a failure is detected | primary | LL.7 | yes/no | LL.7/LL.7DV | yes/no | 7.6.5 d | yes/no | 8.13.10.4 | yes/no | 13.1.5 | yes/no | 7.8 | yes/no |
| Active mitigation if a failure is detected | primary | | | LL.5DV/LL.7DV | yes/no | 7.6.5 d | yes/no | | | | | | |
| Does refrigerant sensor have a defined life? | primary | LL.7 | yes/no | LL.7 | yes/no | | | | | 13.1.5 | yes/no | | |

| Requirement | Priority | Standards | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | IEC 60335-2-40 Edition 6.0 (Jan-2018) | | UL/CSA 60335-2-40 edition 3 | | ASHRAE 15-2019 direct systems | | ASHRAE 15-2019 machinery rooms | | ASHRAE 15.2P (proposed) small residential direct systems | | JRA 4068T: 2016R | |
| If there is a defined life, does sensor have end of life indication meeting the requirements? | primary | LL.7 | after a given period, then the detection system shall initiate an alarm or indication that replacement is required | | | | | | | 13.1.5 | yes/no | | |
| If there is a defined life, is end of life indication omitted? | primary | LL.7 | If sensor becomes more sensitive with aging to generating a false alarm, the end of life alarm can be omitted. | | | | | | | 13.1.5 | yes/no | | |
| Sensor marking and identification meets requirements | secondary | LL.8 | yes/no | LL.8DV | yes/no | | | | | | | | |
| Construction shall meet all requirements of JRA section 6 | | | | | | | | | | | | 6.1-6.6 | adequate Strength and easy maintenance/ Corrosion resistance/ waterproof property/ explosion proof/ easy for operational status check/ protected from unauthorized person |

## Appendix B: Step-change test result for Sensors A, C, D, E (Phase 1*)

Note: Information for Sensors B and F are not shown in this appendix. The data for Sensor B is included in the main part of the report, while Sensor F is an indicating-type sensor.

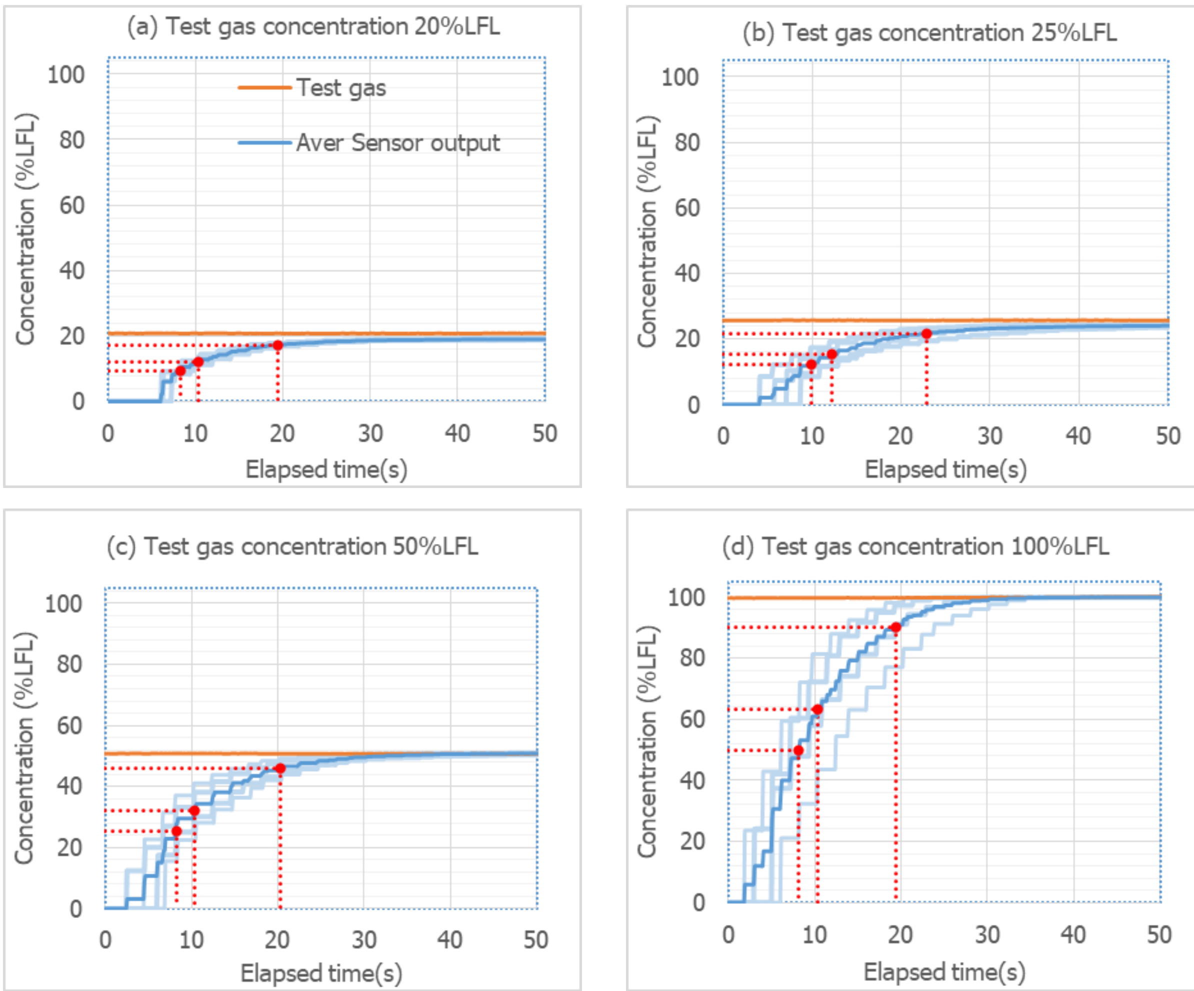



**Figure B-1. Step-change Test Result for Sensor A (Phase 1)**

* Sequence of sensor letter code in Phase 1 is different from Phase 3.

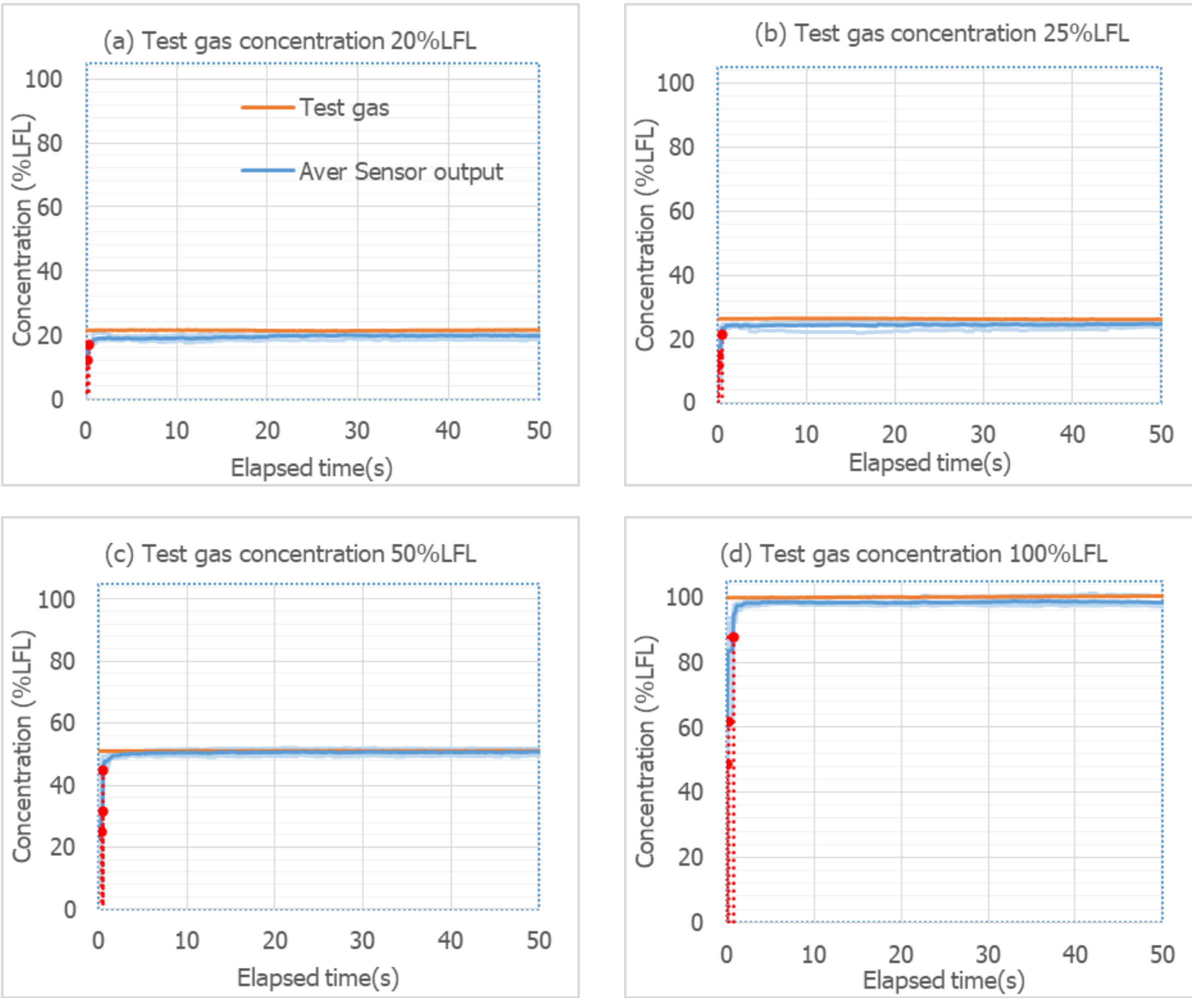



**Figure B-2. Step-change Test Result for Sensor C (Phase 1)**

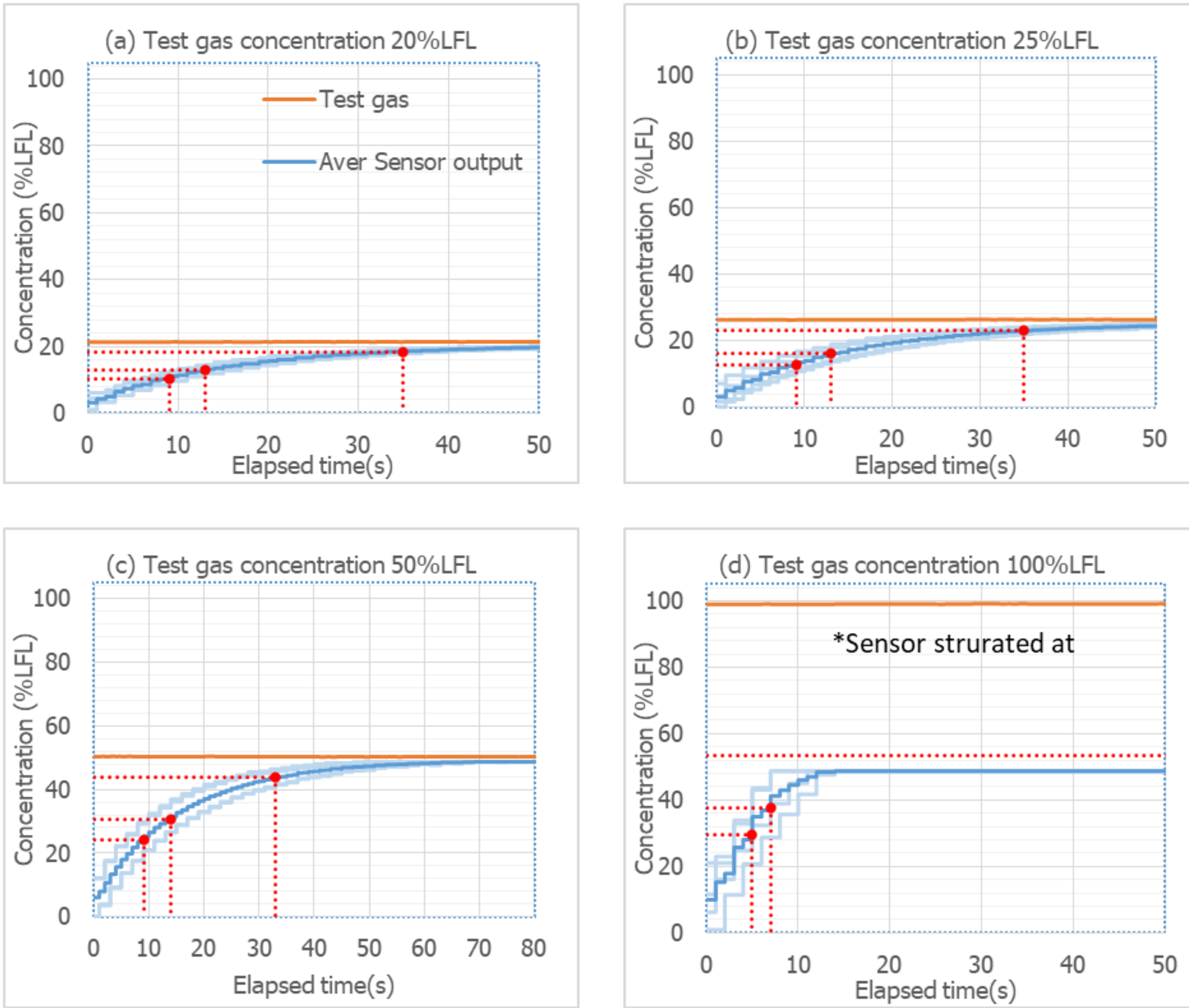



**Figure B-3. Step-change Test Result for Sensor D (Phase 1)**

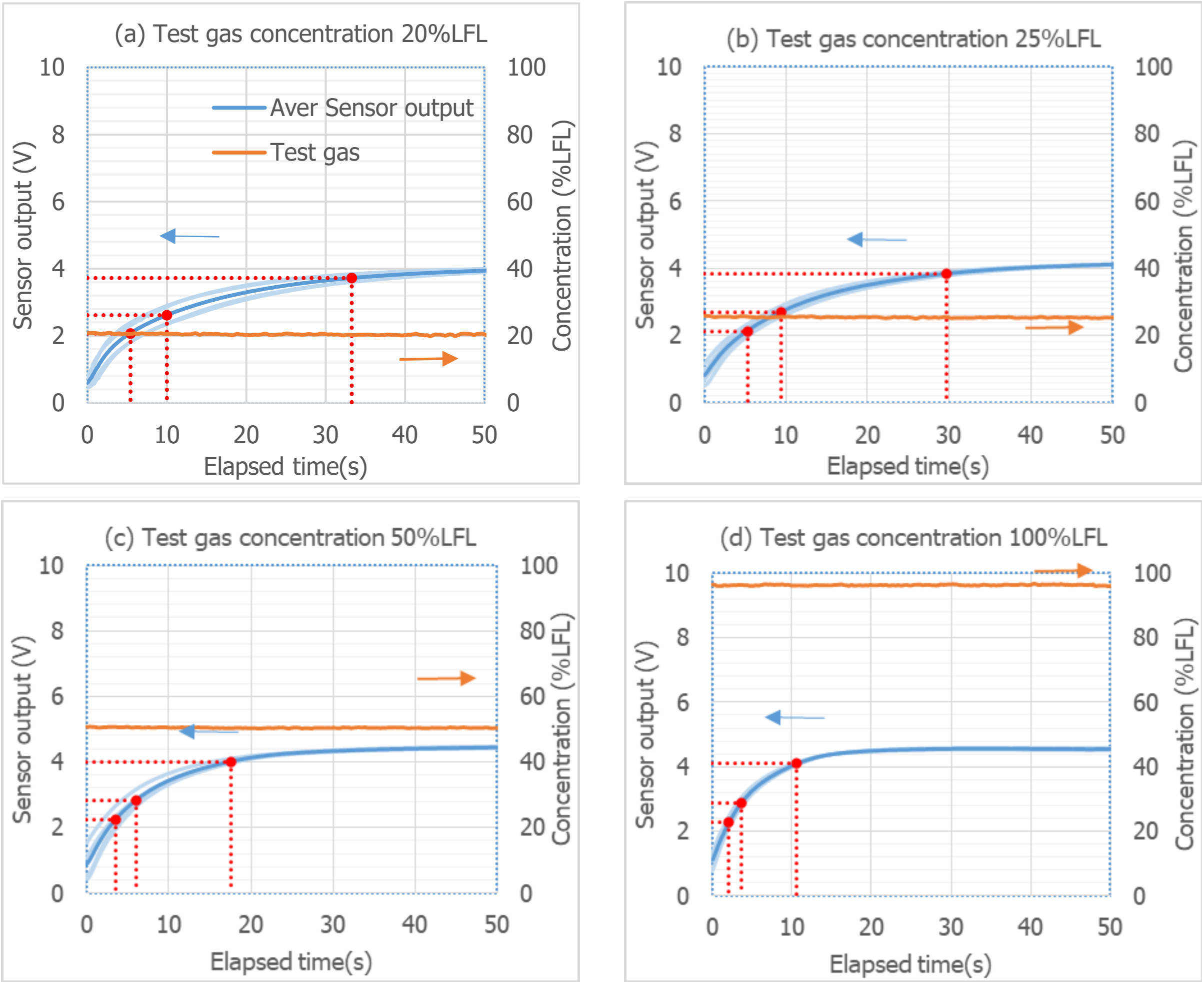



**Figure B-4. Step-change test result for Sensor E (Phase 1)**

## Appendix C: Time-varying test results for Sensors A, C, D, E, F (Phase 1*)

Note: Information for Sensor B is not shown in this appendix. The data for Sensor B is included in the main part of the report.

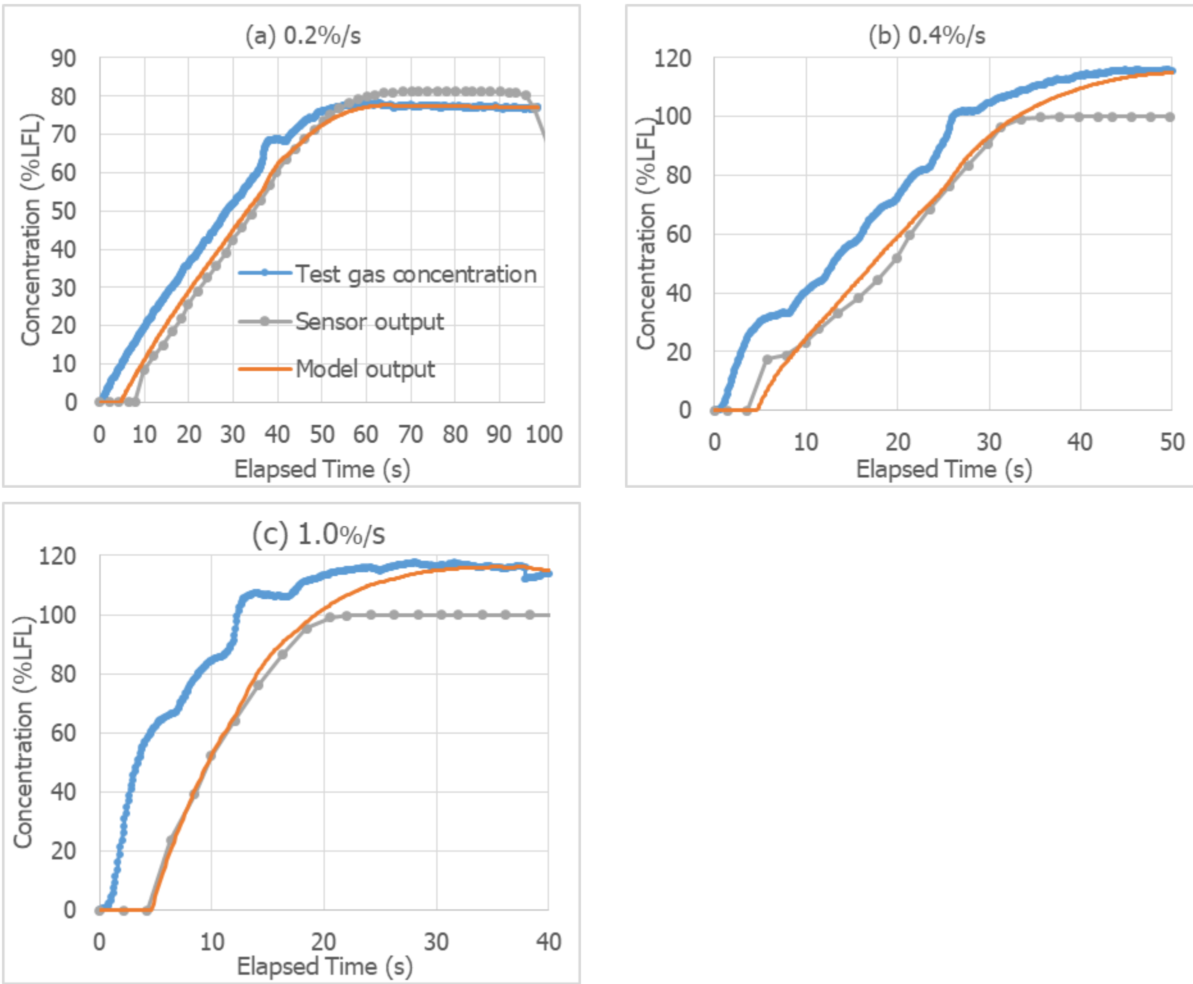



**Figure C-1. Time-varying Test Result for Sensor A (Phase 1)**

* Sequence of sensor letter code in Phase 1 is different from Phase 3.

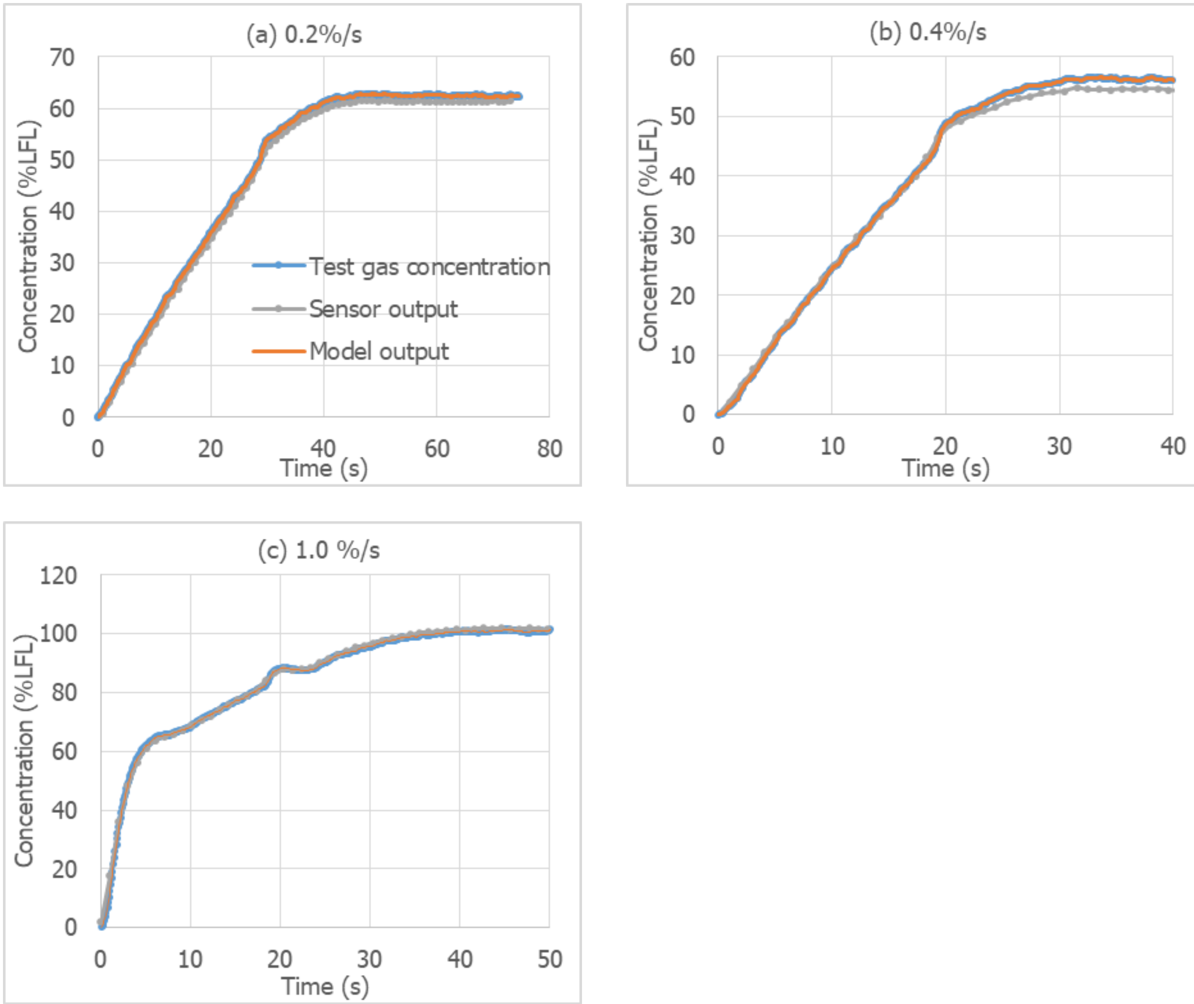



**Figure C-2. Time-varying Test Result for Sensor C (Phase 1)**

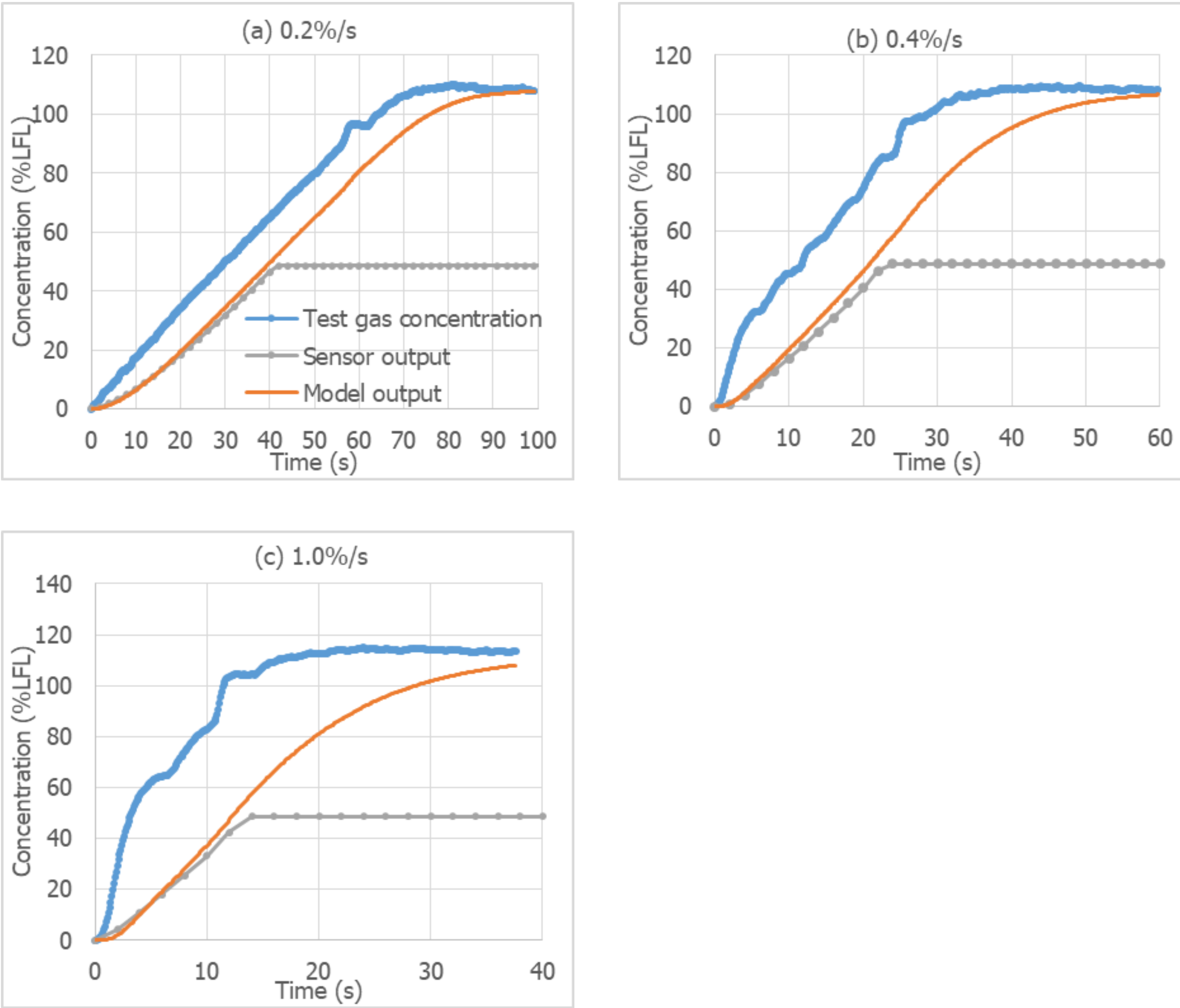



**Figure C-3. Time-varying Test Result for Sensor D (Phase 1)**

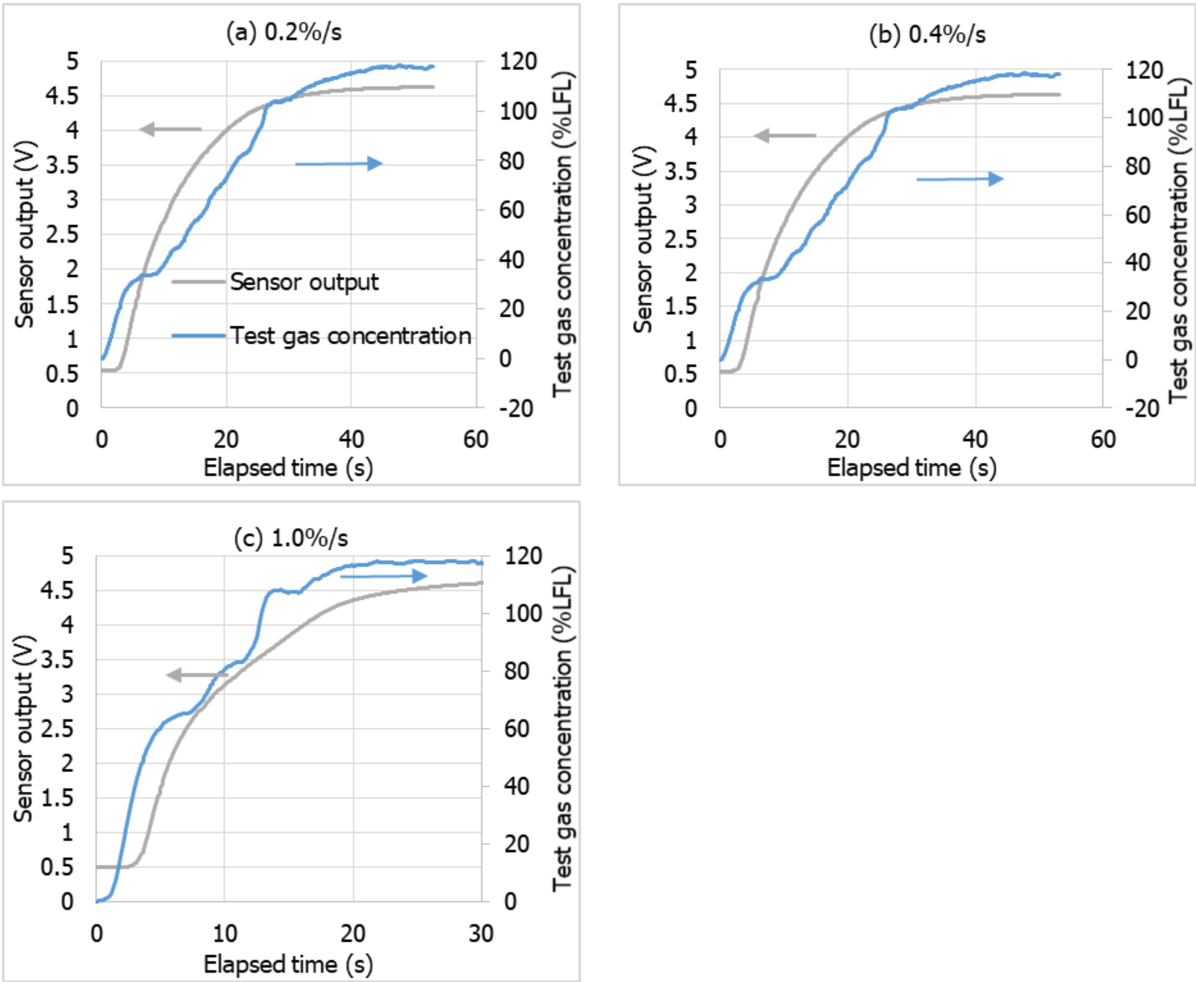



**Figure C-4. Time-varying Test Result for Sensor E (Phase 1)**

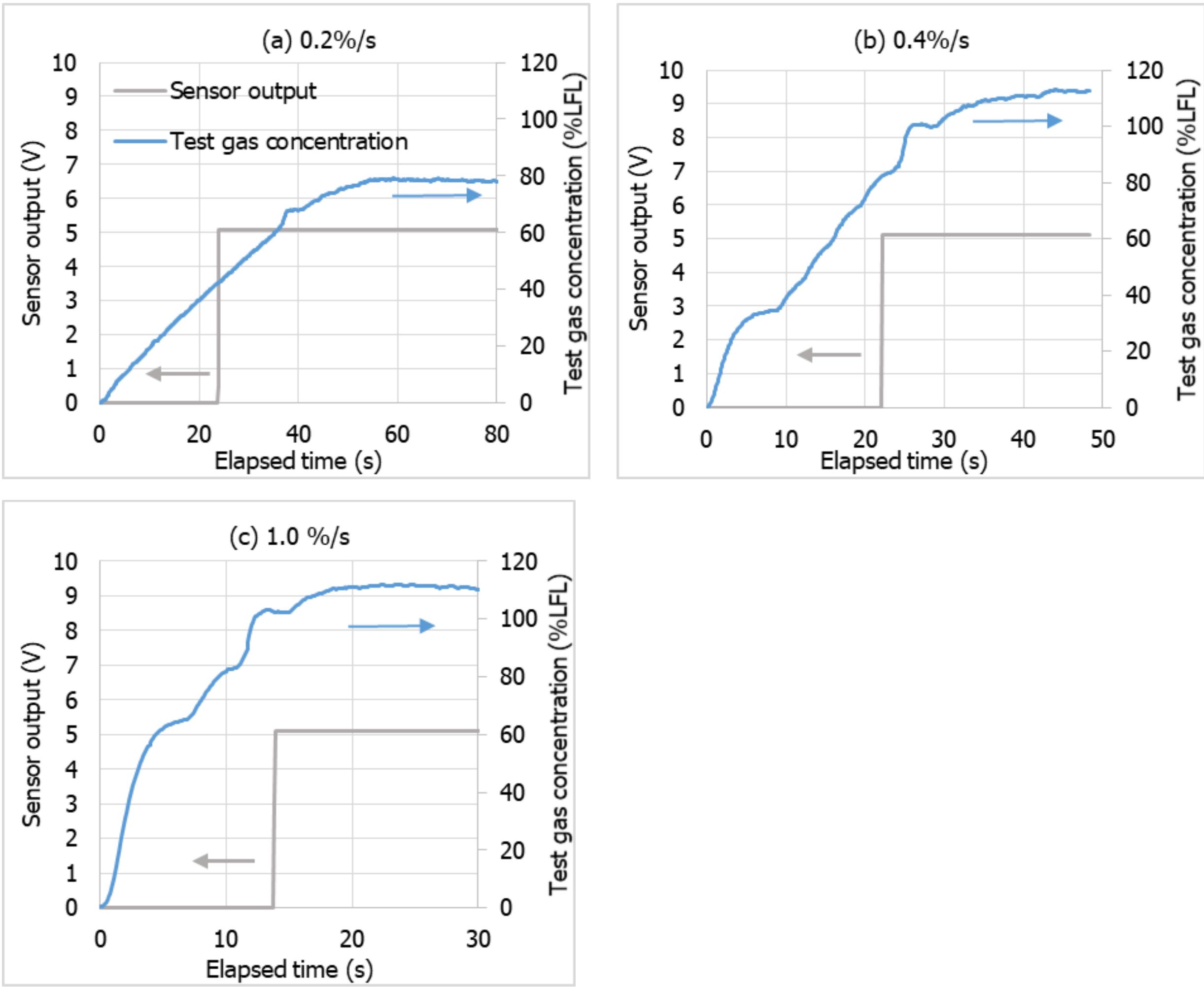



**Figure C-5. Time-varying Test Result for Sensor F (Phase 1)**

## Appendix D: Additions since submission of draft report

### Item A: Improved step-change response for Sensor A (Phase 1*) by updating the firmware

As required by the manufacturer, an additional step-change test has been carried out on Sensor A with updated firmware. The same test setup and test method have been used for this test. The sensor firmware was updated through the manufacturer's website before the test.

Figure D-1 compares the test results before and after the firmware update. The improvement of the time delay, time constant, and the maximum allowable setpoints by the firmware update are summarized in Tables D-1 and D-2.

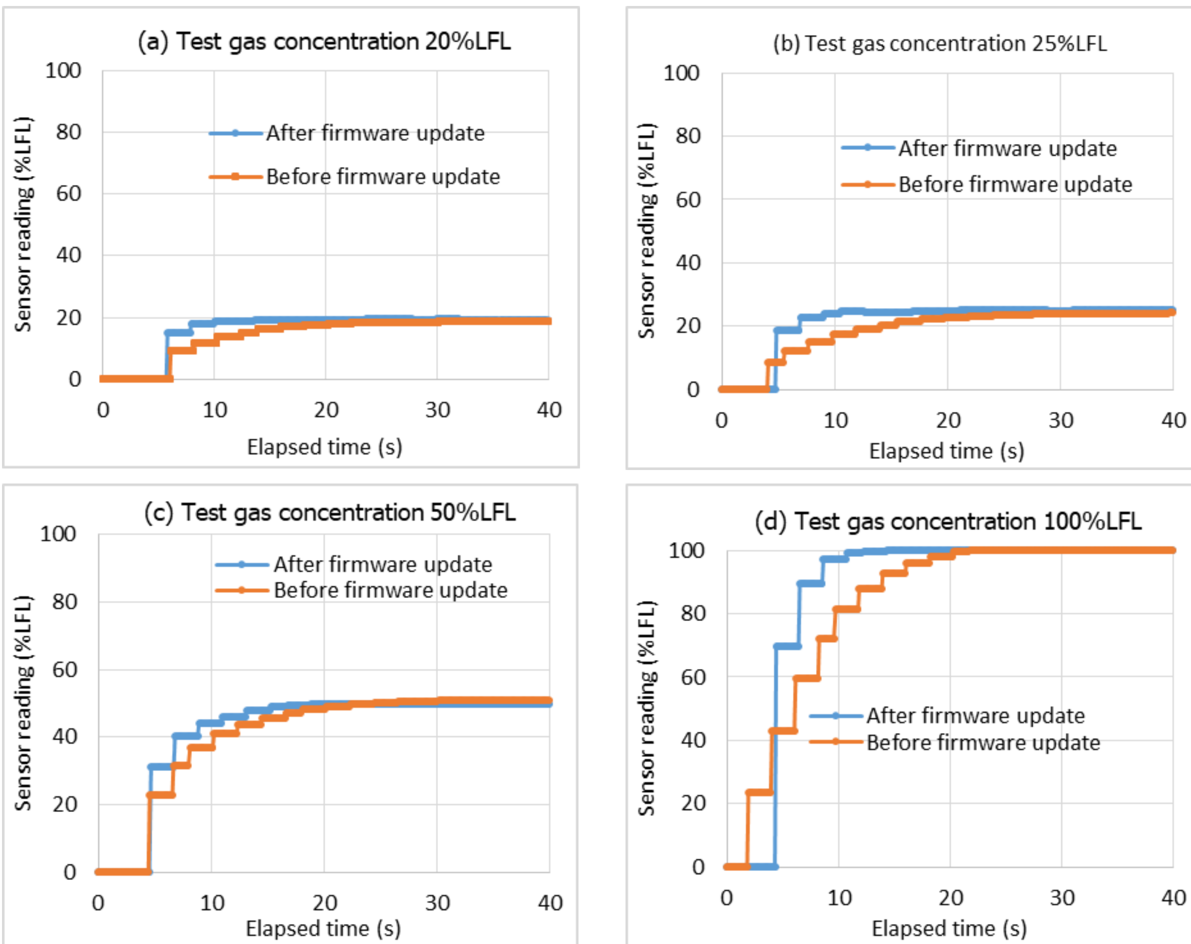



**Figure D-1. Step-change test result for Sensor A (Phase 1) before and after firmware update**

* Sequence of sensor letter code in Phase 1 is different from Phase 3.

**Table D-1. Time Delay and Time Constant for Sensor A (Phase 1) before and after Firmware Update**

| Sensor | | | Time delay $\theta$ (s) | Time constant $\tau$ (s) |
|---|---|---|---|---|
| A | Before firmware update | Sample 1 | 4.4 | 4.7 |
| | | Sample 2 | 6.3 | 6.6 |
| | | Average | 5.4 | 5.6 |
| A | After firmware update | Sample 1 | 4.4 | 0.0 |
| | | Sample 2 | 4.6 | 0.5 |
| | | Average | 4.5 | 0.25 |

**Table D-2. Maximum Allowable Setpoint for Sensor A (Phase 1) before and after Firmware Update**

| Standard | Test gas concentrati on | Response time requirement | Maximum allowable setpoint of Sensor A (%LFL) | |
|---|---|---|---|---|
| | | | Before firmware update | After firmware update |
| ASHRAE 15-2019 | ⩽25%LFL | ⩽15s | 16.4 | 24.5 |
| IEC 60335-2-40 ED6 | ⩽25%LFL | ⩽30s | 21.7 | 24.7 |
| UL/CSA 60335-2-40 ED3 | ⩽100%LFL | ⩽10s | 32.3 | 98.5 |

#### Item B: Improved response for Sensor B (Phase 1*) with updated firmware

As required by the manufacturer, Sensor B has been sent back to the manufacturer for a firmware update. All tests were repeated afterwards. Figure D-2 compares the step-change response of Sensor B before and after the firmware update.

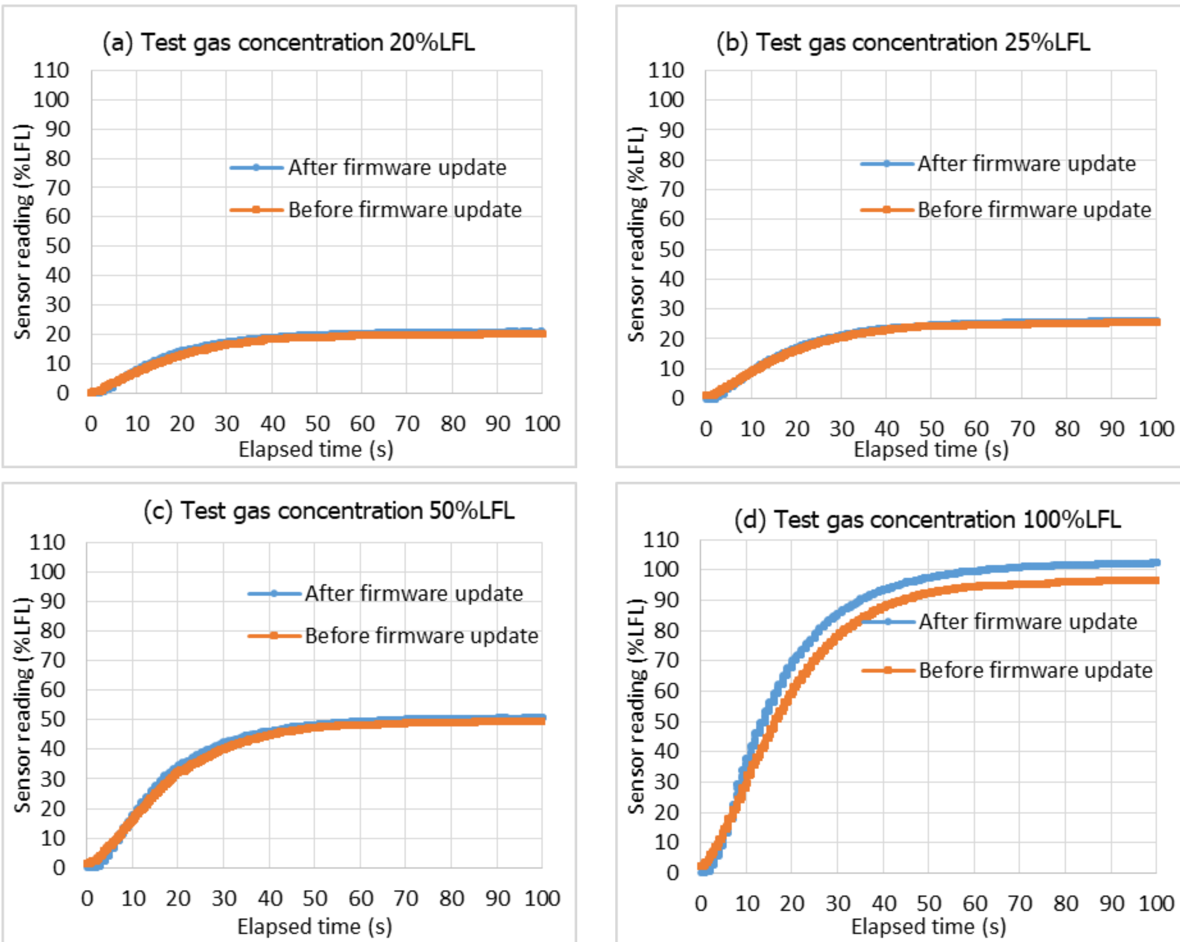



**Figure D-2. Step-change Test Result for Sensor B (Phase 1) before and after Firmware Update**

* Sequence of sensor letter code in Phase 1 is different from Phase 3.

**Table D-3. Time Delay and Time Constant for Sensor B (Phase 1) before and after Firmware Update**

| Sensor | | | Time delay $\theta$ (s) | Time constant $\tau$ (s) |
|---|---|---|---|---|
| B | Before firmware update | Sample 1 | 1.4 | 18.1 |
| | | Sample 2 | 2.4 | 18.3 |
| | | Average | 1.9 | 18.2 |
| B | After firmware update | Sample 1 | 1.2 | 14.8 |
| | | Sample 2 | 2.0 | 16.7 |
| | | Average | 1.6 | 15.8 |

Tables D-3 and D-4 summarize the difference of the time delay, time constant, and the maximum allowable setpoints before and after the firmware update.

**Table D-4. Maximum Allowable Setpoint of Sensor B, Phase 1 (%LFL)**

| Standard | Test gas concentration | Response time requirement | Maximum allowable setpoint of Sensor A (%LFL) | |
|---|---|---|---|---|
| | | | Before firmware update | After firmware update |
| ASHRAE 15-2019 | ⩽25%LFL | ⩽15s | 11.2 | 12.2 |
| IEC 60335-2-40 ED6 | ⩽25%LFL | ⩽30s | 19.4 | 19.9 |
| UL/CSA 60335-2-40 ED3 | ⩽100%LFL | ⩽10s | 22.8 | 33.3 |

The time-varying tests have also been performed on Sensor B with updated firmware. The effects of the new firmware on the 'Time-varying alarm delay' and 'Time over RCL' are shown in Table D-5.

**Table D-5. Time-varying Alarm Delay and Time over RCL for Sensor B (Phase 1) before and after Firmware Update**

| Configuration | Standard to meet | Setpoint (%LFL) | Time-varying alarm delay (s) | | | Time Over RCL* (s) | | |
|---|---|---|---|---|---|---|---|---|
| | | | 0.2%/s | 0.4%/s | 1.0%/s | 0.2%/s | 0.4%/s | 1.0%/s |
| Before firmware update | ASHRAE 15-2019 | 11.2 | 14.8 | 10.7 | 8.1 | 6.9 | 9.0 | 7.5 |
| | IEC 60335-2-40 ED6 | 19.4 | 17.2 | 14.9 | 9.7 | 14.1 | 14.1 | 9.5 |
| | UL/CSA 60335-2-40 ED3 | 22.9 | 18.4 | 15.5 | 11.6 | 17.1 | 15.1 | 11.6 |
| After firmware update | ASHRAE 15-2019 | 12.2 | 13.1 | 8.5 | 5.8 | 6.4 | 6.9 | 5.2 |
| | IEC 60335-2-40 ED6 | 19.9 | 16.2 | 11.6 | 7.4 | 12.5 | 11.0 | 7.2 |
| | UL/CSA 60335-2-40 ED3 | 33.3 | 15.9 | 13.4 | 9.9 | 20.7 | 15.1 | 10.3 |

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*End of Document*

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Effective Date: 3/3/2015

Version B