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XSP Methane Sensors Test and Evaluation Project "M-Step"

Tracy L. Gibson
Southeastern Universities Research Association, Kennedy Space Center, FL

Joel A. Olson
Southeastern Universities Research Association, Kennedy Space Center, FL

Madeleine J. Johnson
Amentum Services Inc., Kennedy Space Center, FL

Carolina Franco
Amentum Services Inc., Kennedy Space Center, FL

Sarah J. Snyder
Amentum Services Inc., Kennedy Space Center, FL

Edgar Zapata
Robert C. Youngquist
Kennedy Space Center, FL

NASA STI Program Report Series

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Robert C. Youngquist
John F. Kennedy Space Center, FL

National Aeronautics and
Space Administration

John F. Kennedy Space Center
Kennedy Space, Florida 32899

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XSP Methane Sensors Test and Evaluation Project
"M-STEP"

An evaluation of commercial methane sensing technology and application to space launch vehicles and facilities

Edgar Zapata and Robert Youngquist
National Aeronautics and Space Administration, Kennedy Space Center, FL

Tracy Gibson, Joel Olson, Madeleine Johnson, Carolina Franco, and Sarah Snyder
Laboratory Support Services and Operations (LASSO), Kennedy Space Center, FL

Contents

1. Introduction ... 1
2. Concept of Operations for a Reusable Launch Vehicle with Methane ... 1
3. Project Approach ... 2
4. Leak Detection Background ... 3
5. Methane Sensing Regulatory and Requirements Background (“Why”) ... 7
6. Methane Sensing Technology (“What”) ... 8
7. Industry and Methane Sensing (“How”) ... 11
8. Methane Sensor Emerging Technologies ... 11
   Tunable Diode Laser Spectroscopy (TDLS) ... 11
   Raman Spectroscopy ... 12
   Surface Plasmon Resonance Sensors ... 12
   Electro-Resistive Sensors ... 13
   Colorimetric Sensors ... 14
9. Survey of Commercial Methane Sensors (“Who”) ... 14
10. Example Sensor Details ... 15
   FLIR GF77 ... 16
   RKI Instruments GX-3R Pro ... 16
   Fireboy®-Xintex® Methane Gas Detector S2B-M-X2 ... 16
   Li-Cor® LI-7700 Open Path CH_4 Analyzer ... 16
   Aeris Technologies Responder™ Advanced Mobile LDS ... 16
   Aeris Technologies MIRA Pico Mobile LDS ... 17
   Edinburgh Sensors Guardian NG Gas Monitor ... 17
   Det-Tronics Combustible Gas Sensor (CGS) ... 17
   Det-Tronics FlexSite™ LS2000 Line-of-Sight Infrared Hydrocarbon Gas Detector ... 17
   Det-Tronics PointWatch Eclipse® PIRECL IR Hydrocarbon Gas Detector ... 17
   Draeger Polytron® 8700 IR ... 17
   Draeger Polytron® 8200 CAT ... 17
   Honeywell GasAlertMicroClip XL ... 18
   MSA Ultima® X5000 Gas Monitor ... 18
   GFG Instrumentation Transmitter IR 29 ... 18
11. Products Selected for Test and Evaluation ... 18
12. Setup and Equipment ... 19
   Det-Tronics PIRECLA11A1T2 Detector ... 19
   Draeger Polytron® 8700 ... 19
   Draeger Polytron® 8200 CAT ... 19

Sensor Details 19
13. Mass Flow Control and Data Collection 21
14. Testing and Results 22
Drift Test 22
Procedure 22
Determining Drift 22
Results – 0% Drift, Air Background 23
Results – 0% Drift, Nitrogen Background 26
Results – 2% Drift, Air Background 29
Results – 2% Drift, Nitrogen Background 32
Lower Detectable Limit Test 35
Procedure – LDL for Increasing Gas Concentrations 35
Determining LDL 36
Results – Air Background Increasing 37
Results – Nitrogen Background Increasing 40
Procedure – LDL for Decreasing Gas Concentrations 42
Determining LDL 43
Results – Air Background 44
Results – Nitrogen Background 47
Stair Step Test 50
Procedure 50
Determining Accuracy 50
Determining Precision 50
Results – Air Background 52
Results – Nitrogen Background 58
Square Wave Test 64
Procedure 64
Determining Repeatability 64
Results – Air Background 66
Results – Nitrogen Background 69
Response Tests 72
Procedure 72
Determining Response Time 72
Determining T-90 and T-10 Times 73
Results – Air Background 74
Results – Nitrogen Background 77

15. Summary........80
16. Acknowledgements........81
Funding........81
Technical Support........81
Hardware and Equipment Support........81
17. Appendix A – Hydrogen Leak and Fire Detector Locations Space Shuttle Launch Pads........82

XSP Methane Sensors Test and Evaluation Project
M-STEP

1. Introduction

Methane sensor technology is employed in industry sectors from oil and gas to agriculture, landfills, and monitoring of natural emissions. The US oil and gas sector is extensive in scale, critical to fulfilling US energy needs, and deals with commodities presenting enormous challenges for personnel safety and the environment. Thus, it is imperative that they have accurate and responsive sensors to detect hazardous gases such as methane.

US space launch systems will increasingly also use liquefied methane and liquefied natural gas (LNG), which is mostly methane, in quantities large and small, as main and auxiliary propulsion and power. Some of these systems will be reusable, which adds the unique challenge of processing a vehicle that has residual commodities and has returned to its launch site to be readied for its next launch.

The methane sensors test and evaluation project (M-STEP) began within the context of a reusable launch system, the Defense Advanced Research Projects Agency (DARPA) Experimental Spaceplane (XSP) program, which would have employed a high-pressure gaseous methane and gaseous oxygen reaction control system. Although the XSP partnership between Boeing and DARPA was terminated by Boeing in early 2020, DARPA and KSC have continued to collaborate in the area of gas sensors with the hydrogen sensor test and evaluation project (H-STEP) and with M-STEP.

The NASA Launch Services program (LSP) invested in M-STEP in FY 2021 "to evaluate and understand the state-of-the-art in methane gas sensors". M-STEP and the LSP effort was complementary, pushing in the same direction to understand US launch system stakeholder needs and approaches, requirements internal (NASA) and external, and commercially available or forthcoming methane sensing technologies, practices, and approaches. In addition, M-STEP (as with H-STEP) enhances KSC capabilities and understanding of these technologies, informing agency investments and further research in these areas.

2. Concept of Operations for a Reusable Launch Vehicle with Methane

There are assorted use cases for a reusable booster that lands with methane to be turned around and re-launched. For the DARPA XSP, the methane scenario involved high pressure gaseous methane and gaseous oxygen composite tanks for its reaction control system and thrusters. While XSP is no longer proceeding, the ingredients of its use case are similar to systems that are forthcoming, particularly (1) residual methane after a return, (2) methane pressure vessels (low and/or high pressure) inside or near adjacent closed compartments, potentially leaking into these enclosed vehicle spaces, and (3) ground support equipment for servicing the methane system.

Large scale methane applications are expected to operate at KSC soon. These include (1) any launcher (aka StarShip) by SpaceX using their Raptor engine, which employs cryogenic liquid methane (CH_4) and liquid oxygen (LOX) including for the reusable booster, (2) the Blue Origin New Glenn launcher with a reusable booster employing LNG, which is mostly methane, and LOX, and (3) the United Launch Alliance Vulcan launcher, using the same engine (BE-4) as New Glenn. These systems will all involve large-scale facilities and ground support equipment. The large scale of the reusable flight systems adds the challenge of large flight tanks and propulsion systems returning to the launch site with residual methane commodities.

3. Project Approach

The M-STEP project approach to testing and evaluating the state-of-the-art in commercial methane sensors was to (1) reach out to US government and industry expertise in the field of methane sensing, (2) reach out to stakeholders, future launch systems, planning to use methane or natural gas in flight and ground systems, (3) understand potential requirements, (4) acquire representative commercially available technologies, and (5) test and evaluate these sensors and technologies at KSC in a laboratory setting.

For the latter, a select number of sensors were procured for test and evaluation. These sensors were chosen as representative of technologies available with an eye on their potential to provide low life-cycle cost, especially low recurring operational costs.

LASSO Project Definition Forms (PDF) #207 and #229 were approved and funded by DARPA and LSP for this task.

Discussions with other US government organizations and agencies include:

- US EPA-planned
- US DOE-planned
- NASA ARC-planned

Discussions with launch system stakeholders include:

- SpaceX
- Blue Origin
- ULA-planned

Initial stakeholder discussions indicated a direction for cryogenic methane or LNG flight systems leak detection is likely similar to traditional systems (discussed ahead, tubing, pulling samples of gas from compartments, analyzing at a ground system, etc.) This traditional direction is likely related to technology maturity, size, and miniaturization (regarding point sensing onboard a mass sensitive vehicle).

However, initial stakeholder discussions have also indicated some lack of definition (natural at this phase) on a vehicle or ground system beyond traditional systems (i.e., what to do with residuals on a reusable flight system, what are goals for the infrastructure, allowable leakage or zero?). Future discussions will continue along these lines.

4. Leak Detection Background

Leak detection and sensing in launch vehicles and facilities at KSC consists of an assortment of systems that together provide situational awareness about system integrity and assure operational safety. On a flight system the hazardous gas and leak detection (HGLD) system may be partly internal and partly external to the vehicle.

By way of example, the Space Shuttle purge, vent, and hazardous gas detection system aboard the Shuttle's external tank (with hydrogen and oxygen tanks) included a gaseous nitrogen (GN2) purge system in its intertank compartment and a vacuum system of other smaller diameter stainless steel tubing pulling a sample of the gases in that compartment as shown in **Figure 1**. These samples would be taken to a system of (rather expensive) mass spectrometers in the ground systems to register the quantities of hydrogen, oxygen, argon, helium, and other gases.

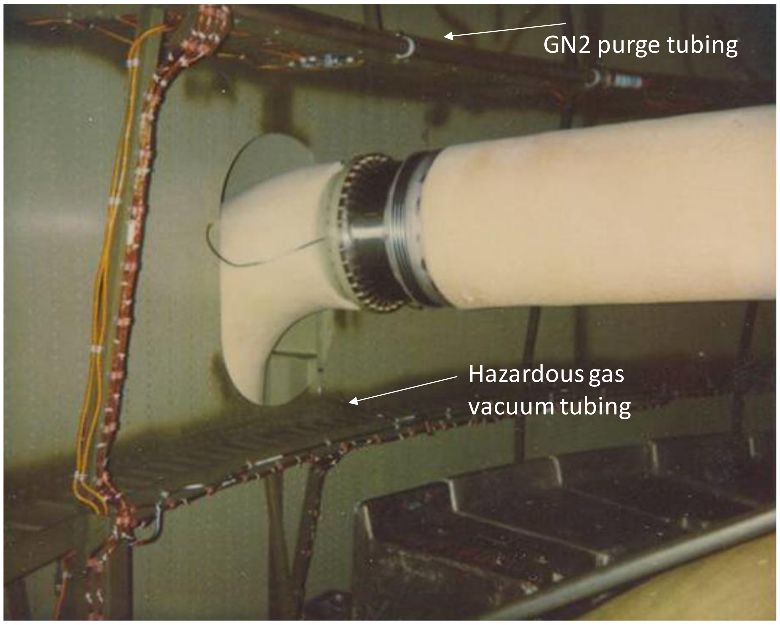


Figure 1: Left, the inside of the Space Shuttle External Tank (ET) intertank, a structural compartment separating the hydrogen and oxygen propellant tanks. The GN2 purge tubing shown filled the compartment with GN2 (provided at an interface to the launch pad facility) and the hazardous gas vacuum tubing pulled samples of the environment (transported off board for analysis by mass spectrometers).

On the Space Shuttle orbiters, the concept was similar to the ET, provide a purge, pull samples of the gas at select locations of the closed compartments (at vents as the gas exits the compartment), analyze and respond. The Space Shuttle orbiter utilized liquid hydrogen throughout its aft compartment main propulsion and engines (just like the XSP would). An added complication on Space Shuttle orbiter vents, since what gas went in as a purge must also have come out, was the need for active, moving vents. The active vent system equalized the unpressurized compartments of the Space Shuttle orbiter to the ambient environment as the orbiter traveled from the pressurized atmosphere of Earth to the vacuum of space.[1] An active vent of this sort (driven by an electromechanical actuator) is shown in **Figure 2**.

On ground systems, leak and fire detectors would also be employed, as in the example in **Figure 3** (also see Appendix A – Hydrogen Leak and Fire Detector Locations Space Shuttle Launch Pads).

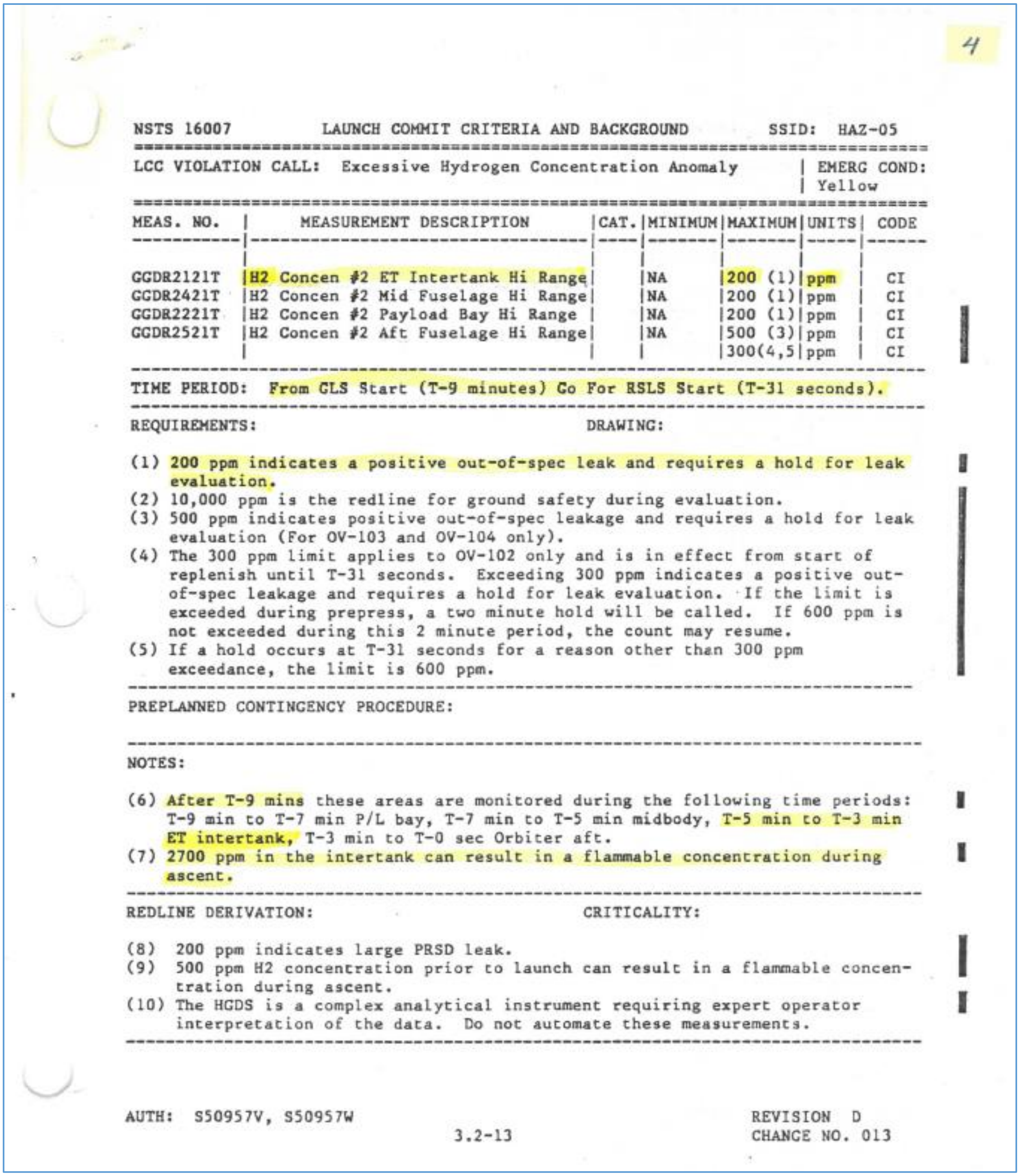
[1] NASA Space Shuttle Handbook, pp.522

During loading of propellants for a Space Shuttle launch all these systems provided critical measurements for assorted launch commit criteria (LCC), at a very fine resolution of parts per million of allowed gases including hydrogen (**Figure 4** shows an example LCC). A violation of these criteria would be cause for a scrub or no-go for launch.

Future methane ground system leak and fire detection systems may look to hydrogen *as a starting point*.

Figure 2: A Space Shuttle orbiters active vent, shown from the inside of the aft compartment.

Figure 3: Launch complex 39-B (LC-39B) hydrogen facility as recently modified after the Space Shuttle program for the Space Launch System. Shown on close-up (bottom image) is one of the new model fire detectors, a Det-Tronics infra-red flame detector focused on water-band emissions. Ultra-violet detectors by the same company have also been installed.



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NSTS 16007 LAUNCH COMMIT CRITERIA AND BACKGROUND SSID: HAZ-05

LCC VIOLATION CALL: Excessive Hydrogen Concentration Anomaly | EMERG COND: Yellow

MEAS. NO.	MEASUREMENT DESCRIPTION	CAT.	MINIMUM	MAXIMUM	UNITS	CODE
GGDR2121T	H2 Concen #2 ET Intertank Hi Range		NA	200 (1)	ppm	CI
GGDR2421T	H2 Concen #2 Mid Fuselage Hi Range		NA	200 (1)	ppm	CI
GGDR2221T	H2 Concen #2 Payload Bay Hi Range		NA	200 (1)	ppm	CI
GGDR2521T	H2 Concen #2 Aft Fuselage Hi Range		NA	500 (3)	ppm	CI
				300(4,5	ppm	CI

TIME PERIOD: From CLS Start (T-9 minutes) Co For RSLS Start (T-31 seconds).

REQUIREMENTS: DRAWING:

(1) 200 ppm indicates a positive out-of-spec leak and requires a hold for leak evaluation.
(2) 10,000 ppm is the redline for ground safety during evaluation.
(3) 500 ppm indicates positive out-of-spec leakage and requires a hold for leak evaluation (For OV-103 and OV-104 only).
(4) The 300 ppm limit applies to OV-102 only and is in effect from start of replenish until T-31 seconds. Exceeding 300 ppm indicates a positive out-of-spec leakage and requires a hold for leak evaluation. If the limit is exceeded during prepress, a two minute hold will be called. If 600 ppm is not exceeded during this 2 minute period, the count may resume.
(5) If a hold occurs at T-31 seconds for a reason other than 300 ppm exceedance, the limit is 600 ppm.

PREPLANNED CONTINGENCY PROCEDURE:

NOTES:

(6) After T-9 mins these areas are monitored during the following time periods: T-9 min to T-7 min P/L bay, T-7 min to T-5 min midbody, T-5 min to T-3 min ET intertank, T-3 min to T-0 sec Orbiter aft.
(7) 2700 ppm in the intertank can result in a flammable concentration during ascent.

REDLINE DERIVATION: CRITICALITY:

(8) 200 ppm indicates large PRSD leak.
(9) 500 ppm H2 concentration prior to launch can result in a flammable concentration during ascent.
(10) The HGDS is a complex analytical instrument requiring expert operator interpretation of the data. Do not automate these measurements.

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Figure 4: An example Space Shuttle launch commit criteria (LCC), the limits of hydrogen leakage allowable for a launch to proceed. Violations of the criteria would scrub the launch, due to an indication of an unacceptable leak.

5. Methane Sensing Regulatory and Requirements Background ("Why")

A complete review of methane sensing and the US government and industry regulatory environment and requirements is beyond the scope of this project; however, a survey of requirements finds many of the same approaches and concerns with methane as for the myriad other fluids and gases that KSC is already familiar with from extensive experience. Safety, sensor reliability, technology limitations in quantifying versus merely detecting a leak, environmental concerns, leakage as waste of a valuable commodity, adverse health effects, and costs of inspections, monitoring, and controls are all important factors. These factors may be put broadly as safety and efficiency. Among the more notable US government agency and industry guidance for methane facilities safety, efficiency and detection of leaks are:

- **Industry**, a sector dominated by gas distribution networks (hundreds of thousands of miles), in partnership with the US Department of Energy (**DOE**), has documented that "a variety of technologies and practices are currently in use across the natural gas industry to detect, quantify, and repair methane leaks".[2]

- The Advanced Research Projects Agency-Energy (**ARPA-E**) at the DOE have invested in novel technologies "to cost-effectively and accurately locate and measure methane emissions associated with natural gas production".[3]

- The US Department of Transportation (**DOT**) Pipeline and Hazardous Materials Safety Administration (PHMSA) "funds LNG research through PHMSA's Pipeline Safety Research and Development grants".[4]

- The US Environmental Protection Agency (**EPA**), Air Emission Measurement Center (EMC) Method 21 sets forth guidance on Volatile Organic Compound leaks, including probes / instruments, methods and other requirements.[5] Acceptable leakage is set in **EPA CFR Part 63**[6] and varies (e.g., from 500pm to 10,000pm; "*There are **25 federal standards** that require facilities to implement LDAR (Leak Detection and Repair) programs.*").[7]

- "Under the Natural Gas Act of 1938 (NGA), **FERC** [the Federal Energy Regulatory Commission] grants federal approval for the siting of new onshore LNG facilities"; this is specific to terminals.

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[2] National Association of Regulatory Utilities Commission (NARUC), "Sampling of Methane Emissions Detection Technologies and Practices for Natural Gas Distribution Infrastructure," A product of the DOE-NARUC Natural Gas Infrastructure Modernization Partnership, https://pubs.naruc.org/pub/0CA39FB4-A38C-C3BF-5B0A-FCD60A7B3098

[3] ARPA-E MONITOR Program, https://arpa-e.energy.gov/?q=programs/monitor

[4] US Department of Transportation, PHMSA, https://www.phmsa.dot.gov/pipeline/liquified-natural-gas/lng-safety

[5] US Environmental Protection Agency, 2017, https://www.epa.gov/sites/production/files/2017-08/documents/method_21.pdf

[6] https://www.govinfo.gov/content/pkg/FR-2006-12-21/pdf/E6-21869.pdf

[7] EPA, "Leak Detection and Repair Best Practices Guide," https://www.epa.gov/compliance/leak-detection-and-repair-best-practices-guide

Of significant consideration in any discussion and planning for launch systems with methane is methane as a powerful greenhouse gas and its contribution to climate change. ***Methane as a powerful greenhouse gas will alone make any discussion about sensing, leaks, residuals, venting, and any emissions, very different from one about other hazardous commodities.***

In summary, the detection and elimination of methane leaks exists in a background of standards, rules and regulations for:

- **Extensive** infrastructure – US oil and gas
- **Safety** – explosive potential, confined spaces; toxicity of Ethyl Mercaptan (odorant)
- Eliminating **waste** – a desire for efficiency, savings, reducing loss of a valuable commodity
- Climate change – CH_4 as a powerful **green-house gas**

A complete review of regulations[8] for methane, sensing and reducing leaks and emissions is beyond the scope of M-STEP. However, stakeholder discussions and sensor test and evaluation will inevitably include approaches in a backdrop of regulatory information, their interpretation as specific requirements and practice.

A discussion of methane leakage, goals, requirements, and technology (apart from safety, efficiency, and cost considerations) inevitably enters into CH_4 as a powerful greenhouse gas. This may mean uncertainty, either tightening of allowed leakage and emissions ("*reduce 2012 levels of methane emissions from crude oil and natural gas wells and machinery by up to 45 percent by 2025*"[9]) or relaxing of requirements ("*…rule would eliminate a 2016 requirement that oil and gas companies monitor and limit methane leaks…*"[10])

6. Methane Sensing Technology ("What")

Various fundamental physical principles for detecting methane led to assorted technology implementations. There are existing surveys of available methane sensing technology[11,12] and assessing the state of the art here is receiving attention in other government agencies and industry (**Figure 5**).

[8] Interstate Technology Regulatory Council, "Evaluation of Innovative Methane Detection Technologies," Chapter 3, Regulations, https://methane-1.itrcweb.org/executive-summary/

[9] https://www.climatecentral.org/news/7-things-to-know-epa-methane-limits-18544

[10] https://www.npr.org/2020/08/13/901863874/trumps-methane-rollback-that-big-oil-doesn-t-want

[11] Interstate Regulator Technology Council, "Evaluation of Innovative Methane Detection Technologies," https://methane-1.itrcweb.org/4-technology/

[12] Air Quality Sensor Performance Evaluation Center, http://www.aqmd.gov/aq-spec/questions

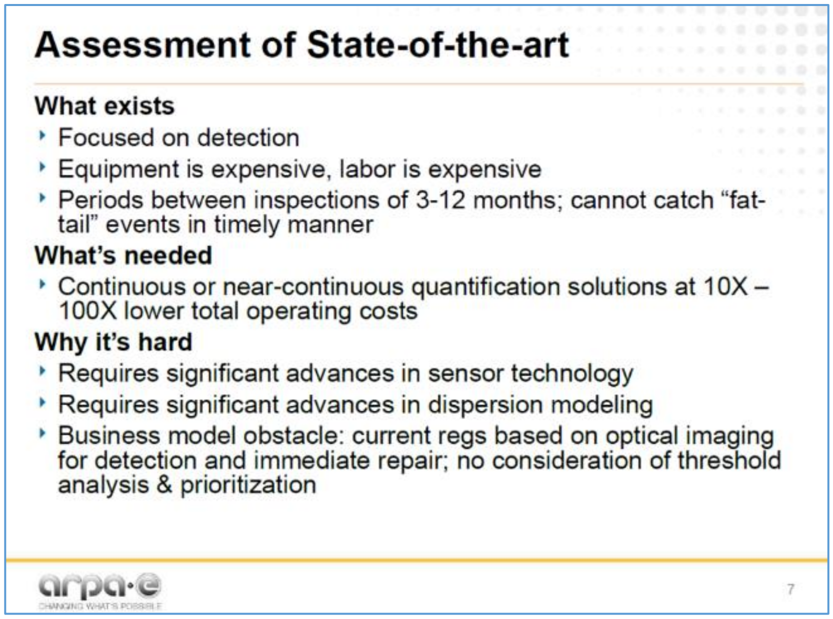

Figure 5: 2015 ARPA-E / Department of Energy assessment of the state of the art in methane sensing.[13]

Methane sensing technology can be categorized under:

1. Flame ionization devices (FIDs)
    - The oldest technology in use.
    - Here, "passing the sample air through a combustion chamber where the sample air is burned at a high temperature in a clear hydrogen flame. Volatile Organic Compound (VOC) and hydrocarbon molecules are charged through the burning process to become ions. The positive charged ions are then collected onto an electrode. The amount of positive charge on the electrode is then proportional to the gas concentration".[14]
2. Semi-conductor metal oxide sensors ("MOS" or "SMO")
    - Measures an increase in electrical current with a drop in oxygen caused by the gas of interest displacing oxygen, allowing the current flow.
    - Manufacturing quality challenges ("…difficulties in applying this process to fabricate gas sensors for mass production with good repeatability and low cost")[15]
    - "…drawbacks for SMO sensors, including poor selectivity, small and high operational temperature range, slow recovery rate, and significant additive dependency. In addition,

[13] Dr. Bryan Willson, DOE, ARPA-E, "Methane quantification & ARPA-E's MONITOR Program," https://19january2017snapshot.epa.gov/sites/production/files/2016-04/documents/21willson.pdf

[14] National Association of Regulatory Utilities Commission (NARUC), "Sampling of Methane Emissions Detection Technologies and Practices for Natural Gas Distribution Infrastructure," A product of the DOE-NARUC Natural Gas Infrastructure Modernization Partnership, pp. 18, https://pubs.naruc.org/pub/0CA39FB4-A38C-C3BF-5B0A-FCD60A7B3098

[15] Chu Manh Hung, Dang Thi Thanh Le, NguyenVan Hieu, 2017, "On-chip growth of semiconductor metal oxide nanowires for gas sensors: A review," https://www.sciencedirect.com/science/article/pii/S2468217917301302

the sensor sensitivity can be affected by the temperature, susceptible to degradation, and sensitive to changes in humidity."[16]

3. Catalytic sensors
   - Measure a change in electrical resistance in the presence of a gas (i.e., via a Wheatstone-bridge circuit).
   - Respond to multiple gases (any combustible).
   - Reliable, to a point; may burn out at high gas concentrations.
   - Susceptible to degradation.
4. Electro-chemical sensors
   - Akin to a fuel cell reaction. The gas being sensed is the fuel, causing an electrical current flow.
5. Infrared (IR) sensors
   - Absorption: methane has an absorption in the wavelengths of 3.3 microns and 7.5 microns. A detector senses when light is missing these wavelengths having passed through methane.
   - This principle does not work for all gases. CH_4 however has a very notable ability to absorb wavelengths detectable with infrared sensors.
6. There is ongoing research in related and other novel approaches:
   - A mass spectrometer on a chip and "photonics".[17]
   - Reflectance spectroscopy where "sensors may provide less specific information but would provide high spatial and temporal resolution, facilitating more rapid responses".[18]
   - Nanotubes, re. NASA Ames Research Center.[19]

Variations on a theme are employing these technologies on drones, laser spectroscopy, mass specs on a chip, optical fiber, LiDAR, and others, even personalized detection capabilities (your cell phone) with an eye on personal awareness (air quality) meets sensor networks.

In summary:

Current methane sensing technology tends to be high cost where high resolution is required and low cost where low resolution is required, and has an ability to locate, but not quantify leaks.

Future system needs / stakeholder wants in technology are generally to have the high resolution at low cost, and to quantify the leak.

[16] Tahani Aldhafeeri, Manh-Kien Tran, Reid Vrolyk, Michael Pope, and Michael Fowler, 2020, "A Review of Methane Gas Detection Sensors: Recent Developments and Future Perspectives," https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwidrvOLg8vrAhUOrFkKHcGbCc8QFjABegQICxAE&url=https%3A%2F%2Fwww.mdpi.com%2F2411-5134%2F5%2F3%2F28%2Fpdf&usg=AOvVaw15QS8-_k93TrF8ksVSLlR6

[17] IBM, https://www.youtube.com/watch?v=hQJYkPSZlw0

[18] Brandy J Johnson1, Jeffrey S Erickson1, Julie Kim2,8, Anthony P Malanoski1, Iwona A Leska3, Stormie M Monk, et al, 2014, "Miniaturized reflectance devices for chemical sensing"; and 2017, "Reflectance-based detection for long term environmental monitoring"

[19] NASA, https://technology.nasa.gov/patent/TOP2-112

7. Industry and Methane Sensing ("How")

Industry approaches implementing methane sensing involve assorted technology. Current practice includes:

1. Walk downs of systems, an audio, visual, olfactory (AVO) survey (**frequently**); olfactory detection requires the addition of a second gas that has an odor since methane is odorless.
2. Gas sensing of wide areas on a less regular basis
    a. An inspector with an infrared (IR) camera visually noting problems, locations, inspection time and dates.
    b. Similar IR technology on aerial drones, especially for difficult to access locations at heights, inside large, closed compartments, in hazardous and cramped spaces.
    c. Similar IR technology (laser scanner and/or hand-held) deployed on some schedule for a survey of a wide area
    d. A technician with an IR camera guiding another technician in locating a leak with a hand-held probe.
3. Monitoring using point sensors, installed permanently, fixed (**continuous**)
    a. IR point, catalytic, semiconductor sensors, etc.

8. Methane Sensor Emerging Technologies

Tunable Diode Laser Spectroscopy (TDLS)

The primary traditional methods of methane detection (IR absorption, and electro-catalysis sensors) have the advantage of being well-established and reliable. There is a more recently developed detection method that is a variation on the IR absorption technique, namely tunable diode laser spectroscopy (TDLS).[20,21] For this method, a diode IR laser is tuned to the absorption peak maximum of a target analyte. Then the wavelength of the tunable laser is adjusted to be just off the peak maximum a small amount. By measuring just a few wavelengths near the peak maximum, the peak center and height can be measured, thus confirming the identity of the analyte, as well as providing the concentration (assuming a calibration standard was measured). This approach takes advantage of the high absorptivities of organic compounds in the IR spectral range, as well as the reliable absorption wavelengths for gas-phase organics but simplifies the required optical system. Also, unlike many of the emerging technologies, it does not depend on analyte adsorption onto a transducer surface, which may degrade or become poisoned. Systems of this type are already being implemented, including as harmful gas sensors on the ISS.[22,23] The primary limitation of this approach as a sensor is that it can only measure analytes that have IR-active absorption bands. For instance, this approach would be unsuitable for detection of hydrogen or nitrogen.

[20] Shemshad, J.; Aminossadati, S. M.; Kizil, M. Siddik. A Review of Developments in near Infrared Methane Detection Based on Tunable Diode Laser. Sens. Actuators B Chem. 2012, 171–172, 77–92. https://doi.org/10.1016/j.snb.2012.06.018

[21] Shuk, P.; Mcguire, C.; Brosha, E. Methane Gas Sensing Technologies in Combustion: Comprehensive Review. 2019, *229* (1), 10.

[22] Mudgett, P. D.; Pilgrim, J. S.; Ruff, G. A. PORTABLE MULTIGAS MONITORS FOR INTERNATIONAL SPACE STATION. *SAMAP* 2011, 10.

[23] Silver, J. A.; Kane, D. J. Diode Laser Measurements of Concentration and Temperature in Microgravity Combustion. *Meas. Sci. Technol.* 1999, *10* (10), 845–852. https://doi.org/10.1088/0957-0233/10/10/303.

Raman Spectroscopy

Raman scattering is an optical phenomenon that occurs whenever light scatters from a molecule whose polarizability is also periodic due to some other rotational or vibrational (rovibronic) molecular movement.[24] While the main, (Rayleigh) scattering line is observed, the interacting rovibronic movement can be observed as satellite Stokes and anti-Stokes lines that appear to either side of the primary Rayleigh peak in a spectrum. The difference in frequency from the Rayleigh line is equal to the frequency of the active rovibronic motion (indeed, the Raman scattering phenomenon is the direct result of the addition or subtraction of the rovibronic frequency to the root scattering frequency). While Raman spectroscopy is considered to be closely associated with IR spectroscopy (since it also measures rovibronic motions), it is important to note that IR and Raman vibrational modes do not coincide; some vibrational modes are IR active, some are Raman active, some are active for both, and some are active for neither (predicting the activity of these vibrational modes is based on molecular symmetry and vibrationally-induced changes in dipole moments, so there is no simple rule of thumb). Historically, Raman spectroscopy for chemical analysis was primarily limited to condensed-phase samples due to the low amount of scattering produced by transparent gas samples. The intensity of scattered light can be increased by either increasing the incident light intensity and/or increasing the pathlength of the light through the gas. Recent developments in Raman-based gas sensing have done exactly that. One recent approach uses a laser incident beam, with a reflective cell that increases the optical pathlength by reflecting it numerous times through the cell.[25] Developed as a DOE funded project, such a system can quantitatively measure numerous gas types, including some that are not IR active (e.g., oxygen and nitrogen). One significant advantage of Raman spectroscopy over IR spectroscopy is that Raman can be performed with visible light lasers, and therefore Raman does not require an IR optical system.

Surface Plasmon Resonance Sensors

Surface plasmons are transverse electron waves at the surfaces of (typically) metals that can be thought of as analogous to waves on the ocean. Indeed, it is the absorption of surface plasmons that give metals such as gold and copper their characteristic and distinctive colors, and also give rise to the colors associated with metal nanoparticles. As might be expected, surface plasmon absorption is very sensitive to the surface upon which it travels. Thus, if an analyte were to adsorb to the surface, it would alter the characteristics of the surface plasmon absorption. One implementation of this phenomenon into a sensor is the surface plasmon resonance (SPR) scheme.[26] In this arrangement, a thin, optically transmissive layer of gold is applied to the surface of an optical prism. Then a laser is used to irradiate the gold from the back (prism) side. Since the gold layer is thin enough to be optically transmissive, the laser light can interact with the surface of the gold to absorb light to form a surface plasmon (i.e., a resonance, thus SPR). The SPR absorption intensity is dependent on the incidence angle of the laser and can be measured as a reduction of the reflected light. If the laser angle of incidence is adjusted, an SPR maximum can be observed as a minimum in the reflected light. The angle at which the absorption maximum occurs is remarkably sensitive to the surface conditions at the top of the gold layer. Thus, if an analyte adsorbs to the surface (typically even in sub-monolayer amounts), the angle of the SPR absorption maximum will shift accordingly, and the amount of shift is dependent on the surface concentration, which is in-turn dependent on the partial pressure of the gas above the surface. Thus, SPR can be used for quantitative measurements. Advantages of SPR

[24] Long, D. A. The Raman Effect: A Unified Treatment of the Theory of Raman Scattering by Molecules; Wiley, 2002.

[25] Buric, M.; Falk, J.; Woodruff, S.; Chorpening, B. Gas Phase Raman Scattering: Methods and Applications in the Energy Industry. In *Encycl. Spectrosc. Spectrom. (3rd Ed.)*; Elsevier Ltd., 2017; Vol. 2, pp 8–17. https://doi.org/10.1016/b978-0-12-409547-2.12165-1.

[26] Masson, J.-Francois. Portable and Field-Deployed Surface Plasmon Resonance and Plasmonic Sensors. Anal. Camb. U. K. 2020, 145, 3776–3800. https://doi.org/10.1039/d0an00316f.

systems is that they show very high sensitivities, and thus very low detection limits. They can also be easily miniaturized and have been implemented in so-called "lab on a chip" architectures.[27] However, SPR itself does not provide selectivity; any adsorbing analyte will induce an SPR response (indeed, this is a limitation of most adsorption-based sensor transducers). Therefore, much of the work in SPR sensors is directed toward gaining specificity by chemical modification of the gold surface typically via the fabrication of chemically functionalized self-assembled monolayers (SAMs). With an array of such chemically functionalized SPR transducers, specificity for different analytes can be achieved by comparing the responses of the different sensor elements (this is the so-called "electronic nose" approach).

Electro-Resistive Sensors

These devices can vary widely in geometry, but generally involve either a thin film or (more recently) a thin layer of nanotubes. Typically, the thin film is either a semiconductor or insulator. The basis for these types of sensors is simply to place a voltage across the thin film, and then measure the resulting current to find the resistivity of the thin film. Adsorption of an analyte onto the surface of the thin film induces changes in the near-surface electronic structure. For a bulk material, these changes would not be noticeable since the majority of electrical conduction occurs through the bulk. However, for thin films, the only conductive path lies in the near-surface region, and thus depends heavily on the electronic structure there. Thus, the adsorption of an analyte can manifest itself as a change in the resistivity. There are myriad ways to arrange such a system, with myriad materials. While the concept has been investigated for decades, recent work has used zinc oxide, gallium oxide, tin oxide, and carbon nanotubes (CNTs).[28, 29, 30, 31, 32, 33, 34] These sensors are adsorption-based, and thus have the same difficulties with selectivity and surface poisoning as the SPR approach. The use of CNTs as sensor transducers is a more recent development, including a complete device fabricated by researchers at NASA.[35] CNTs have several advantages: they are very inert (and thus not as

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[27] Schuster, T.; Herschel, R.; Neumann, N.; Sfaeffer, C. G. Miniaturized Long-Period Fiber Grating Assisted Surface Plasmon Resonance Sensor. J. Light. Technol. 2012, 30, 1003–1008. https://doi.org/10.1109/JLT.2011.2166756.

[28] Shah, N. A.; Gul, M.; Abbas, M.; Amin, Muhammad. Synthesis of Metal Oxide Semiconductor Nanostructures for Gas Sensors. In Gas Sens.; IntechOpen Ltd., 2020; pp 1–23. https://doi.org/10.5772/intechopen.86815.

[29] Mounasamy, V.; Mani, G. K.; Madanagurusamy, Sridharan. Vanadium Oxide Nanostructures for Chemiresistive Gas and Vapour Sensing: A Review on State of the Art. Microchim. Acta 2020, 187, 253. https://doi.org/10.1007/s00604-020-4182-2.

[30] Kamieniak, J.; Randviir, E. P.; Banks, C. E. The Latest Developments in the Analytical Sensing of Methane. *TrAC Trends Anal. Chem.* 2015, *73*, 146–157. https://doi.org/10.1016/j.trac.2015.04.030.

[31] Gadkari, A. B.; Shinde, T. J.; Vasambekar, P. N. Ferrite Gas Sensors. IEEE Sens. J. 2011, 11, 849–861. https://doi.org/10.1109/JSEN.2010.2068285.

[32] Kohl, C. D.; Kelleter, J.; Geyer, W.; Ochs, Th.; Krummel, C.; Fleischer, M.; Meixner, H.; Petig, H. Emergent Application Fields for Semiconductor Gas Sensors. Electron Technol. 2000, 33, 13–21.

[33] Khan, Md. A. H.; Rao, M. V. Gallium Nitride (GaN) Nanostructures and Their Gas Sensing Properties: A Review. *Sensors* 2020, *20*, 3889. https://doi.org/10.3390/s20143889.

[34] Basu, S.; Basu, P. K. Nanocrystalline Metal Oxides for Methane Sensors: Role of Noble Metals. J. Sens. 2009, https://doi.org/10.1155/2009/861968.

[35] Sultana, Mahmooda. 3D-Printed Nanosensors for Space Applications. In Abstracts of Papers, 254th ACS National Meeting & Exposition, Washington, DC, USA, August 20-24, 2017; American Chemical Society, 2017; p POLY-616.

susceptible to poisoning), their electronic properties can be tuned by the nanotube geometry, and they can be chemically functionalized to provide an added degree of analyte specificity. Also, the CNT systems can be miniaturized, and thus can be fabricated into an ‘electronic nose’ type of sensor array.

Colorimetric Sensors

The concept of colorimetric changes in the presence of a chemical analyte is as old as the field of chemistry itself. Numerous such tests have been devised and implemented where an analytical indicator changes color when in the presence of an analyte. However, they typically take the form of solution-phase phenomena that are used qualitatively to detect the presence of an analyte (i.e., pH indicators/litmus paper, or the colorimetric drug field test kits used by law enforcement officers), or quantitatively in conjunction with UV-vis spectrophotometry (this forms the basis for numerous analytical methods used in blood tests, for instance). For gas sensing, colorimetric approaches have been used as well. Typically, this takes the form of immobilizing the analytical indicator as a thin film (in order to increase the surface area, and thus the interaction), and then measuring the absorption and/or reflection of the film. One recent embodiment of this approach uses porphyrins immobilized on paper substrates. Porphyrins are colored compounds, ubiquitous in nature (heme and chlorophyll are two examples) and have numerous possible variations in metal ion center and peripheral chemical functionalization. Thus, they can be easily varied with regard to their binding interactions with particular analytes. In general, porphyrins will change colors in the presence of binding compounds. The implementation of this approach uses small colorimetric photo sensors to monitor the paper that has been impregnated with a porphyrin.[36, 37, 38, 39] This approach was developed and has been tested at the Naval Research Laboratory for the purpose of sensing chemical warfare agents but could easily be applied to methane sensing as well.

9. Survey of Commercial Methane Sensors (“Who”)

This survey is not intended to be complete. Rather, this survey is intended to be merely representative of available technologies. Sensors initially identified as being of interest are shown in **Table 1**. Of note:

- Catalytic and IR point sensors for methane appear to have an especially large supplier base.

- Oil and gas industry applications (e.g., Class, Div., etc.), by quantity/hazard, lead to very robust, heavy duty housings for devices vs. the same technology in other applications (environmental/air quality, landfills, agriculture, natural emission monitoring).

- Life cycle cost cases (as advertised by suppliers) seem to favor initially expensive but operationally reliable and no to low maintenance devices. The device that is low cost to acquire, reliable, of high resolution and low cost to own remains elusive, although “low cost” is relative in the context of

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[36] Johnson, B. J.; Malanoski, A. P.; Erickson, J. S. Development of a Colorimetric Sensor for Autonomous, Networked, Real-Time Application. *Sensors* 2020, *20*, 5857. https://doi.org/10.3390/s20205857.

[37] Erickson, J. S.; Johnson, B. J.; Malanoski, A. P. Field Demonstration of a Distributed Microsensor Network for Chemical Detection. Sensors 2020, 20, 5424. https://doi.org/10.3390/s20185424.

[38] Johnson, B. J.; Erickson, J. S.; Kim, J.; Malanoski, A. P.; Leska, I. A.; Monk, S. M.; Edwards, D. J.; Young, T. N.; Verbarg, J.; Bovais, C.; Russell, R. D.; Stenger, D. A. Miniaturized Reflectance Devices for Chemical Sensing. Meas. Sci. Technol. 2014, 25, 095101/1-095101/10, 10 pp. https://doi.org/10.1088/0957-0233/25/9/095101.

[39] Johnson, B. J.; Liu, R.; Neblett, R. C.; Malanoski, A. P.; Xu, M.; Erickson, J. S.; Zang, L.; Stenger, D. A.; Moore, M. H. Reflectance-Based Detection of Oxidizers in Ambient Air. Sens. Actuators B Chem. 2016, 227, 399–402. https://doi.org/10.1016/j.snb.2015.12.040.

extremely expensive infrastructure investment, and "resolution" also requires context against requirements.

Table 1: Commercial methane sensors types and corresponding URL

FLIR IR Camera	https://www.flir.com/news-center/press-releases/flir-launches-its-first-uncooled-methane-gas-detection-camera/	Visual ($$$)
RKI Portable Monitor	https://www.rkiinstruments.com/product/gx-3r-pro/	Catalytic
Fire-boy Xintex System	https://www.fireboy-xintex.com/methane-gas-detection-systems/#Detector	Metal-oxide
LI-COR LI-7700	https://www.licor.com/env/products/eddy_covariance/LI-7700.html	
Aeris Pico-Analyzer	http://aerissensors.com/pico-series/	Drone
Edinburgh Sensors	https://edinburghsensors.com/products/gas-monitors/gas-monitor-guardian-ng/	IR point
LongPath Technologies	https://www.longpathtech.com/home	For large but open areas
Det-Tronics IR Point Sensor	https://www.det-tronics.com/products/pointwatch-eclipse-pirecl-infrared-gas-detector	IR point
Det-Tronics IR Line of Sight System	https://www.det-tronics.com/products/flexsight-ls2000-optical-infrared-gas-detector	IR line of sight
Pergam Suisse AG Laser Methane Mini	https://pergam-suisse.ch/handheld	
Black-line Safety 4-gas Monitor	https://www.blacklinesafety.com/blog/four-gas-monitor-gas-detection	Catalytic
GDS Corp. IR Sensor	https://www.gdscorp.com/Catalog/gds-ir/	Company has many types incl. IR line of sight

10. Example Sensor Details

The following sensors are examples of commercially available methane detectors. This list is meant to be representative and is not, by any means, exhaustive. Images, schematics, technical details, and specifications were sourced from product webpages. Costs, where provided, are based on 2020 quotes provided to NASA by vendors and may have changed.

FLIR GF77

The FLIR GF77 gas sensors[40] are optical gas imaging units. They are available for purchase, and units cost $30,737 each, but the vendor may loan KSC a unit for evaluation. The FLIR GF77 is primarily focused on handheld gas detection applications but has Wi-Fi and Bluetooth® connection options. Units are battery powered, with a typical battery life of four hours under typical use. They are capable of detecting methane in concentrations less than 100 ppm at a distance of one meter. Detailed specifications are given on the product's website.

RKI Instruments GX-3R Pro

The RKI Instruments GX-3R Pro gas detectors[41] are catalytic sensors that have four internal sensors to monitor for multiple gases at once: carbon monoxide and hydrogen sulfide, methane, oxygen, and toxins such as hydrogen cyanide, NO_2, CO_2, or SO_2. There is an optional sample draw pump attachment, otherwise hand aspiration of samples is required. These units are available for purchase and cost $1,362 each (including the pump attachment). These units communicate via Bluetooth® to an app available for iOS and Android and can send text messages to indicate an alarm state. They are battery-powered, with a full charge lasting 25 hours. Detailed specifications are given on the product's website.

Fireboy®-Xintex® Methane Gas Detector S2B-M-X2

The Fireboy®-Xintex® Methane Gas Detector S2B-M-X2 system[42] is a metal oxide/semiconductor-based system, designed such that the presence of air and oxygen at normal levels reduces a current flow across the sensor to zero, but when a combustible gas is present displacing air and oxygen, electrons will flow across the sensor substrate, indicating the presence of the gas. It is designed for use in vehicles, with the monitors designed for mounting in the dash of trucks and buses and optional monitors designed for mounting on the exterior of vehicles. These sensor systems are available for purchase and cost $578. The system manual indicates that the monitor will indicate 20% LEL visually and alarm at 50% LEL but does not indicate any data logging or other communications options. Detailed specifications are given on the product's website.

Li-Cor® LI-7700 Open Path CH_4 Analyzer

The Li-Cor® LI-7700 Open Path CH_4 Analyzer[43] is an IR sensor that uses wavelength modulation spectroscopy to measure methane in ambient air, looking for eddy covariance flux. It was designed for use outdoors, finding methane emissions in the landscape, so it is designed to work in a wide range of environmental conditions. These units are available for purchase. Detailed specifications are given on the product's website.

Aeris Technologies Responder™ Advanced Mobile LDS

The Aeris Technologies Responder™ Advanced Mobile LDS[44] is a portable leak detection system designed for use in any standard vehicle to monitor for methane and ethane as the vehicle is driving, creating a real-time leak map and can also be used as a handheld leak detection system. These sensors use a combination of mid-IR laser spectroscopy and sonic anemometry to determine leak locations and have sensitivity in the ppb range. They are available for purchase at a cost of $36,500. Detailed specifications are given on the product's website.

[40] https://www.flir.com/products/gf77/

[41] https://www.rkiinstruments.com/product/gx-3r-pro/

[42] https://www.fireboy-xintex.com/methane-gas-detection-systems/#Detector

[43] https://www.licor.com/env/products/eddy_covariance/LI-7700.html

[44] http://aerissensors.com/wp-content/uploads/2019/12/MIRA-Responder-LDS_191208_FINAL_quartz.pdf

Aeris Technologies MIRA Pico Mobile LDS

The Aeris Technologies MIRA Pico Mobile LDS[45] is similar to the company's Responder™ sensors, using mid-IR laser spectroscopy to detect methane and ethane with 1 ppb sensitivity. The Pico units are smaller and do not have the incorporated anemometers to factor in wind speed. These units are also available for sale. Detailed specifications are given on the product's website.

Edinburgh Sensors Guardian NG Gas Monitor

The Edinburgh Sensors Guardian NG gas monitor[46] is an infrared gas sensor designed to monitor for the presence of either methane, N_2O, or CO_2. The sensors are designed to be wall-mounted units capable of sensing gases from a distance of 30 meters. They provide data via RS232 or Ethernet interfaces. These sensors are available for purchase. Detailed specifications are given on the product's website.

Det-Tronics Combustible Gas Sensor (CGS)

The Det-Tronics CGS[47] is a catalytic bead sensor that is explosion-proof. It is compatible with all Det-Tronics combustible gas transmitters and controllers and can be up to 500 ft from its connection point. These units are available for purchase at a cost of $2,305. Detailed specifications and a schematic are given on the product's website.

Det-Tronics FlexSite™ LS2000 Line-of-Sight Infrared Hydrocarbon Gas Detector

The Det-Tronics FlexSite™ LS2000 Line-of-Sight Infrared Hydrocarbon Gas Detector[48] is designed for outdoor use. The sensor set has two units, a transmitter and a receiver, that can be up to 120 m apart, detecting gases between them. They come in Class I, Div 1 or 2 housings and have 4-20 mA output. These units are available for purchase at a cost of $12,967. Detailed specifications are given on the product's website.

Det-Tronics PointWatch Eclipse® PIRECL IR Hydrocarbon Gas Detector

The Det-Tronics PointWatch Eclipse® PIRECL IR Hydrocarbon Gas Detector[49] is a diffusion-based IR sensor that is calibrated for the detection of methane, propane, ethylene, and butane. These sensors are designed for use in harsh environments and provide a 4-20 mA serial output. These units are available for purchase at a cost of $2,722. Detailed specifications are given on the product's website.

Draeger Polytron® 8700 IR

The Draeger Polytron® 8700 IR[50] is an infrared sensor with a Class I, Div 1, explosion proof housing designed for use in offshore conditions. Its gas library has 100 gases that the unit can be calibrated to detect. The sensors also have an optional accessory for remote calibration and operation of the unit from up to 30 meters away. They have 4-20 mA outputs as well as electronic controls. These units are available for purchase at a cost of $3,465. Specifications are given on the product's website.

Draeger Polytron® 8200 CAT

The Draeger Polytron® 8200 CAT[51] is a catalytic bead sensor designed for detecting flammable gases and vapors. These sensors come in Class I, Div 1 housings and are designed for use in harsh environments. They have 4-20 mA outputs as well as electronic options and, like the Draeger Polytron® 8700, have remote

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[45] http://aerissensors.com/wp-content/uploads/2019/12/MIRA-Responder-LDS_191208_FINAL_quartz.pdf
[46] https://edinburghsensors.com/products/gas-monitors/gas-monitor-guardian-ng/
[47] https://www.det-tronics.com/products/catalytic-combustible-gas-detector
[48] https://www.det-tronics.com/products/flexsight-ls2000-optical-infrared-gas-detector
[49] https://www.det-tronics.com/products/pointwatch-eclipse-pirecl-infrared-gas-detector
[50] https://www.draeger.com/en-us_us/Products/Polytron-87
[51] https://www.draeger.com/en-us_us/Products/Polytron-8200

calibration and operation accessories available. These units are available for purchase at a cost of $1,798. Additional specifications are given on the product's website.

Honeywell GasAlertMicroClip XL

The Honeywell GasAlertMicroClip XL[52] is a catalytic sensor for the detection of O_2, H_2S, CO, and combustible gases. These sensors are designed for use as personal exposure monitors that clip to workers' clothing and alarm in the presence of detected gases. Their batteries last 18 hours under ideal conditions, or 12 hours in cold environments. Real time monitoring of these sensors is available using Honeywell BW™ Connect, an add-on accessory that transmits data from the sensor to a smartphone via Bluetooth®. These units are available for purchase at a cost of $469, not including the cost of the Honeywell BW™ Connect accessory. Additional details are given on the product's website.

MSA Ultima® X5000 Gas Monitor

The MSA Ultima® X5000 Gas Monitor[53] has both catalytic bead and infrared sensors. These units have explosion proof housings and have both a 4-20 mA output and Bluetooth® connection for remote operation and data collection. They are capable of detecting a large number of gases. They are available for purchase. Additional details are given on the product's website.

GFG Instrumentation Transmitter IR 29

The GFG Instruments Transmitter IR 29[54, 55] is an infrared sensor for combustible gas detection. These sensors have an optional accessory called the SB1 Safety Barrier that allows data to be accessed up to 2000 meters away from the source. These devices also store 24 hours of data in internal ring buffers. They are available for purchase at a cost of $2479. Additional details are given on the product's website.

11. Products Selected for Test and Evaluation

Of the prior list, the following methane sensors were down selected to procure, test, and evaluate. Selections were based on available funds and on selecting different, but representative, types of sensors. Testing was conducted in the second half of fiscal year 2021 and completed in the first quarter of fiscal year 2022 in the Kennedy Space Center Applied Chemistry Laboratory with support from the Kennedy Space Center Applied Physics Laboratory. Details of the test conditions and results are shown in later sections of this report.

- Fireboy-Xintex S2B-M-X2 Total Sensor
- Det-Tronics PIRECLA11A1T2 Detector
- Draeger Polytron 8700 334 d S 4-20/HART Stainless Steel Body without relays
- Draeger Polytron 8200 DQ d S 4-20/HART Stainless Steel Body without relays, sensors included
- BW Honeywell GasAlert MicroClip XL Multi-Gas Monitor, MCXL-XWHM-Y-NA
- RKI GX-3R Pro for LEL / O_2 with Alkaline and Li-Ion battery pack with 100-200 VAC charger with RP-3R pro pump w/ 10ft hose

[52] https://www.honeywellanalytics.com/en/products/GasAlertMicroClip-Series
[53] https://us.msasafety.com/c/ULTIMA%C2%AE-X5000-Gas-Monitor/p/000070001800001133
[54] https://goodforgas.com/product/ir-29-gas-transmitter/
[55] https://goodforgas.com/wp-content/uploads/2013/12/IR29_Data_Sheet_V10_Hi.pdf

12. Setup and Equipment

Six sensors were procured for testing and evaluation in the ACL at KSC. The sensors procured were Fireboy-Xintex S2B-M-X2 Total Sensor; Det-Tronics PIRECLA11A1T2 Detector; Draeger Polytron® 8700 334 d S 4-20/HART Stainless Steel Body without relays; Draeger Polytron® 8200 DQ d S 4-20/HART Stainless Steel Body without relays (CAT sensor included); BW Honeywell GasAlert MicroClip XL Multi-Gas Monitor, MCXL-XWHM-Y-NA; and the RKI GX-3R Pro for LEL / O_2 with Alkaline and Li-Ion battery pack with 100-200 VAC charger and RP-3R pro pump w/ 10ft hose. Of the sensors procured, three were chosen for testing and evaluation and three were chosen not to be tested. Those chosen for testing were the Det-Tronics PIRECLA11A1T2 Detector, the Draeger Polytron® 8700, and the Draeger Polytron® 8200. The Fireboy-Xintex S2B-M-X2 sensor was not chosen for testing since it did not have the capability to capture the real-time methane concentration data (it is an audible alarm-only system). The BW Honeywell and RKI products were not chosen since they require proprietary software for downloading the concentration data (the software is not NASA approved) and the data cannot be downloaded in real-time (data is stored on-board the sensor units). Details for the procured sensors follows.

Det-Tronics PIRECLA11A1T2 Detector

The PIRECLA11A1T2 Detector is a rugged stainless steel, point infrared sensor. The performance is certified for methane, propane, ethylene, and butane and is shipped factory set and calibrated for one of these gases.

Draeger Polytron® 8700

The Draeger Polytron® 8700 IR is an advanced explosion proof transmitter for the detection of hydrocarbon gases in the lower explosion limit (LEL) and ppm. It uses a high performance infrared Draeger PIR 7000 sensor, which will quickly detect most common hydrocarbon gases.

Draeger Polytron® 8200 CAT

The Draeger Polytron® 8200 CAT is an advanced explosion-proof transmitter for the detection of combustible gases in the lower explosion limit (LEL). It uses a catalytic bead DraegerSensor® Ex that will detect most flammable gases and vapors.

Sensor Details

The following sensors were tested in this evaluation:

- Det-Tronics PIRECL
    - SN: 20NOV123024
- Draeger Polytron® 8700
    - SN: ARNL-0854 (Draeger Polytron 8700)
    - SN: ARNK-2840 (Draeger PIR 7000)
- Draeger Polytron® 8200
    - SN: ARMK-1278 (Polytron 8200)
    - SN: ARMH-1535 (DraegerSensor Ex)

All of the sensors were tested with background gases of air and nitrogen to determine their efficacy in various potential uses.

A list of the sensors tested, along with the gases used in their evaluation and manufacturer specified methane detection limits, appears in **Table 2**. **Figure 6** shows the general test setup for methane sensor testing.

Table 2: Methane sensors tested along with gases used during the evaluation.

Sensor	Manufacturer-Specified Background Gases	Background Gases Tested	Methane Detection Limits (per Manufacturer)
Det-Tronics PIRECL	Air, Nitrogen, Oxygen	Air, Nitrogen	0-100% LFL
Draeger Polytron® 8700	Air, Nitrogen, Oxygen	Air, Nitrogen	0-100% LEL (0-100 vol %)
Draeger Polytron® 8200	Air, Oxygen	Air, Nitrogen	0-100% LEL

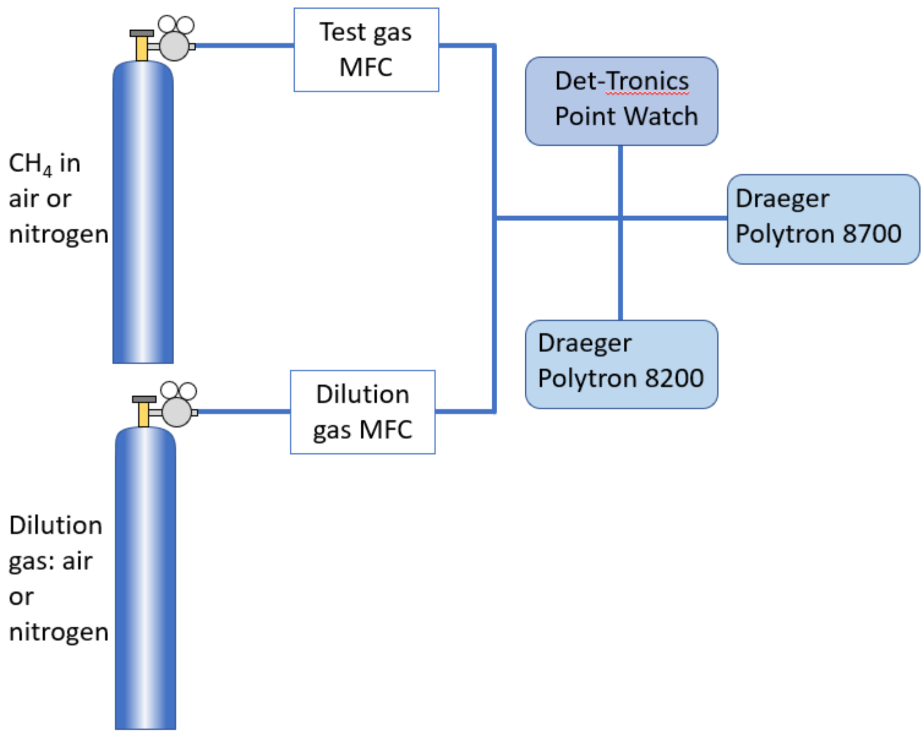

Figure 6: Set-up for methane sensor testing.

Methane gas was provided to all sensors under test from a cylinder of gas with a known concentration of methane in the desired background gas. The upper methane concentrations were limited by safety constraints from the gas vendor. To provide lower concentrations of methane to the sensors, this gas was mixed with an additional source of the background gas. MKS mass flow controllers (MFCs) regulated gas flow from both sources, delivering known concentrations of methane.

The sensors were connected to the methane flow setup using hose barb connectors that put the sensing elements adjacent to the flow of gas through the system. The Det-Tronics sensor came equipped with a hose barb connector and calibration caps were procured for the two Draeger Polytron® sensors to allow them to be connected to the methane gas flow. The connected sensors are shown in **Figure 7**.

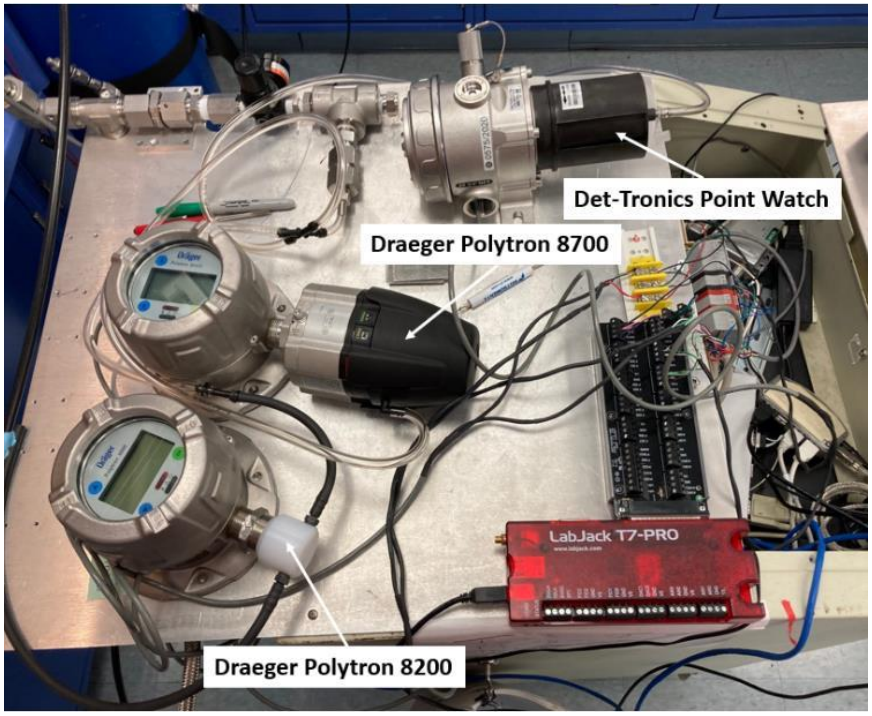

Figure 7: Real set-up for methane sensor testing showing the three different sensors.

13. Mass Flow Control and Data Collection

Control of the MFCs and data collection from all sensors utilized an in-house developed LabVIEW program. Its interface is shown in **Figure 8**. The LabVIEW program interfaced a LabJack™ and one of the computer's COM ports to interact with the sensors and MFCs. The MFCs were controlled using two of the LabJack's data acquisition channels, and their outputs were read using two of its analog input channels.

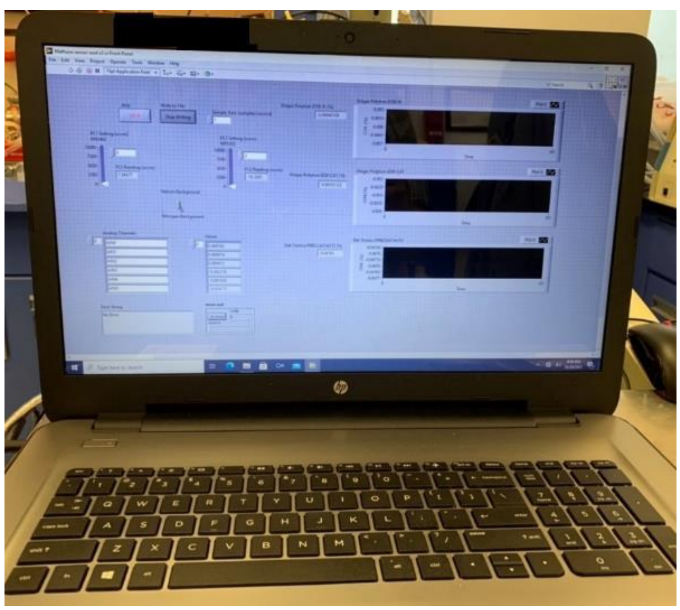

Figure 8: Interface LabView Program.

It is important to note that the absolute values of $\%CH_4$ that were read (and reported herein) for each of the sensor units may show some variance from the expected values for concentration. This is a result of the load resistor that was used for the measurements in the LabJack™ interface. The sensors are calibrated for a particular load resistance; however, a precision resistor of that resistance value was not available. Therefore, the testing system used a resistor whose resistance was close in value to the proscribed precision resistor, but not exactly the requisite value. Also, the sensors were not calibrated with standard gas samples over the full range of detection. **Thus, these results cannot be considered calibrated for the measurements taken.** Despite this difference, the tests that were performed may still be compared in relative terms since the difference in resistance value affected all data proportionally.

14. Testing and Results

Drift Test

To determine each sensor's drift, the change in sensor output was measured while a fixed methane concentration was provided. For these tests, drift was measured using concentrations of ~0% methane and 2% methane. Due to commodity constraints, drift tests varied in length from 15 minutes to two hours.

Procedure

1. Connect methane gas mixture and appropriate background gas to the test system.
2. Power on the methane sensors.
3. Allow appropriate warm-up time, per manufacturer specification, prior to continuing.
4. Begin gas flow, set to the desired methane concentration.
5. Begin data collection.
6. Allow outputs to stabilize.
7. Collect data for the desired duration.

Determining Drift

To reduce the effects of potential noise in the sensor output on calculated results, the average output values over one-minute timeframes were used to calculate drift.

$$Drift = output_{final} - output_{initial}$$

where:

$output_{final}$ = average output during the last minute of data collection

$output_{initial}$ = average output during the first minute after stabilization

The flow settings for the 0% and 2% drift tests are shown in **Table 3** and **Table 4**. All flow rates are in standard cubic centimeters per minute (sccm).

Table 3: Flow settings for 0% drift test.

$\%CH_4$ Setpoint	Start Time	FC1 (methane gas)	FC2 (dilution gas)
0.00	0:00	0	6556
STOP	1:00	0	6556

Table 4: Flow settings for 2% drift test.

%CH_4 Setpoint	**Start Time**	**FC1 (methane gas)**	**FC2 (dilution gas)**
0.00	0:00	4445	2111
STOP	1:00	0	6556

Results – 0% Drift, Air Background

To evaluate drift at approximately 0% methane, the mass flow controller providing methane was set to its minimum value, while the dilution gas's mass flow controller was set to a high flow rate.

Figure 9 through **Figure 11** show the data collected for each sensor during the 0% drift tests.

The Draeger IR held steady at just below 0.00% methane.

The Draeger CAT held steady at just below 0.00% methane (slightly closer to the actual 0.00% value than the Draeger IR).

The Det-Tronics IR held steady at a value just below 0.00% methane. The Det-Tronics IR 0% drift in air value was the farthest away from the actual value for the sensors evaulated.

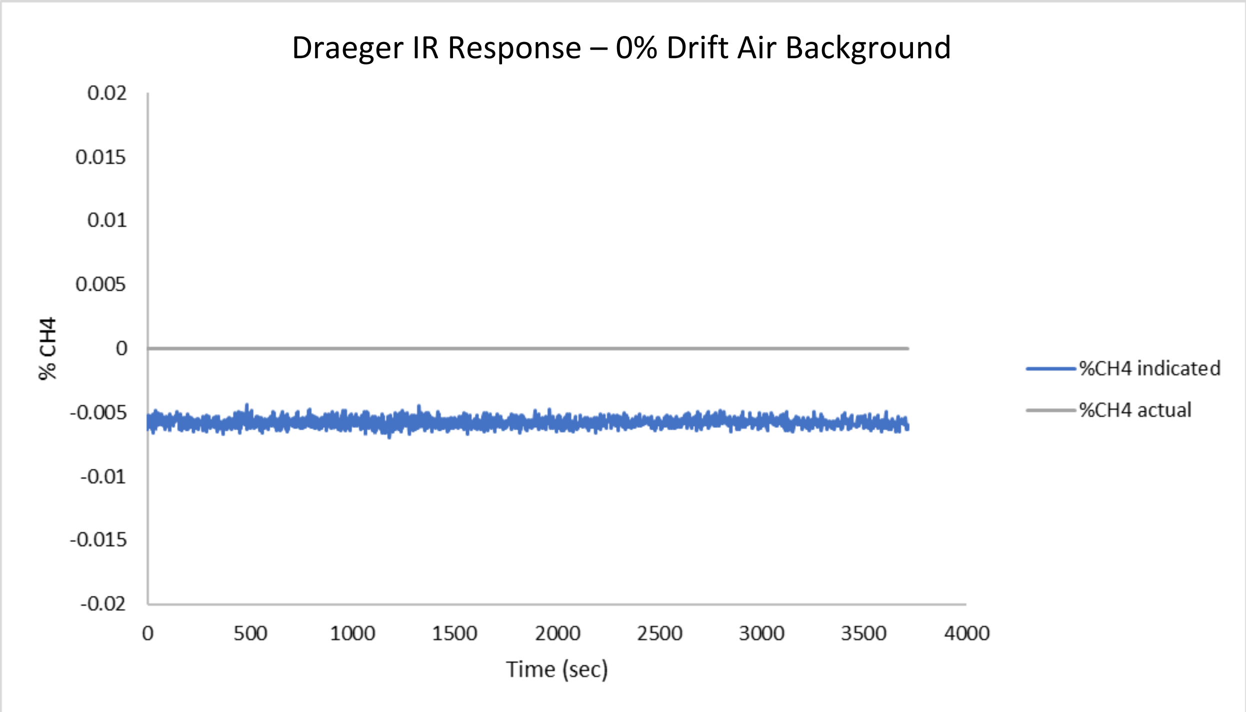

Figure 9: Draeger IR data for the 0% drift test with an air background.

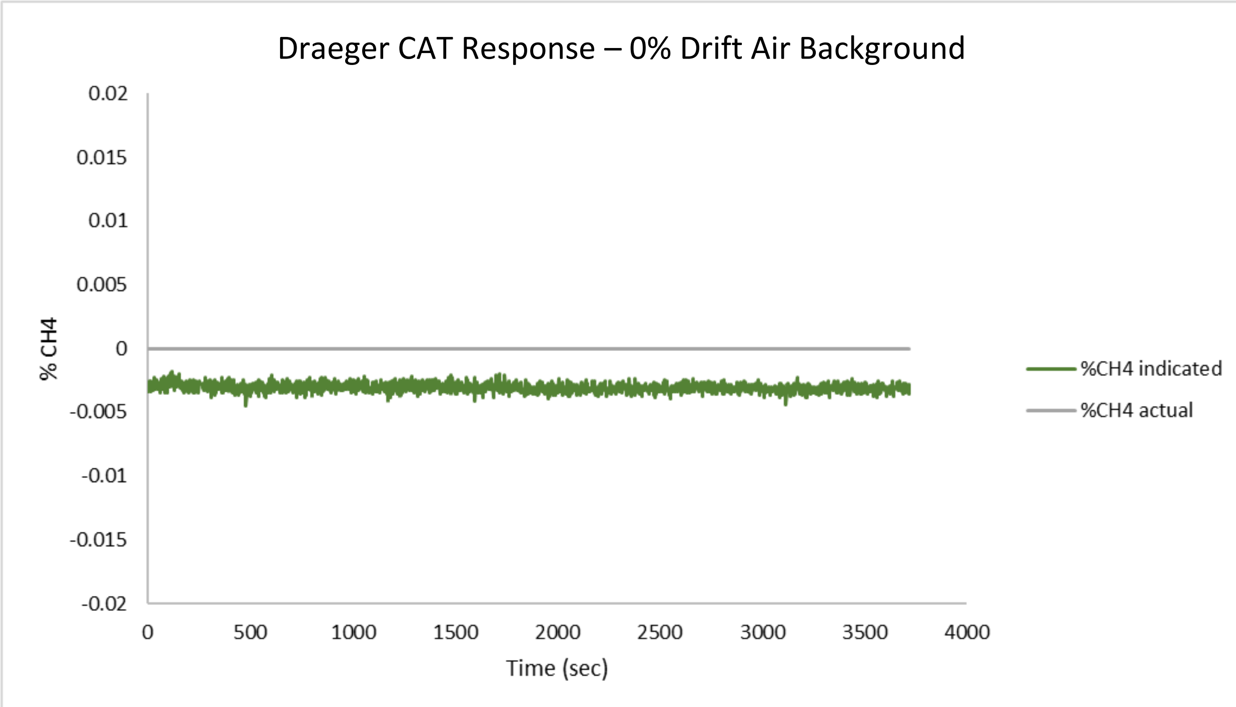

Figure 10: Draeger CAT data for the 0% drift test with an air background.

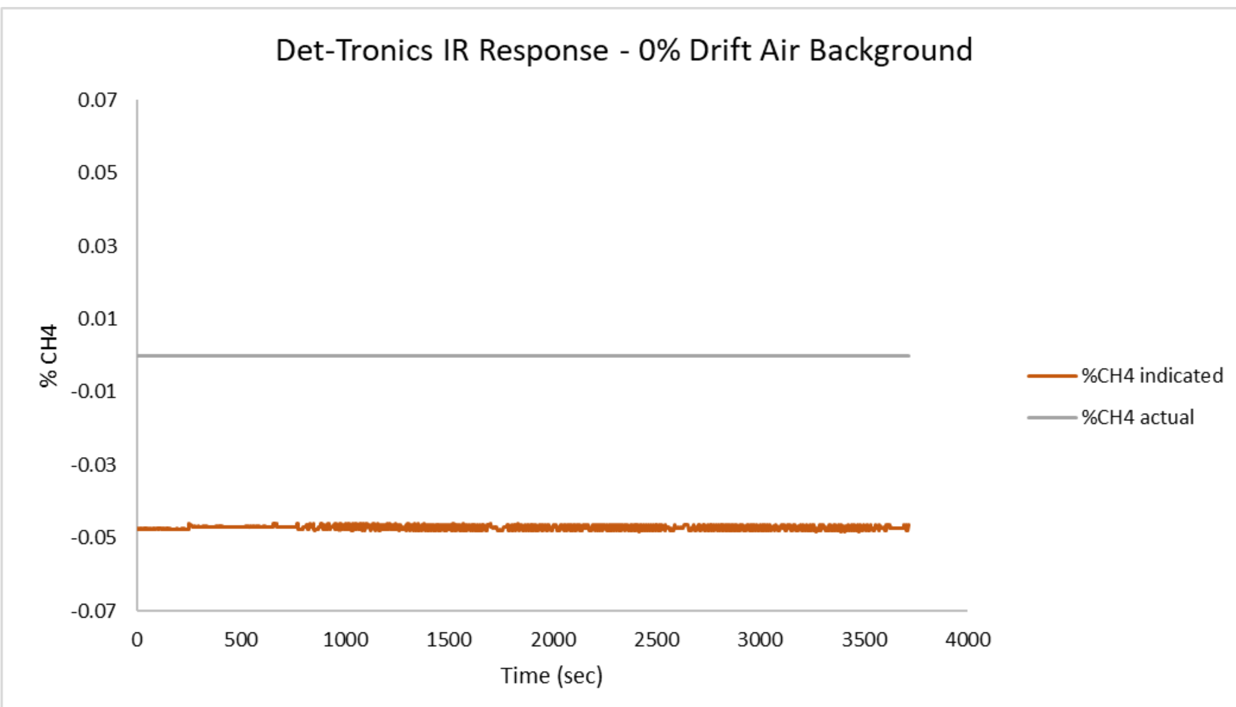

Figure 11: Det-Tronics IR data for the 0% drift test with an air background.

Table 5 gives the results of the 0% drift test with a background of air. Overall, the sensor outputs remained very stable. The drift specification for the Draeger IR is that the long-term drift is ≤ ±1% LEL

after 12 months. The drift specification for the Draeger CAT is that the long-term drift is ≤ 3% LEL after 6 months. The drift specification for the Det-Tronics IR is not available.

Table 5: 0% Drift Test Results – Air Background.

Sensor	**Test Duration (min)**	**% Methane Source**	**Sensor Output Drift (% CH_4)**
Draeger IR	60	0.00	-0.00028
Draeger CAT	60	0.00	-0.00031
Det-Tronics IR	60	0.00	0.00036

Results – 0% Drift, Nitrogen Background

To evaluate drift at approximately 0% methane, the mass flow controller providing methane was set to its minimum value, while the dilution gas's mass flow controller was set to a high flow rate.

Figure 12 through **Figure 14** show the data collected for each sensor during the 0% drift tests.

The Draeger IR held steady at just below 0.00% methane.

The Draeger CAT held steady at just below 0.00% methane (slightly closer to the actual 0.00% value than the Draeger IR).

The Det-Tronics IR held steady at a value just below 0.00% methane. The Det-Tronics IR O% drift in nitrogen value was the farthest away from the actual value for the sensors evaulated.

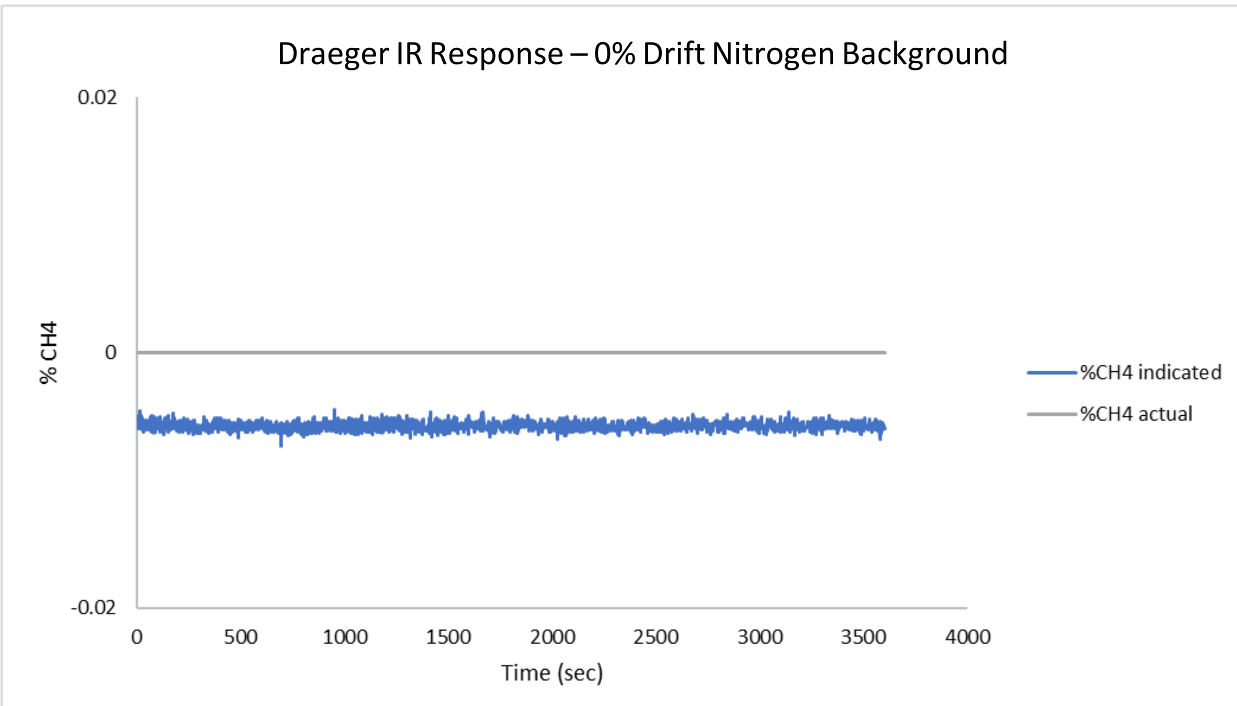

Figure 12: Draeger IR data for the 0% drift test with a nitrogen background.

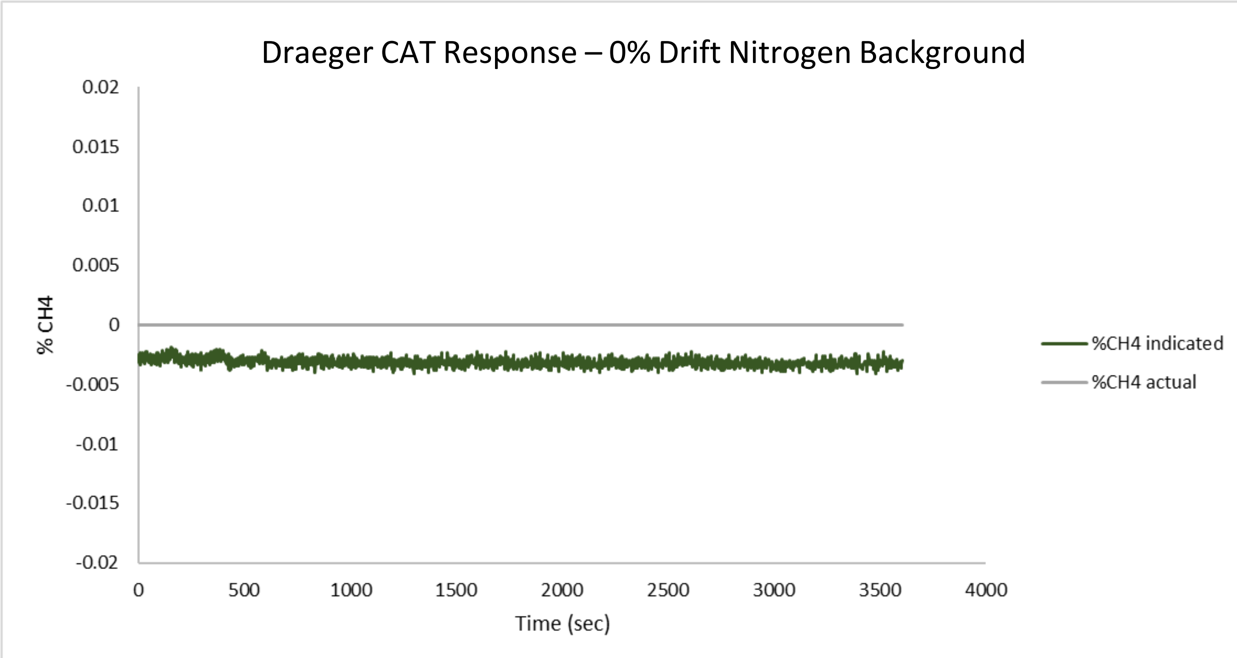

Figure 13: Draeger CAT data for the 0% drift test with a nitrogen background.

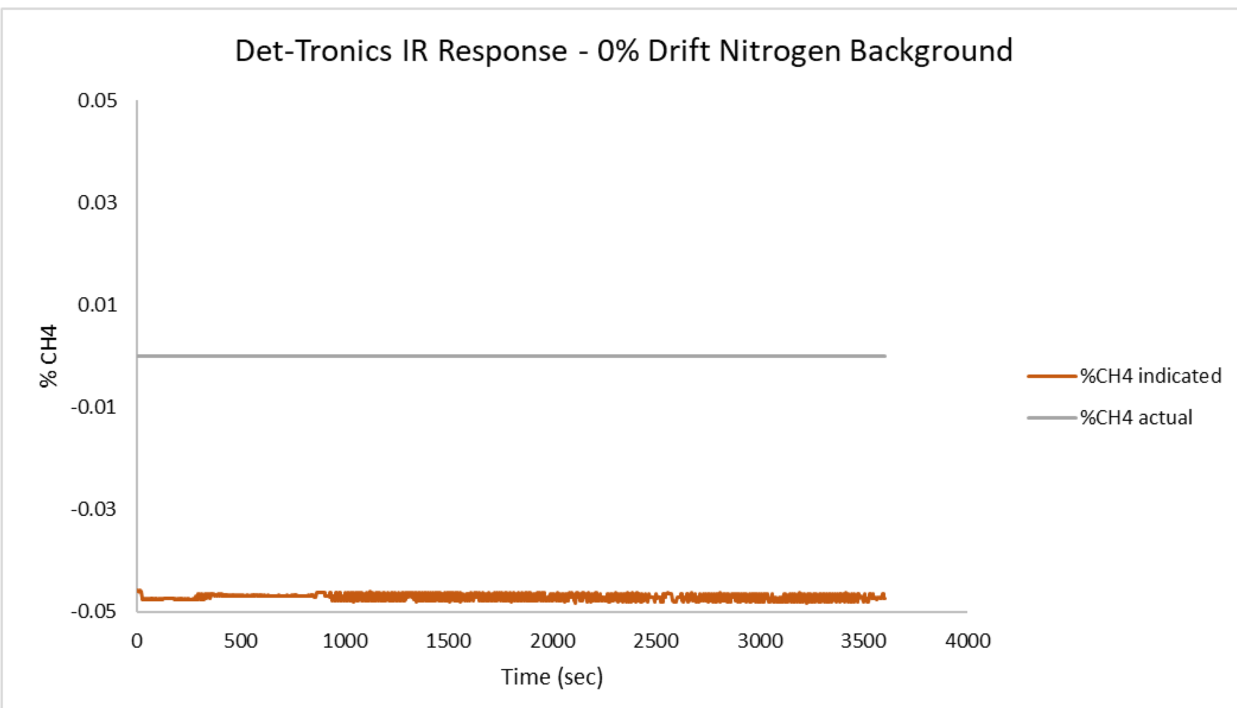

Figure 14: Det-Tronics data for the 0% drift test with a nitrogen background.

Table 6 gives the results of the 0% drift test with a background of nitrogen. Overall, the sensor outputs remained very stable. The drift specification for the Draeger IR is that the long-term drift is ≤ ±1% LEL

after 12 months. The drift specification for the Draeger CAT is that the long-term drift is ≤ 3% LEL after 6 months. The drift specification for the Det-Tronics IR is not available.

Table 6: 0% Drift Test Results – Nitrogen Background.

Sensor	**Test Duration (min)**	**% Methane Source**	**Sensor Output Drift (% CH_4)**
Draeger IR	60	0.00	-0.00014
Draeger CAT	60	0.00	-0.00044
Det-Tronics IR	60	0.00	0.00037

Results – 2% Drift, Air Background

Figure 15 through **Figure 17** show the data collected for each sensor during the 2% drift tests.

The Draeger IR's values did not change very much throughout the test. The average sensor output was very slightly higher than 2%.

The Draeger CAT's values did not change very much throughout the test. The average sensor output was very slightly less than 2%.

The Det-Tronics IR's values did not change very much throughout the test. The average sensor output was very slightly higher than 2%.

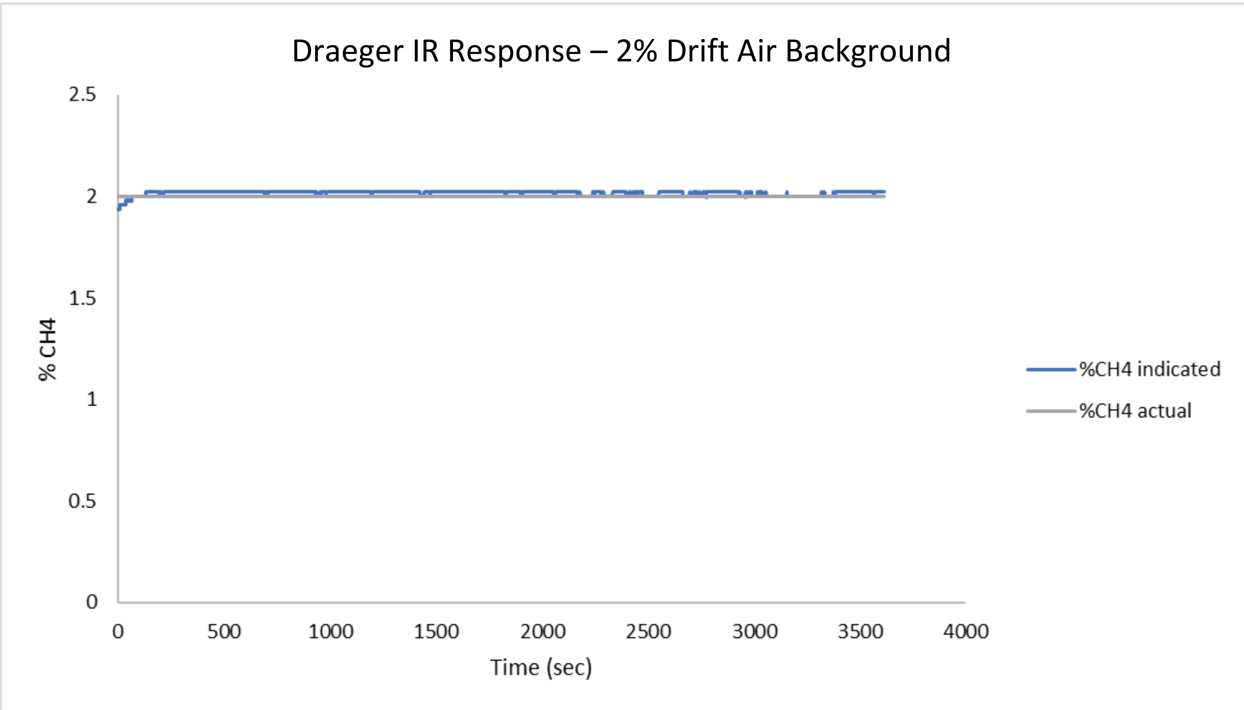

Figure 15: Draeger IR data for the 2% drift test with an air background.

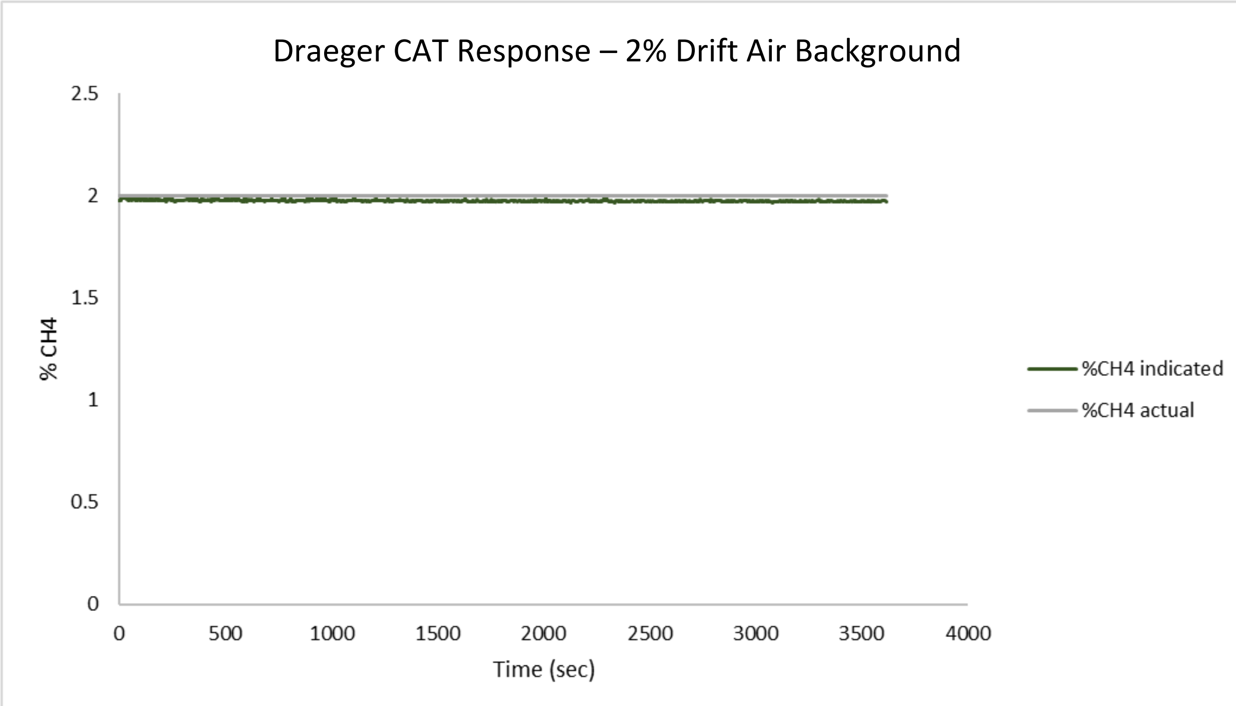

Figure 16: Draeger CAT data for the 2% drift test with an air background.

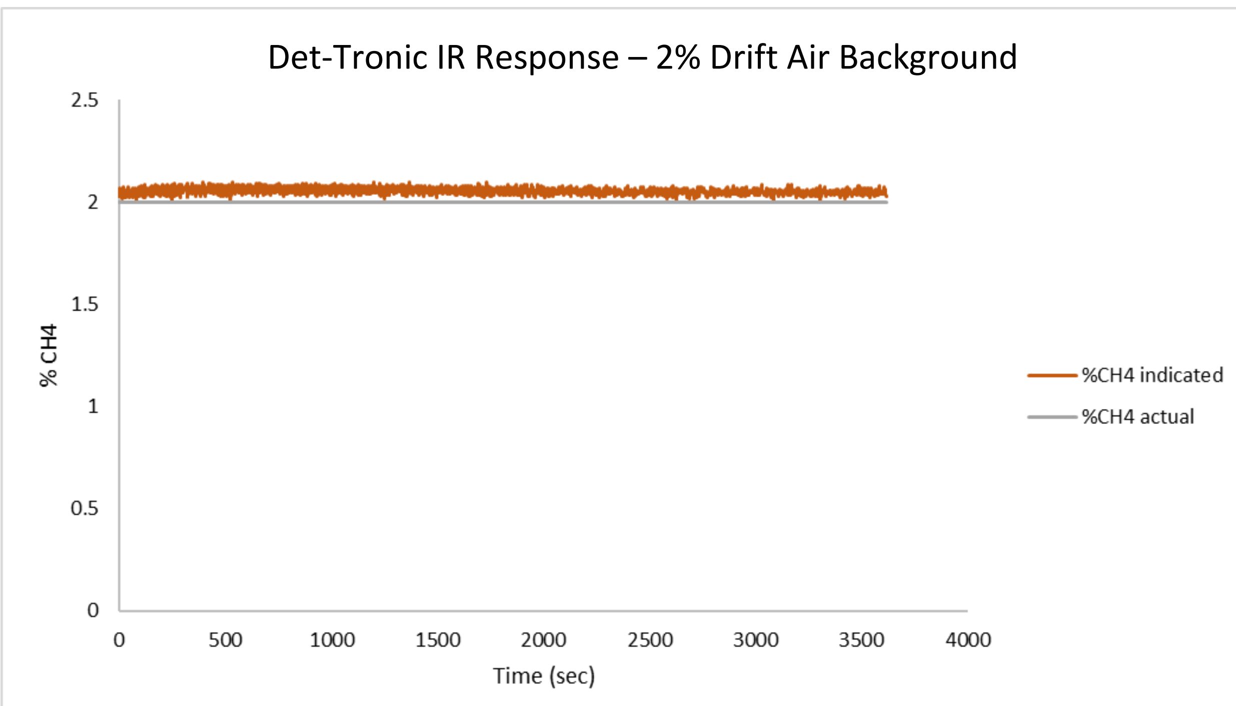

Figure 17: Det-Tronics data for the 2% drift test with an air background.

Table 7 gives the results of the 2% drift test with a background of air. Overall, the sensor outputs remained very stable. The drift specification for the Draeger IR is that the long-term drift is ≤ ±1% LEL

after 12 months. The drift specification for the Draeger CAT is that the long-term drift is ≤ 3% LEL after 6 months. The drift specification for the Det-Tronics IR is not available.

Table 7: 2% Drift Test Results – Air Background.

Sensor	Test Duration (min)	% Methane Source	Sensor Output Drift (% CH_4)
Draeger IR	60	2.00	0.022
Draeger CAT	60	2.00	-0.0077
Det-Tronics IR	60	2.00	0.0017

Results – 2% Drift, Nitrogen Background

Figure 18 through **Figure 20** show the data collected for each sensor during the 2% drift tests.

The Draeger IR showed a slight increase in output throughout the test, starting just below 2% methane and finishing just above 2% methane.

The Draeger CAT did not show a response since the sensor requires the presence of oxygen to operate.

The Det-Tronics IR showed a slight increase in output throughout the test, with values consistently slightly greater than 2% methane.

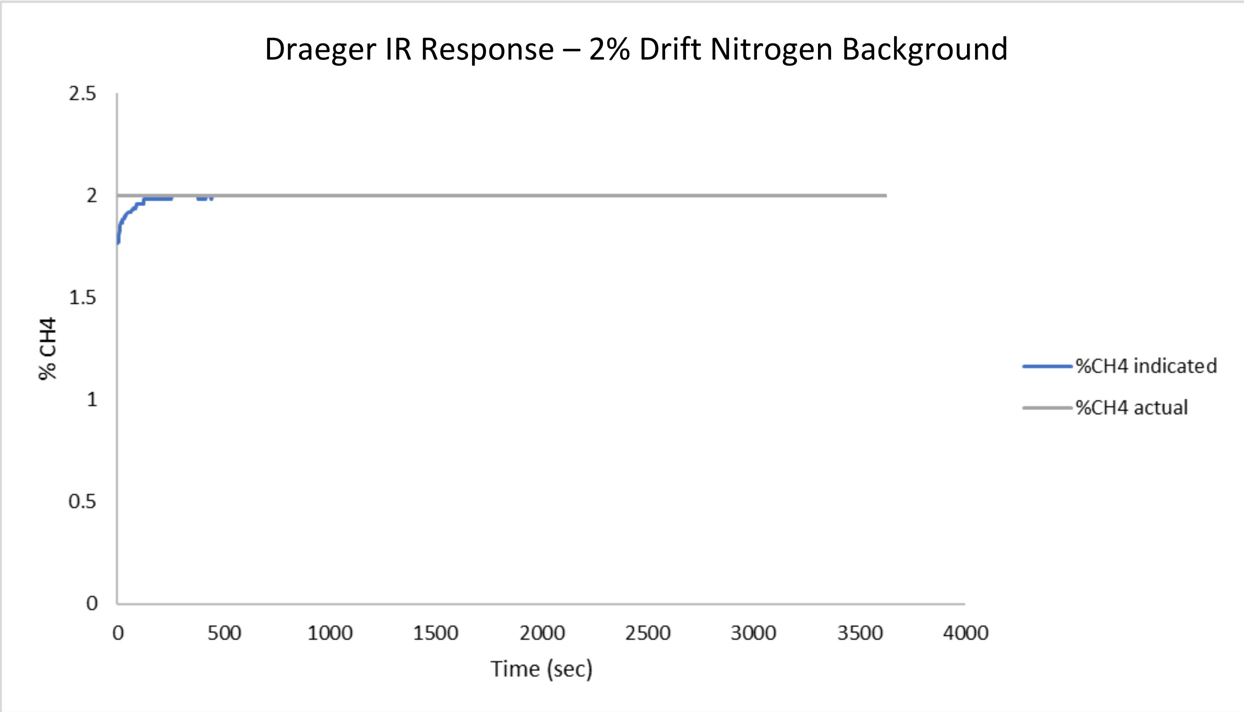

Figure 18: Draeger IR data for the 2% drift test with a nitrogen background.

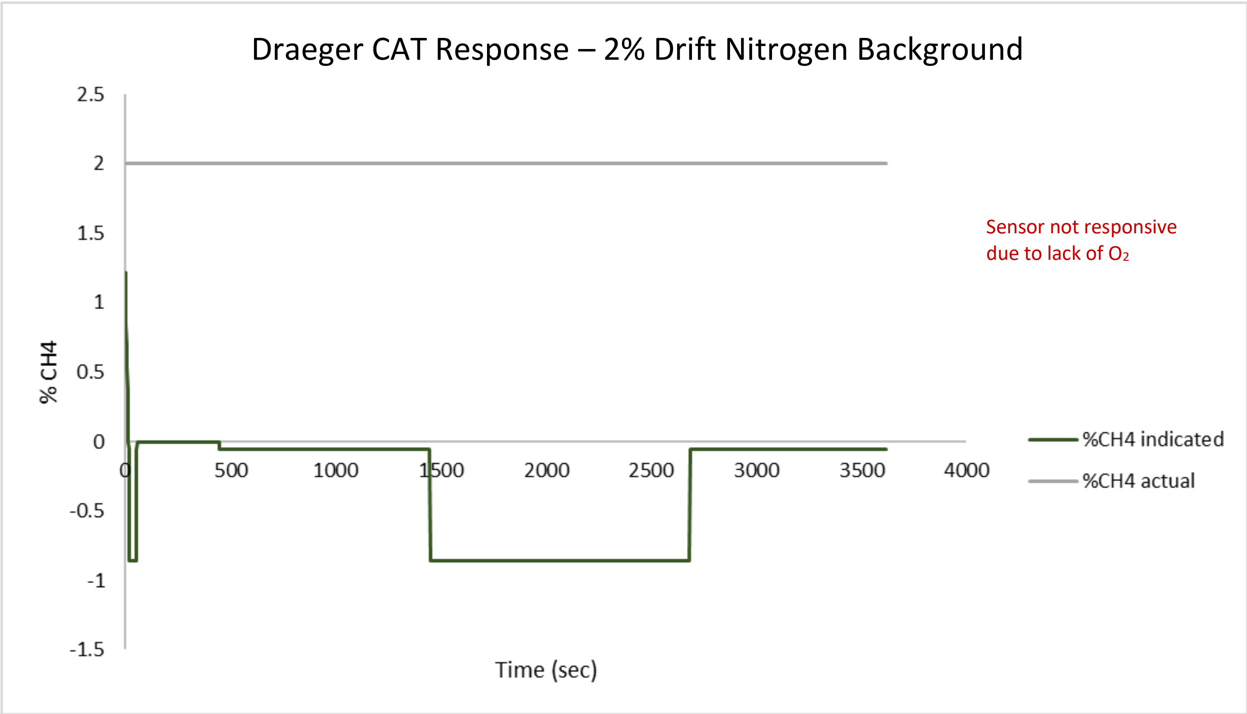

Figure 19: Draeger CAT data for the 2% drift test with a nitrogen background.

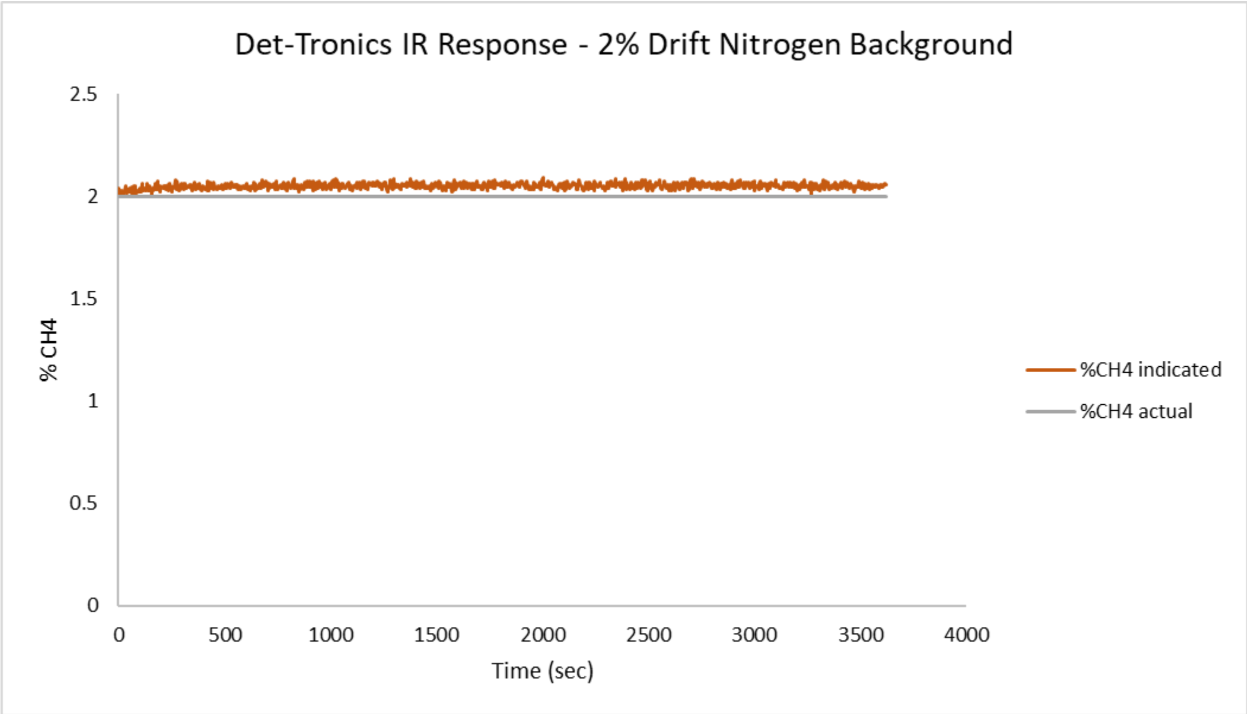

Figure 20: Det-Tronics data for the 2% drift test with a nitrogen background.

Table 8 gives the results of the 2% drift test with a background of nitrogen. Overall, the sensor outputs remained very stable. The drift specification for the Draeger IR is that the long-term drift is ≤ ±1% LEL after 12 months. The drift specification for the Det-Tronics IR is not available.

Table 8: 2% Drift Test Results – Nitrogen Background.

Sensor	Test Duration (min)	% Methane Source	Sensor Output Drift (% CH_4)
Draeger IR	60	2.00	0.054
Draeger CAT	60	2.00	**
Det-Tronics IR	60	2.00	0.0165

** Catalytic sensor requires the presence of oxygen and did not respond to the test gas.

Lower Detectable Limit Test

The lower detectable limit (LDL) refers to the lowest concentration of methane that can be detected by a sensor in the given background gas. This test was used to determine the LDL for each of the methane sensors in their background gas. Because LDL can vary for increasing and decreasing concentrations, both were tested.

<u>Procedure – LDL for Increasing Gas Concentrations</u>

1. Connect methane gas mixture and appropriate (matching) background gas to the test system.
2. Power on methane sensors.
3. Allow appropriate warm-up time, per manufacturer specification, prior to continuing.
4. Begin data collection.
5. Begin flow of methane gas mixture and appropriate (matching) background gas, setting gas flows for a concentration of ~0% methane.
6. Collect data for several minutes to allow outputs to stabilize (this can be shortened if the previous test was conducted at 0% methane).
7. Adjust gas flows, increasing the methane concentration in the smallest increment available.
8. Allow outputs to stabilize.
9. Repeat the process of increasing the methane concentration until, at a minimum, all sensors have responded.

   The flow settings for the lower detectable limit (increasing) are shown in **Table 9**. All flow rates are in standard cubic centimeters per minute (sccm).

Table 9: Flow settings for lower detectable limit increasing test (dilution gas was changed first throughout test).

CH_4% Setpoint	Time	FC1 (methane gas)	FC2 (dilution gas)
0.000	0:00	0	6556
0.046	0:05	100	6456
0.068	0:06	150	6406
0.091	0:07	200	6356
0.114	0:08	250	6306
0.137	0:09	300	6256
0.160	0:10	350	6206
0.182	0:11	400	6156
0.205	0:12	450	6106
0.228	0:13	500	6056
0.251	0:14	550	6006
0.274	0:15	600	5956
0.296	0:16	650	5906
0.319	0:17	700	5856
0.342	0:18	750	5806
0.365	0:19	800	5756
0.388	0:20	850	5706
0.410	0:21	900	5656

0.433	0:22	950	5606
0.456	0:23	1000	5556
0.479	0:24	1050	5506
0.502	0:25	1100	5456
0.524	0:26	1150	5406
0.547	0:27	1200	5356
0.570	0:28	1250	5306
0.593	0:29	1300	5256
0.616	0:30	1350	5206
0.638	0:31	1400	5156
0.661	0:32	1450	5106
0.684	0:33	1500	5056
0.707	0:34	1550	5006
0.730	0:35	1600	4956
0.753	0:36	1650	4906
0.775	0:37	1700	4856
0.798	0:38	1750	4806
0.821	0:39	1800	4756
0.844	0:40	1850	4706
0.867	0:41	1900	4656
0.889	0:42	1950	4606
0.912	0:43	2000	4556
0.935	0:44	2050	4506
0.958	0:45	2100	4456
0.981	0:46	2150	4406
1.003	0:47	2200	4356
1.026	0:48	2250	4306

Determining LDL

The LDL is determined by evaluating the data collected. For each sensor, the lowest concentration of methane that had an accurate reading, above 0%, is the sensor’s LDL.

Results – Air Background Increasing

With the test setup and equipment used, the minimum concentration of methane possible for each LDL test was 0% methane. Increments of 0.023% methane were used during the LDL increasing test (air background).

Figure 21 through **Figure 23** show the data collected during the LDL increasing in air background test.

The Draeger IR was responsive to the small changes in gas concentrations above its LDL. The LDL was around 0.091% methane.

The Draeger CAT was responsive to the small changes in gas concentration above its LDL. The LDL was around 0.18% methane.

The Det-Tronics IR responded to all methane concentration changes above its LDL. The LDL was around 0.091% methane.

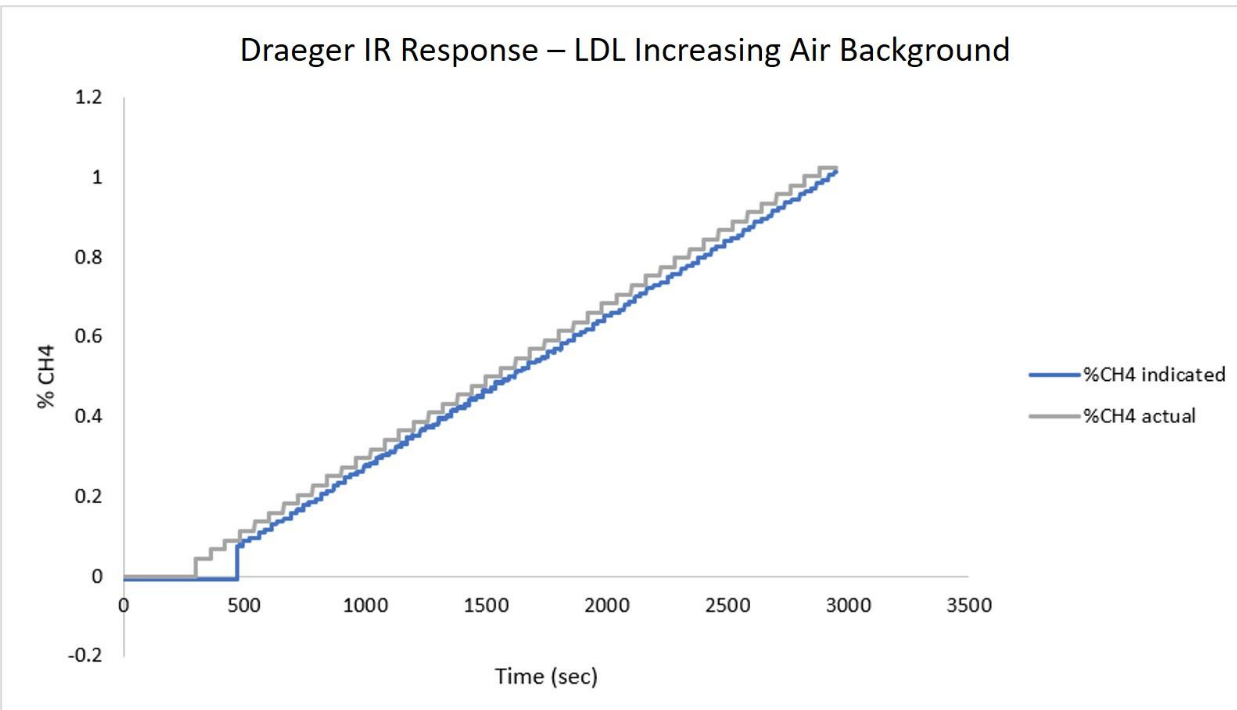

Figure 21: Draeger IR data for the LDL increasing test with an air background.

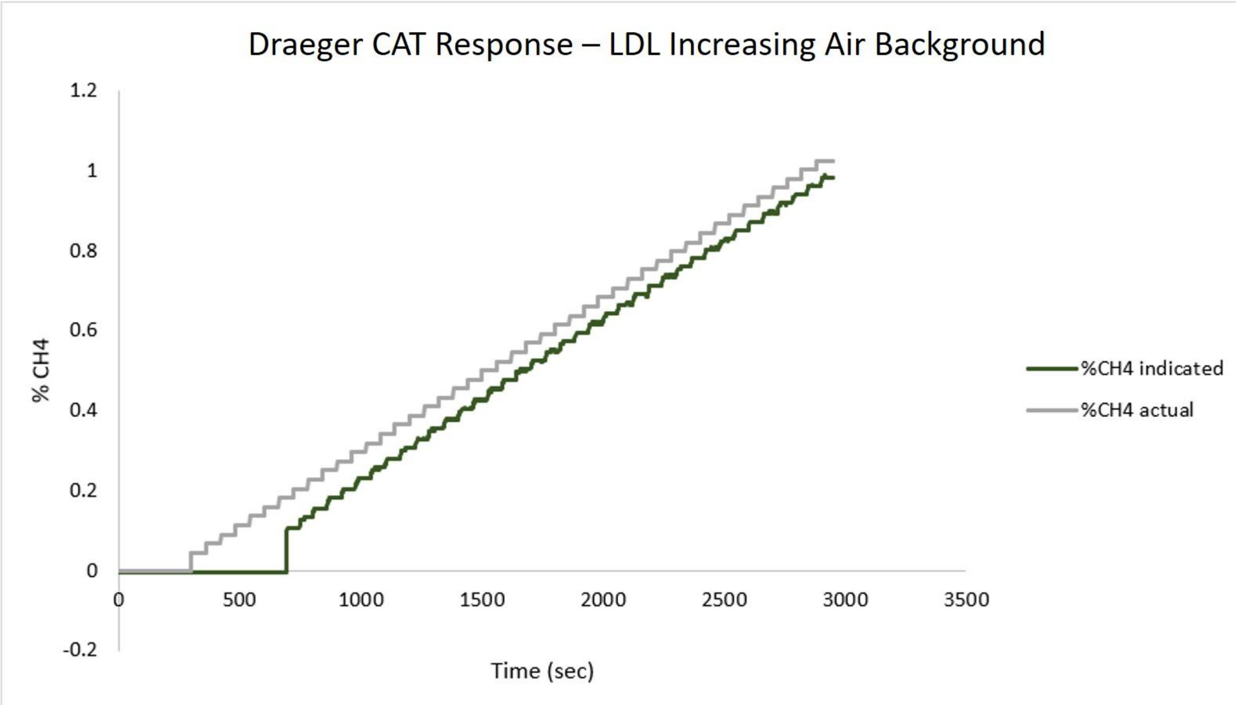

Figure 22: Draeger CAT data for the LDL increasing test with an air background.

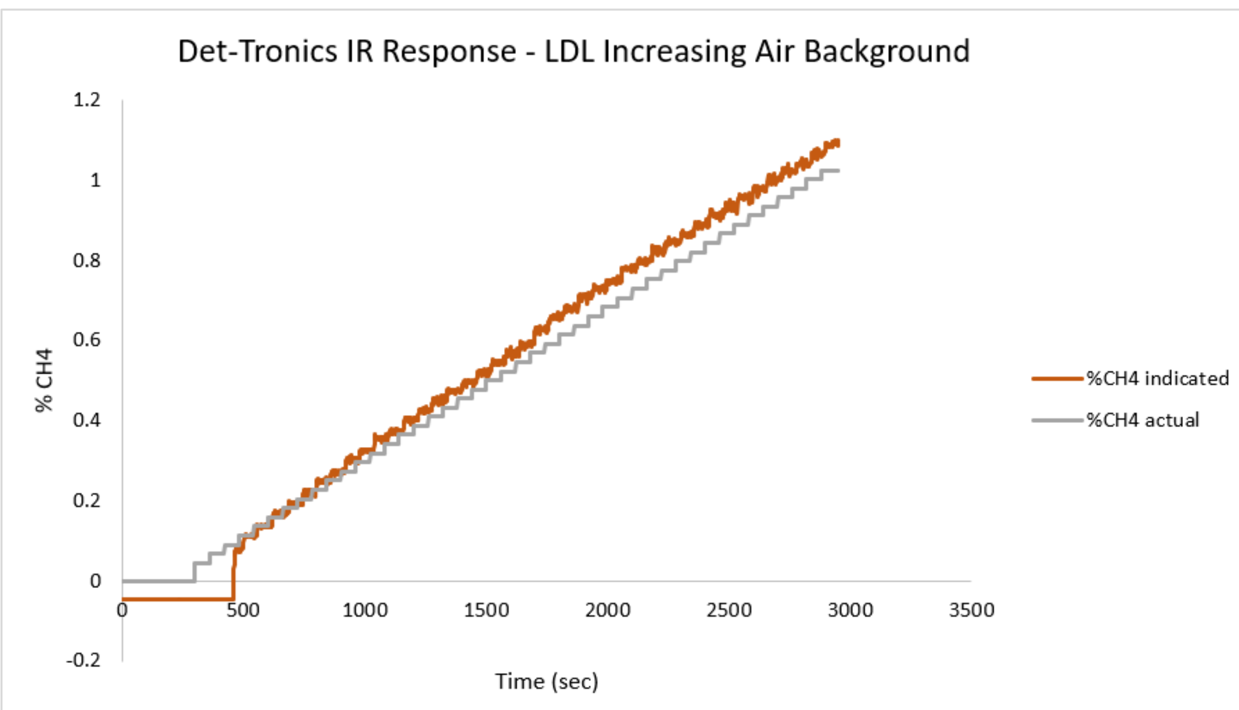

Figure 23: Det-Tronics data for the LDL increasing test with an air background.

It should be noted that the concentrations specified, or shown as “actual” methane concentrations on the charts, are based on MFC-provided values for their outputs. To achieve the minimum concentrations and small increments used in this test, the MFCs were used at values between zero and their first calibration point, which could have impacted the accuracy of their outputs.

Table 10 gives the results of the LDL testing in air background. Overall, the sensors were able to detect less than 0.2% methane in an air background. The specifications for the Draeger IR state the ability to detect 0-100% LEL (lower explosive limit). The specifications for the Draeger CAT state the ability to detect 0-100% LEL (lower explosive limit). The specifications for the Det-Tronics IR state the ability to detect 0-100% LFL (lower flammability limit). No LDL information was provided.

Table 10: Lower Detectable Limit Test Results – Air Background.

Sensor	**LDL Increasing % Methane (% CH_4)**
Draeger IR	0.091
Draeger CAT	0.18
Det-Tronics IR	0.091

Results – Nitrogen Background Increasing

With the test setup and equipment used, the minimum concentration of methane possible for each LDL test was 0% methane. Increments of 0.023% methane were used during the LDL increasing test (nitrogen background).

Figure 24 through **Figure 26** show the data collected during the LDL increasing in nitrogen background test.

The Draeger IR was responsive to the small changes in gas concentrations above its LDL. The LDL was around 0.13% methane.

The Draeger CAT did not show a response since the sensor requires the presence of oxygen to operate.

The Det-Tronics IR responded to all methane concentration changes above its LDL. The LDL was around 0.13% methane.

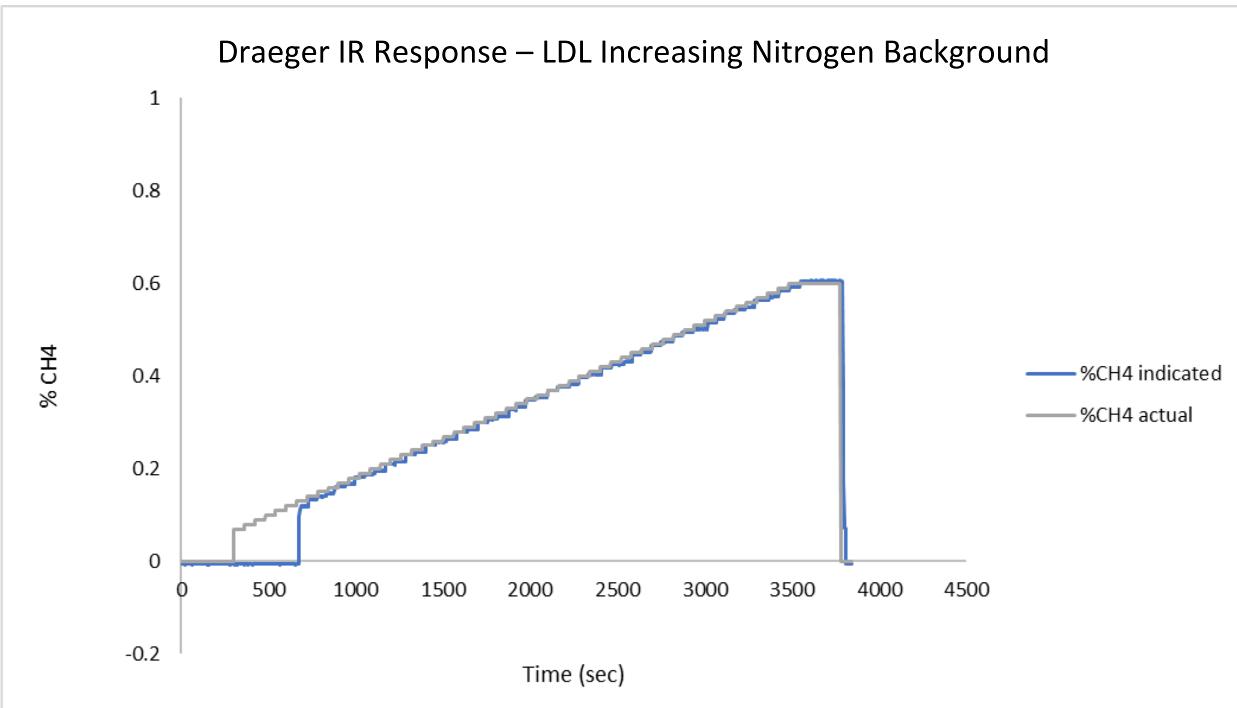

Figure 24: Draeger IR data for the LDL increasing test with a nitrogen background.

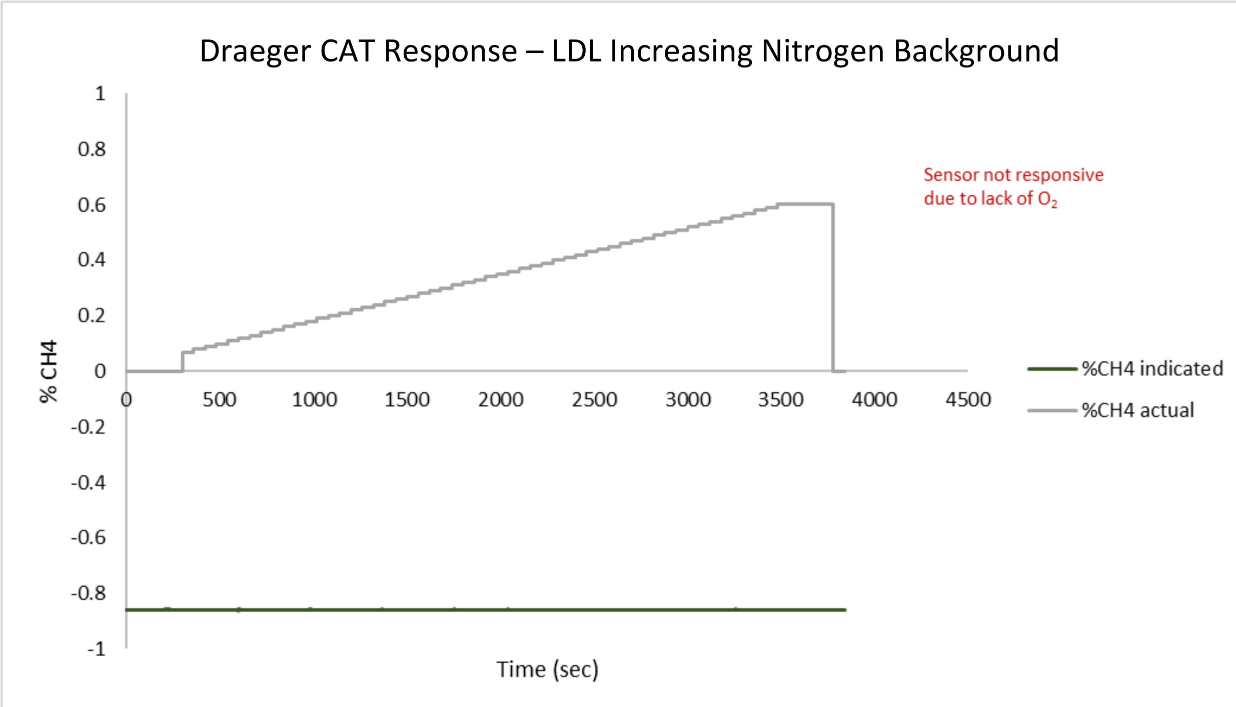

Figure 25: Draeger CAT data for the LDL increasing test with a nitrogen background.

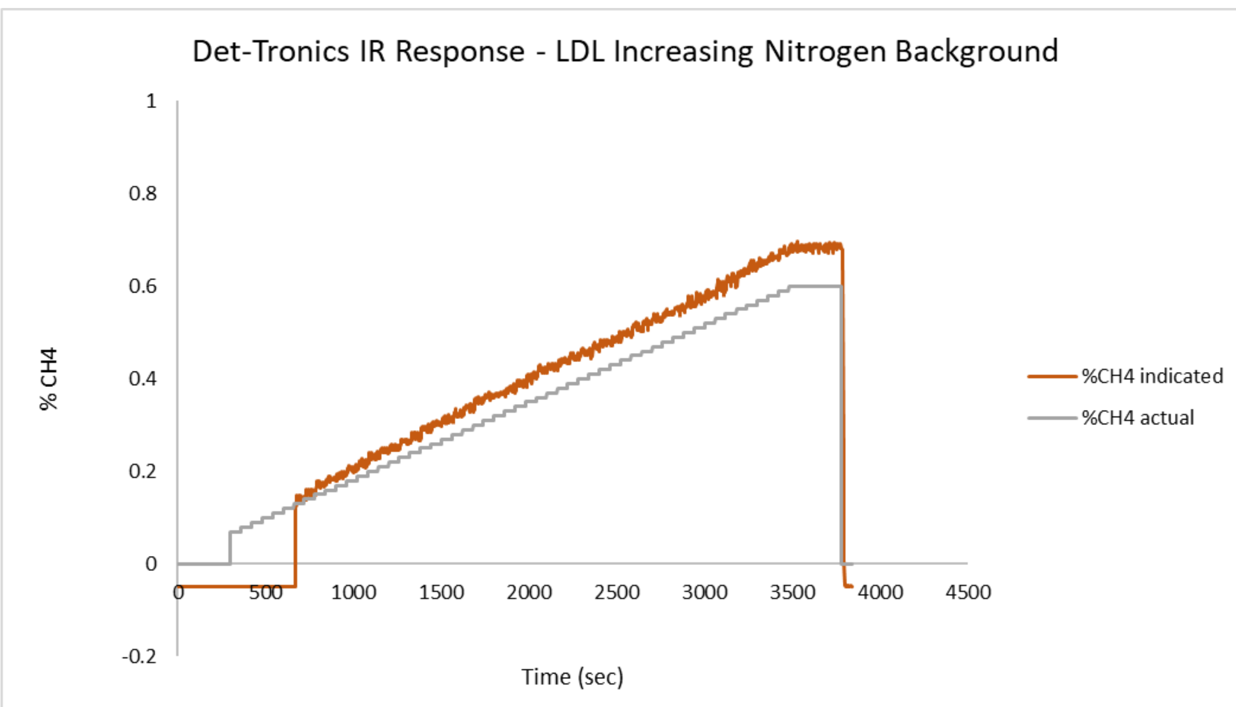

Figure 26: Det-Tronics data for the LDL increasing test with a nitrogen background.

It should be noted that the concentrations specified, or shown as "actual" methane concentrations on the charts, are based on MFC-provided values for their outputs. To achieve the minimum concentrations and

small increments used in this test, the MFCs were used at values between zero and their first calibration point, which could have impacted the accuracy of their outputs.

Table 11 gives the results of the LDL testing in nitrogen background. Overall, the sensors were able to detect less than 0.15% methane in a nitrogen background. The specifications for the Draeger IR state the ability to detect 0-100% LEL (lower explosive limit). The specifications for the Det-Tronics IR state the ability to detect 0-100% LFL (lower flammability limit). No LDL information was provided.

Table 11: Lower Detectable Limit Test Results – Nitrogen Background.

Sensor	**LDL Increasing % Methane (% CH_4)**
Draeger IR	0.13
Draeger CAT	**
Det-Tronics IR	0.13

** Catalytic sensor requires the presence of oxygen and did not respond to the test gas.

<u>Procedure – LDL for Decreasing Gas Concentrations</u>

1. Connect methane gas mixture and appropriate (matching) background gas to the test system.
2. Power on methane sensors.
3. Allow appropriate warm-up time, per manufacturer specification, prior to continuing.
4. Begin data collection.
5. Begin flow of methane gas mixture and appropriate (matching) background gas, setting gas flows for a concentration of ~1% methane (or other reasonable value at which all sensors are responding).
6. Collect data for several minutes to allow outputs to stabilize (this can be shortened if the previous test was conducted at the desired methane concentration).
7. Adjust gas flows, decreasing the methane concentration in the smallest increment available.
8. Allow outputs to stabilize.
9. Repeat the process of decreasing the methane concentration until all sensors have stopped responding or the minimum methane concentration possible has been reached.

The flow settings for the lower detectable limit (decreasing) are shown in **Table 12**. All flow rates are in standard cubic centimeters per minute (sccm).

Table 12: Flow settings for lower detectable limit decreasing test (methane gas was changed first throughout test).

%CH_4 Setpoint	**Time**	**FC1 (methane gas)**	**FC2 (dilution gas)**
1.012	0:00	2250	4306
0.990	0:05	2200	4356
0.967	0:06	2150	4406
0.945	0:07	2100	4456
0.922	0:08	2050	4506
0.900	0:09	2000	4556
0.877	0:10	1950	4606

0.855	0:11	1900	4656
0.832	0:12	1850	4706
0.810	0:13	1800	4756
0.787	0:14	1750	4806
0.765	0:15	1700	4856
0.742	0:16	1650	4906
0.720	0:17	1600	4956
0.697	0:18	1550	5006
0.675	0:19	1500	5056
0.652	0:20	1450	5106
0.630	0:21	1400	5156
0.607	0:22	1350	5206
0.585	0:23	1300	5256
0.562	0:24	1250	5306
0.540	0:25	1200	5356
0.517	0:26	1150	5406
0.495	0:27	1100	5456
0.472	0:28	1050	5506
0.450	0:29	1000	5556
0.427	0:30	950	5606
0.405	0:31	900	5656
0.382	0:32	850	5706
0.360	0:33	800	5756
0.337	0:34	750	5806
0.315	0:35	700	5856
0.292	0:36	650	5906
0.270	0:37	600	5956
0.247	0:38	550	6006
0.225	0:39	500	6056
0.202	0:40	450	6106
0.180	0:41	400	6156
0.157	0:42	350	6206
0.135	0:43	300	6256
0.112	0:44	250	6306
0.090	0:45	200	6356
0.067	0:46	150	6406
0.045	0:47	100	6456
0.000	0:48	0	6556

Determining LDL

The LDL is determined by evaluating the data collected. For each sensor, the lowest concentration of methane that had an accurate reading, above 0%, is the sensor's LDL.

Results – Air Background

With the test setup and equipment used, the minimum concentration of methane possible for each LDL test was 0% methane. Increments of 0.022% methane were used during the LDL decreasing test (air background).

Figure 27 through **Figure 29** show the data collected during the LDL decreasing in air background test.

The Draeger IR was responsive to the small changes in gas concentrations above its LDL. The LDL was around 0.07% methane.

The Draeger CAT was responsive to the small changes in gas concentration above its LDL. The LDL was around 0.23% methane.

The Det-Tronics IR responded to all methane concentration changes above its LDL. The LDL was around 0.05% methane.

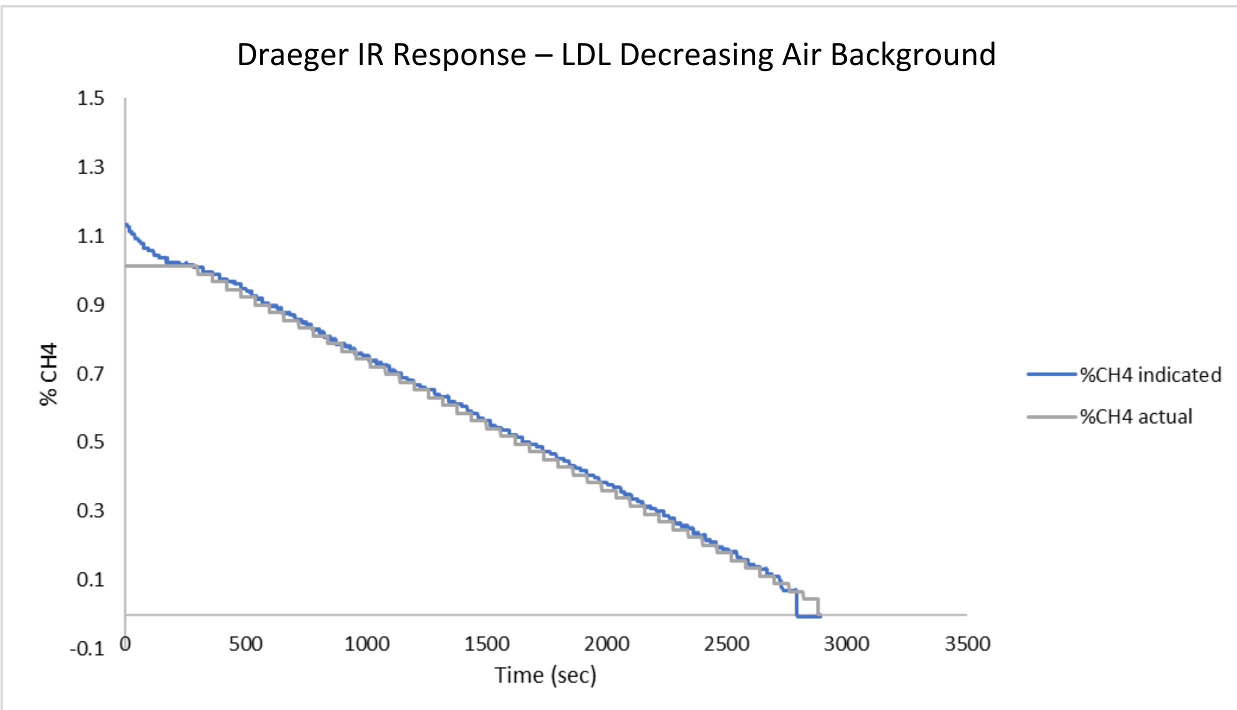

Figure 27: Draeger IR data for the LDL decreasing test with an air background.

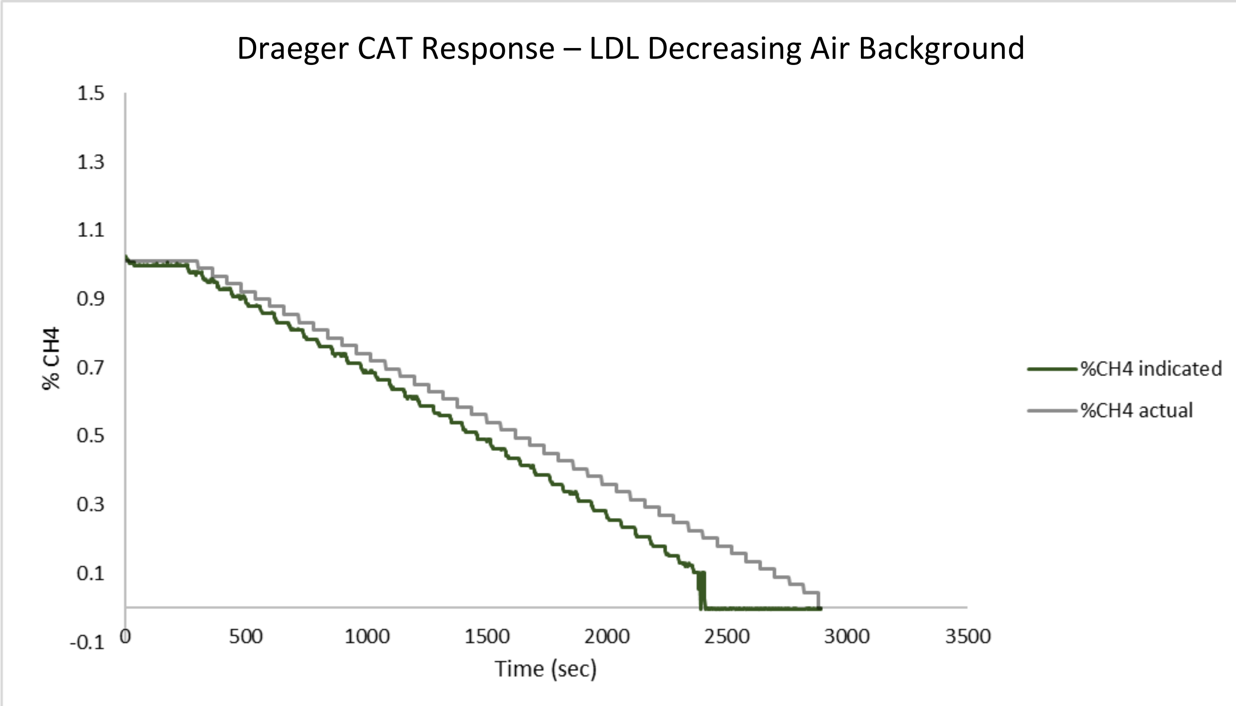

Figure 28: Draeger CAT data for the LDL decreasing test with an air background.

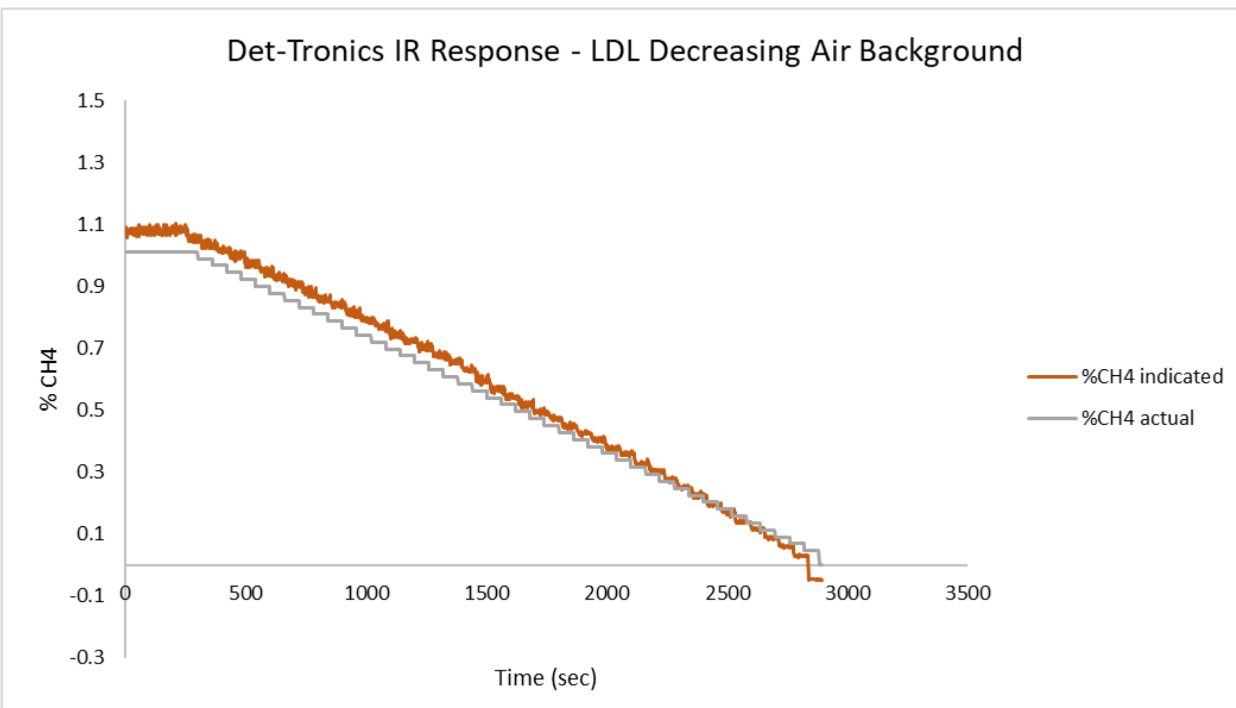

Figure 29: Det-Tronics data for the LDL decreasing test with an air background.

It should be noted that the concentrations specified, or shown as "actual" methane concentrations on the charts, are based on MFC-provided values for their outputs. To achieve the minimum concentrations and

small increments used in this test, the MFCs were used at values between zero and their first calibration point, which could have impacted the accuracy of their outputs.

Table 13 gives the results of the LDL testing in air background. Overall, the sensors were able to detect less than 0.15% methane in a nitrogen background. The specifications for the Draeger IR state the ability to detect 0-100% LEL (lower explosive limit). The specifications for the Draeger CAT state the ability to detect 0-100% LEL (lower explosive limit). The specifications for the Det-Tronics IR state the ability to detect 0-100% LFL (lower flammability limit). No LDL information was provided.

Table 13: Lower Detectable Limit Test Results – Air Background.

Sensor	LDL Increasing % Methane (% CH_4)
Draeger IR	0.07
Draeger CAT	0.23
Det-Tronics IR	0.05

Results – Nitrogen Background

With the test setup and equipment used, the minimum concentration of methane possible for each LDL test was 0% methane. Increments of 0.022% methane were used during the LDL decreasing test (nitrogen background).

Figure 30 through **Figure 32** show the data collected during the LDL decreasing in nitrogen background test.

The Draeger IR was responsive to the small changes in gas concentrations above its LDL. The LDL was around 0.07% methane.

The Draeger CAT did not show a response since the sensor requires the presence of oxygen to operate.

The Det-Tronics IR responded to all methane concentration changes above its LDL. The LDL was around 0.08% methane.

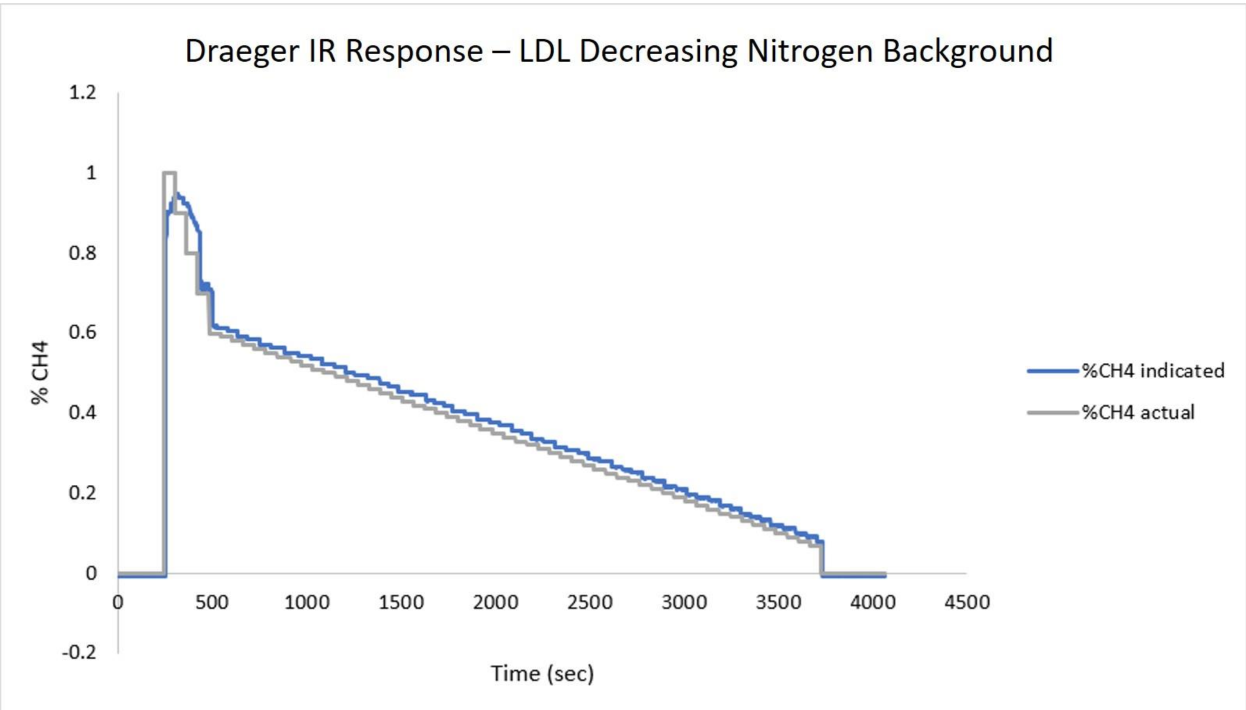

Figure 30: Draeger IR data for the LDL decreasing test with a nitrogen background.

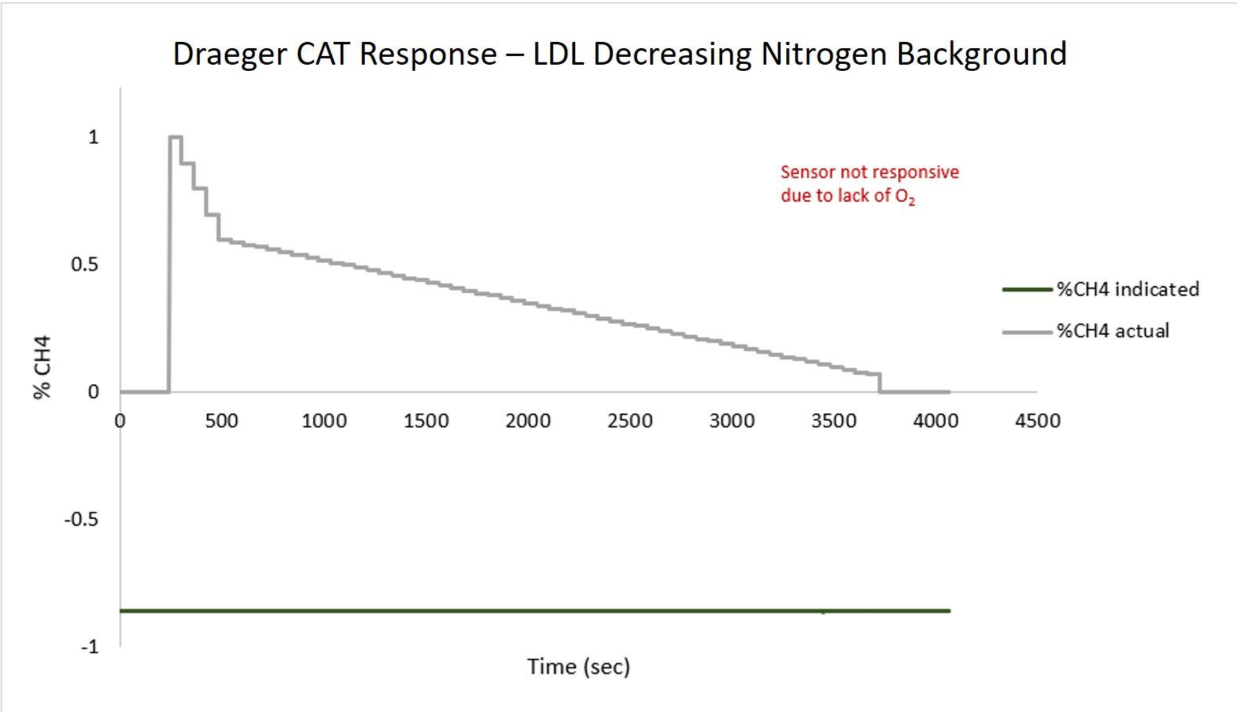

Figure 31: Draeger CAT data for the LDL decreasing test with a nitrogen background.

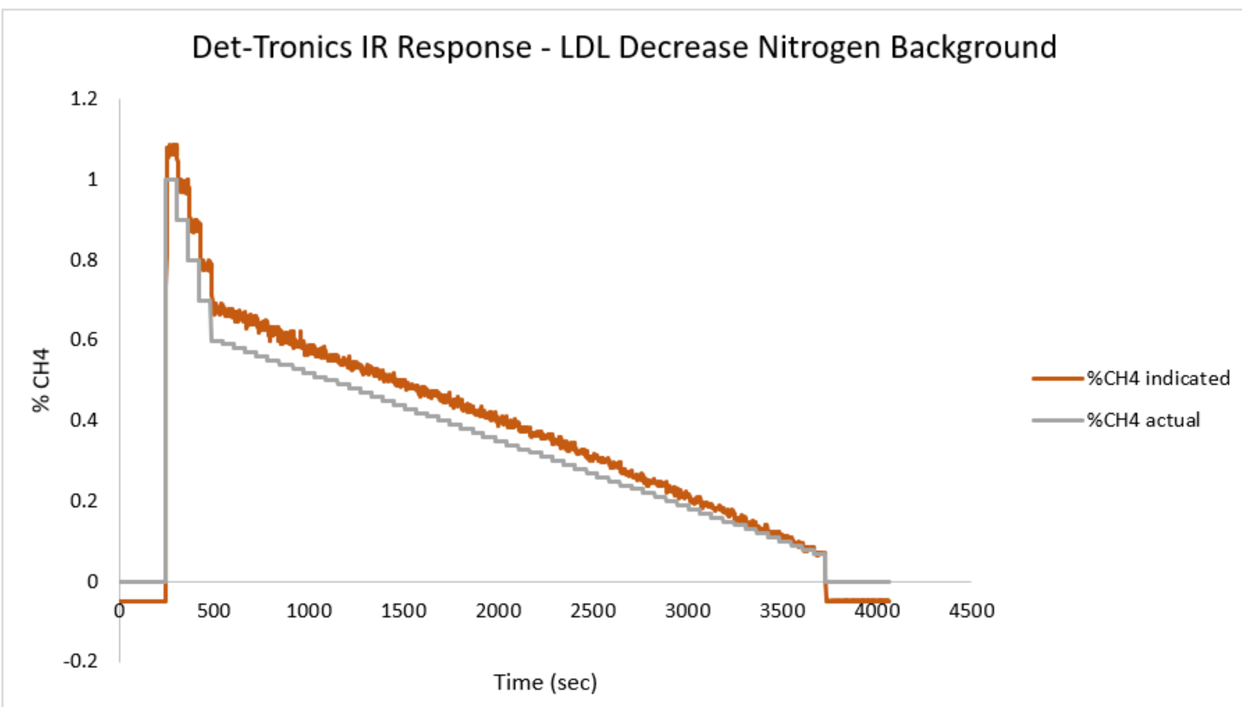

Figure 32: Det-Tronics data for the LDL decreasing test with a nitrogen background.

It should be noted that the concentrations specified, or shown as "actual" methane concentrations on the charts, are based on MFC-provided values for their outputs. To achieve the minimum concentrations and

small increments used in this test, the MFCs were used at values between zero and their first calibration point, which could have impacted the accuracy of their outputs.

Table 14 gives the results of the LDL testing in nitrogen background. Overall, the sensors were able to detect less than 0.10% methane in a nitrogen background. The specifications for the Draeger IR state the ability to detect 0-100% LEL (lower explosive limit). The specifications for the Det-Tronics IR state the ability to detect 0-100% LFL (lower flammability limit). No LDL information was provided.

Table 14: Lower Detectable Limit Test Results – Nitrogen Background.

Sensor	**LDL Increasing % Methane ($\% CH_4$)**
Draeger IR	0.07
Draeger CAT	**
Det-Tronics IR	0.08

** Catalytic sensor requires the presence of oxygen and did not respond to the test gas.

Stair Step Test

This test was used to determine the accuracy and precision of the sensors. Methane concentrations were increased and decreased in a stair step pattern to determine the sensor outputs at various concentrations relative to both increasing and decreasing methane concentrations.

Procedure

1. Connect methane gas mixture and appropriate background gas to the test system.
2. Power on the sensors.
3. Allow appropriate warm-up time, per manufacturer specification, prior to continuing.
4. Begin data collection.
5. Begin flow of appropriate background gas to provide ~0% methane.
6. Allow outputs to stabilize.
7. Adjust gas flows for a methane concentration of 0.5%.
8. Collect data for a sufficient time to allow outputs to stabilize.
9. Increase the methane concentration in steps, going up 0.5% (or similar value, based on available methane concentrations) each time, until the maximum methane concentration is reached, collecting data for a sufficient duration to allow output stabilization each time.
10. Using the same methane concentrations, step the concentration down incrementally back to ~0% methane, collecting data for a sufficient duration to allow output stabilization each time.
11. Repeat this process for a total of three cycles.

Determining Accuracy

Accuracy, also known as relative error, compares the expected sensor outputs to the recorded sensor outputs.

Accuracy was calculated for each methane concentration as follows.

$$Accuracy = \left(\frac{output_{sensor} - output_{expected}}{output_{expected}}\right) \times 100\%$$

where:

$output_{expected}$ = the known methane concentration provided to the sensor

$output_{sensor}$ = the average sensor output for data collected after stabilization

It is important to note that, using this equation, lower numbers for accuracy represent better results (less error).

Determining Precision

Precision, also known as relative standard error, compares the standard deviation of the sensor's outputs to its mean output for a given input.

Precision was calculated for each methane concentration as follows.

$$Precision = \left(\frac{\sigma_{output}}{\overline{output}_{sensor}}\right) \times 100\%$$

where:

σ_{output} = the standard deviation of recorded sensor output values after stabilization

$\overline{\text{output}}_{\text{sensor}}$ = the mean of the recorded sensor output values after stabilization

It is important to note that, using this equation, smaller numbers for precision represent better results (less error).

The flow settings for the stair step test with an air background are shown in **Table 15**. All flow rates are in standard cubic centimeters per minute (sccm).

Table 15: Flow settings for stair step test (methane gas was changed first throughout test).

%CH_4 Setpoint	**Time**	**FC1 (methane gas)**	**FC2 (dilution gas)**
0.00	0:00	0	6556
0.50	0:05	1096	5460
1.00	0:10	2193	4363
1.50	0:15	3289	3267
2.00	0:20	4385	2171
2.50	0:25	5482	1074
2.00	0:30	4385	2171
1.50	0:35	3289	3267
1.00	0:40	2193	4363
0.50	0:45	1096	5460
0.00	0:50	0	6556
0.50	0:55	1096	5460
1.00	1:00	2193	4363
1.50	1:05	3289	3267
2.00	1:10	4385	2171
2.50	1:15	5482	1074
2.00	1:20	4385	2171
1.50	1:25	3289	3267
1.00	1:30	2193	4363
0.50	1:35	1096	5460
0.00	1:40	0	6556
0.50	1:45	1096	5460
1.00	1:50	2193	4363
1.50	1:55	3289	3267
2.00	2:00	4385	2171
2.50	2:05	5482	1074
2.00	2:10	4385	2171
1.50	2:15	3289	3267
1.00	2:20	2193	4363
0.50	2:25	1096	5460
0.00	2:30	0	6556

Results – Air Background

Figure 33 through **Figure 35** show data collected during the stair step test with an air background.

The Draeger IR showed each step consistently. The sensor's outputs were very close to the actual methane concentrations being supplied.

The Draeger CAT showed each step consistently. The sensor's outputs varied slightly from the actual methane concentrations being supplied but could improve with calibration.

The Det-Tronics IR showed each step consistently. The sensor's outputs were consistently higher than the actual methane concentrations being supplied but could improve with calibration.

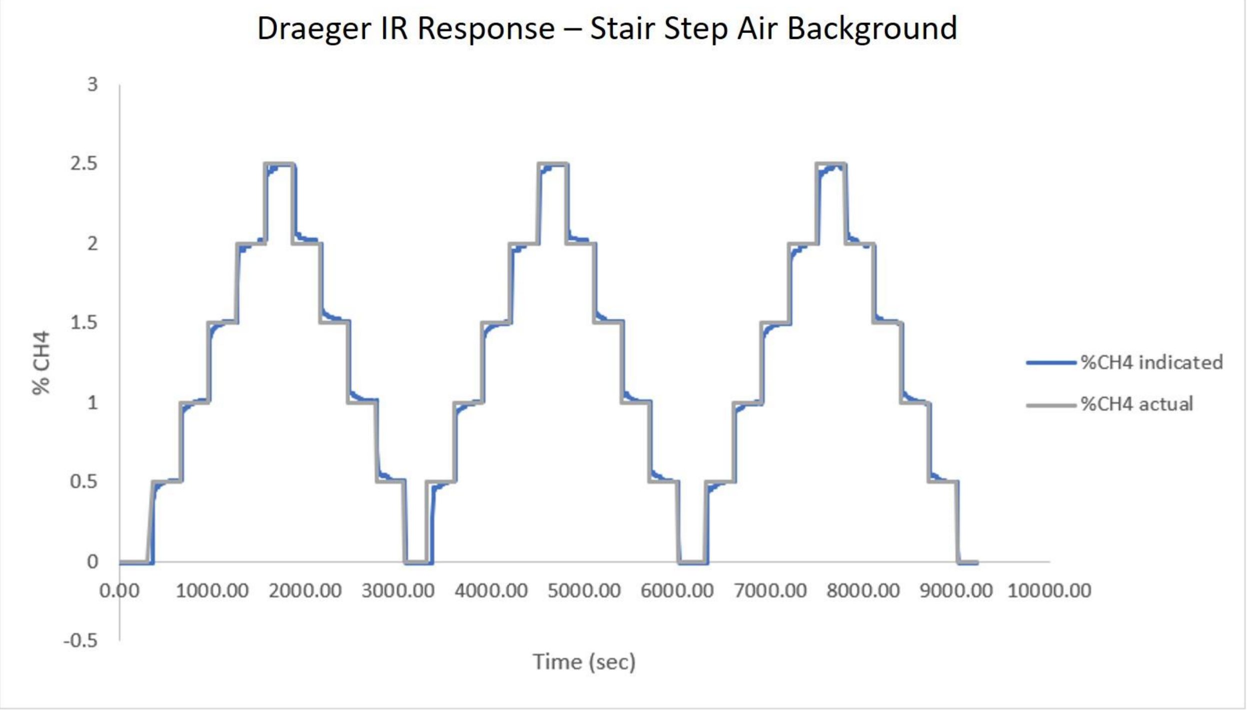

Figure 33: Draeger IR data for the stair step test with an air background.

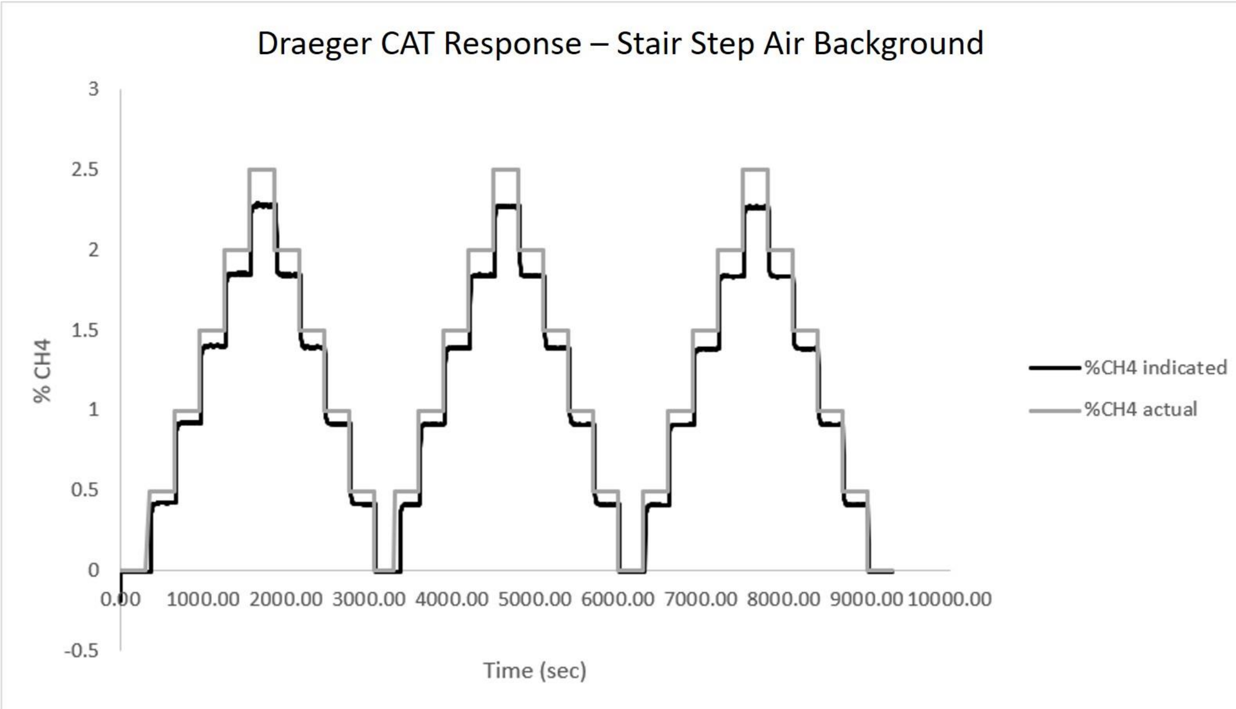

Figure 34: Draeger CAT data for sensor 2 step test with an air background.

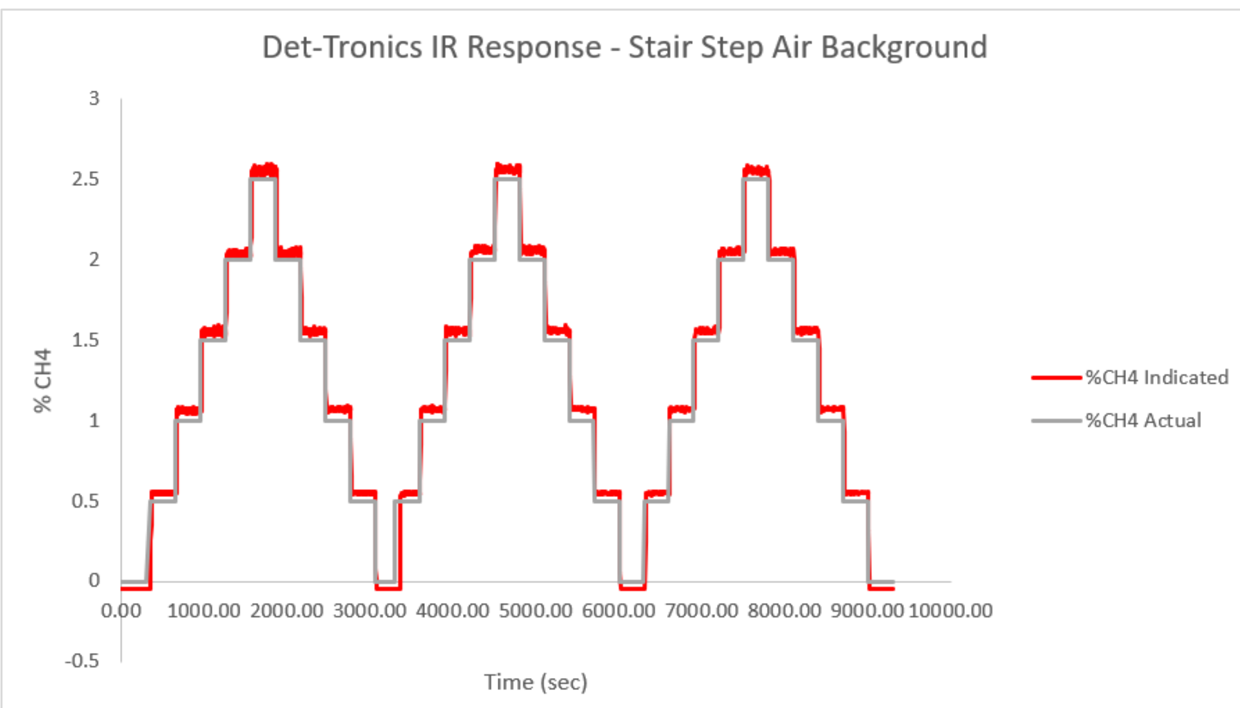

Figure 35: Det-Tronics data for the stair step test with an air background.

Table 16 lists the average output value for each time the sensor reached a particular "step," along with the average accuracy and precision calculated for those steps. Missing accuracy and precision values are cases of division by zero errors or values not collected. Accuracies for each sensor and value are also represented graphically in **Figure 36** through **Figure 38**.

The accuracy values for the Draeger IR were all less than 1.5% and were the lowest for the sensors tested. The accuracy values for the Draeger CAT were the largest values for the sensors testing, with the measured values consistently lower than the test values. The accuracy values for the Det-Tronics IR were all less than 10%, with the measured values consistently higher than the test values.

In most cases, the precision values were very low, which is good. In one instance, the Draeger IR had a precision of 109.5% due to the sensor output toggling between -0.01% and 0.00% for a 0.00% methane concentration.

For most sensors and methane concentrations, the outputs were very similar across the three repetitions of the stair step pattern. Small variations were typically the outputs settling at one value for steps which resulted from an increased methane concentration and another for steps which resulted from a decreased methane concentration.

These individual accuracy values were averaged for each sensor, not including the ~0% values for accuracy, which are skewed exceptionally large due to the very small concentrations. The Draeger IR has an average accuracy of 0.81%, the Draeger CAT has an average accuracy of -9.72%, and the Det-Tronics IR has an average accuracy of 5.10%. The vendors' specifications for accuracy for each sensor are as follows: Draeger IR = ≤ ±1% LEL; Draeger CAT = ≤ 1% LEL; and Det-Tronics IR = ±1% of the full-scale reading.

Table 16: Accuracy and Precision Results – Air Background.

Sensor	%CH_4	1	2	3	4	5	6	Average Accuracy	Average Precision
Draeger IR	0.0	-0.01	-0.01	-0.01	0.00	0.00	0.00	-	-109.5%
	0.5	0.51	0.51	0.50	0.52	0.50	0.50	1.33%	1.76%
	1.0	1.00	1.03	1.00	1.02	1.00	1.02	1.17%	1.24%
	1.5	1.51	1.53	1.50	1.52	1.49	1.51	0.67%	0.97%
	2.0	2.00	2.03	2.00	2.02	2.00	2.01	0.50%	0.57%
	2.5	2.49	2.49	2.49	2.49	2.49	2.49	-0.40%	0.03%
Draeger CAT	0.0	0.00	0.00	0.00	0.00	0.00	0.00	-	-
	0.5	0.43	0.42	0.41	0.43	0.41	0.42	-16.00%	1.91%
	1.0	0.92	0.92	0.91	0.92	0.91	0.91	-8.50%	0.67%
	1.5	1.40	1.40	1.39	1.39	1.38	1.39	-7.22%	0.42%
	2.0	1.85	1.85	1.84	1.84	1.84	1.84	-7.83%	0.31%
	2.5	2.28	2.28	2.27	2.27	2.27	2.27	-9.07%	0.28%
Det-Tronics IR	0.0	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-	0%
	0.5	0.55	0.55	0.55	0.55	0.55	0.55	10.00%	0.33%
	1.0	1.06	1.07	1.07	1.07	1.07	1.07	6.83%	0.41%
	1.5	1.55	1.56	1.56	1.56	1.56	1.56	3.89%	0.26%
	2.0	2.04	2.04	2.06	2.06	2.05	2.05	2.50%	0.45%
	2.5	2.55	2.55	2.56	2.56	2.56	2.56	2.27%	0.14%

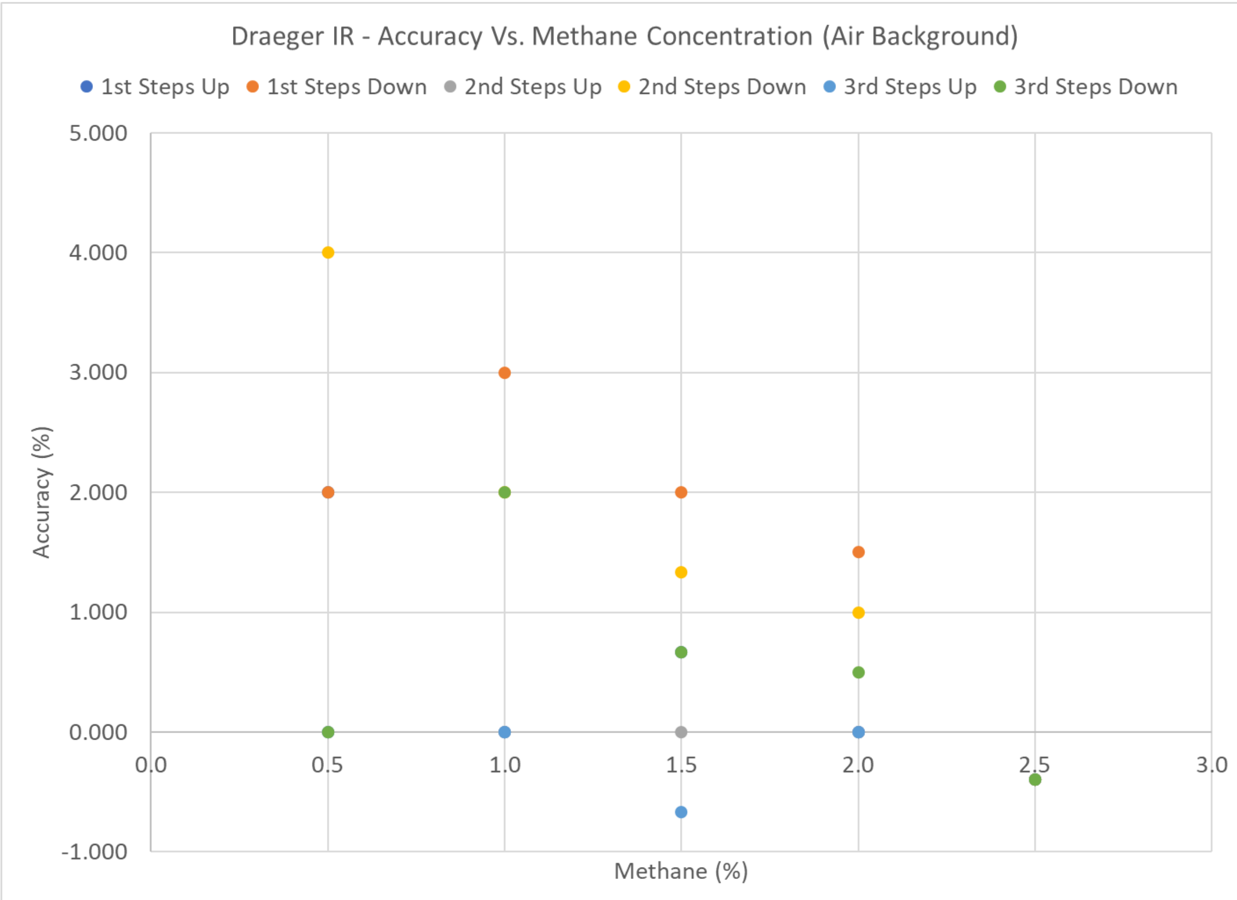

Figure 36: Draeger IR accuracy vs. methane concentration with an air background.

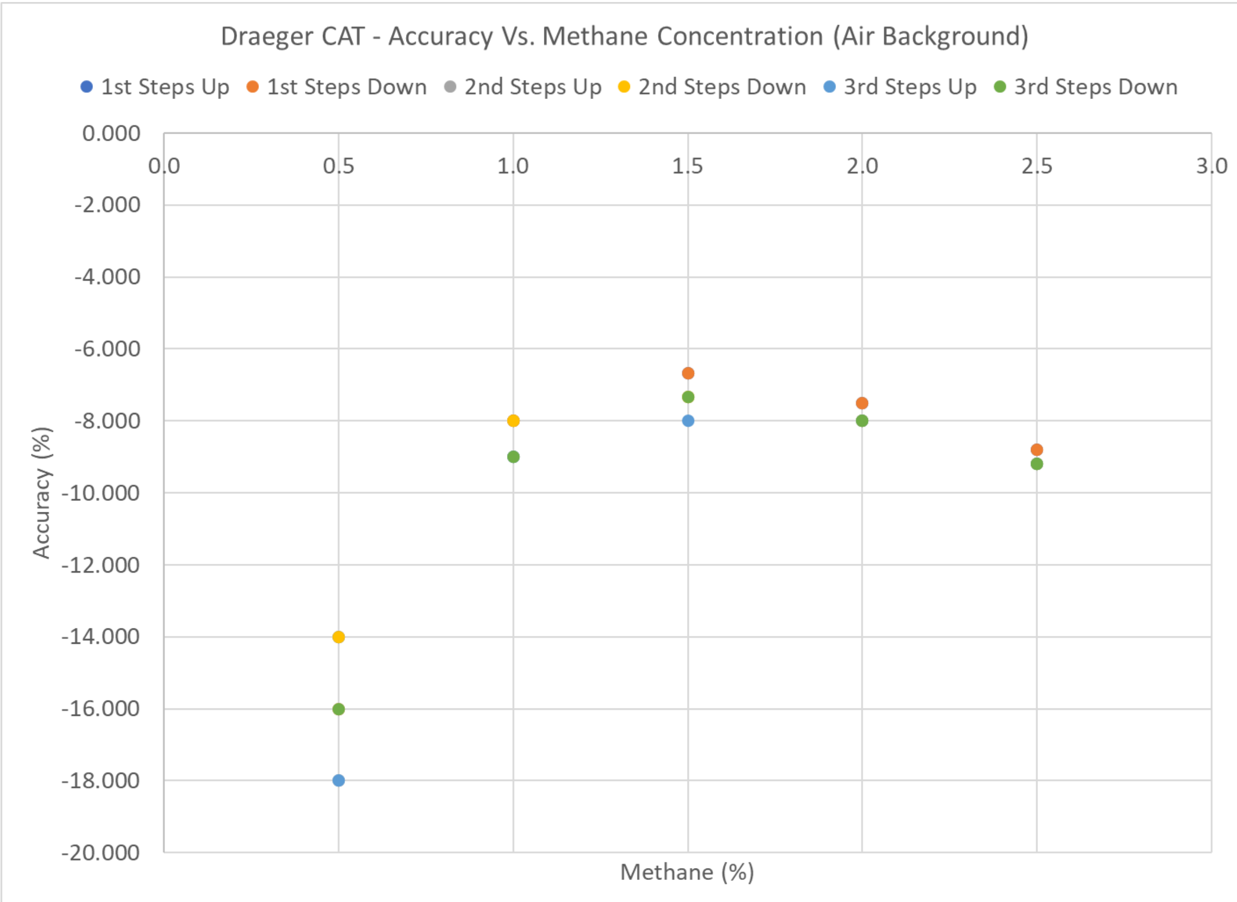

Figure 37: Draeger CAT accuracy vs. methane concentration with an air background.

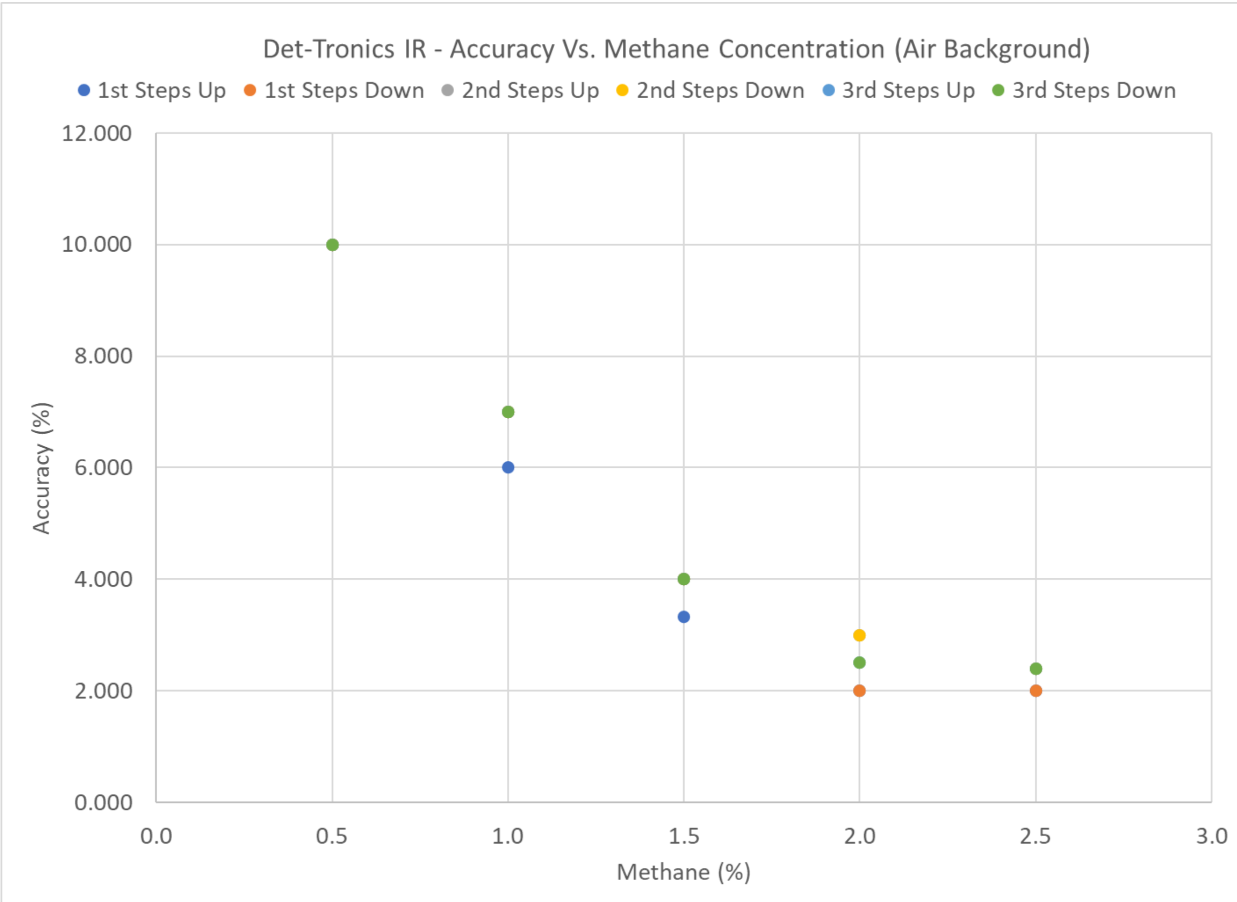

Figure 38: Det-Tronics IR accuracy vs. methane concentration with an air background.

Results – Nitrogen Background

The flow settings for the stair step test with a nitrogen background are shown in **Table 17**. All flow rates are in standard cubic centimeters per minute (sccm).

Table 17: Flow settings for stair step test (methane gas was changed first throughout test).

%CH_4 Setpoint	Time	FC1 (methane gas)	FC2 (dilution gas)
0.00	0:00	0	6556
0.50	0:05	730	5826
1.00	0:10	1460	5096
1.50	0:15	2190	4366
2.00	0:20	2920	3636
2.50	0:25	3650	2906
2.00	0:30	2920	3636
1.50	0:35	2190	4366
1.00	0:40	1460	5096
0.50	0:45	730	5826
0.00	0:50	0	6556
0.50	0:55	730	5826
1.00	1:00	1460	5096
1.50	1:05	2190	4366
2.00	1:10	2920	3636
2.50	1:15	3650	2906
2.00	1:20	2920	3636
1.50	1:25	2190	4366
1.00	1:30	1460	5096
0.50	1:35	730	5826
0.00	1:40	0	6556
0.50	1:45	730	5826
1.00	1:50	1460	5096
1.50	1:55	2190	4366
2.00	2:00	2920	3636
2.50	2:05	3650	2906
2.00	2:10	2920	3636
1.50	2:15	2190	4366
1.00	2:20	1460	5096
0.50	2:25	730	5826
0.00	2:30	0	6556

Figure 39 through **Figure 41** show data collected during the stair step test with an air background.

The Draeger IR showed each step consistently. The sensor's outputs were very close to the actual methane concentrations being supplied.

The Draeger CAT did not show a response since the sensor requires the presence of oxygen to operate.

The Det-Tronics IR showed each step consistently. The sensor's outputs were consistently higher than the actual methane concentrations being supplied but could improve with calibration.

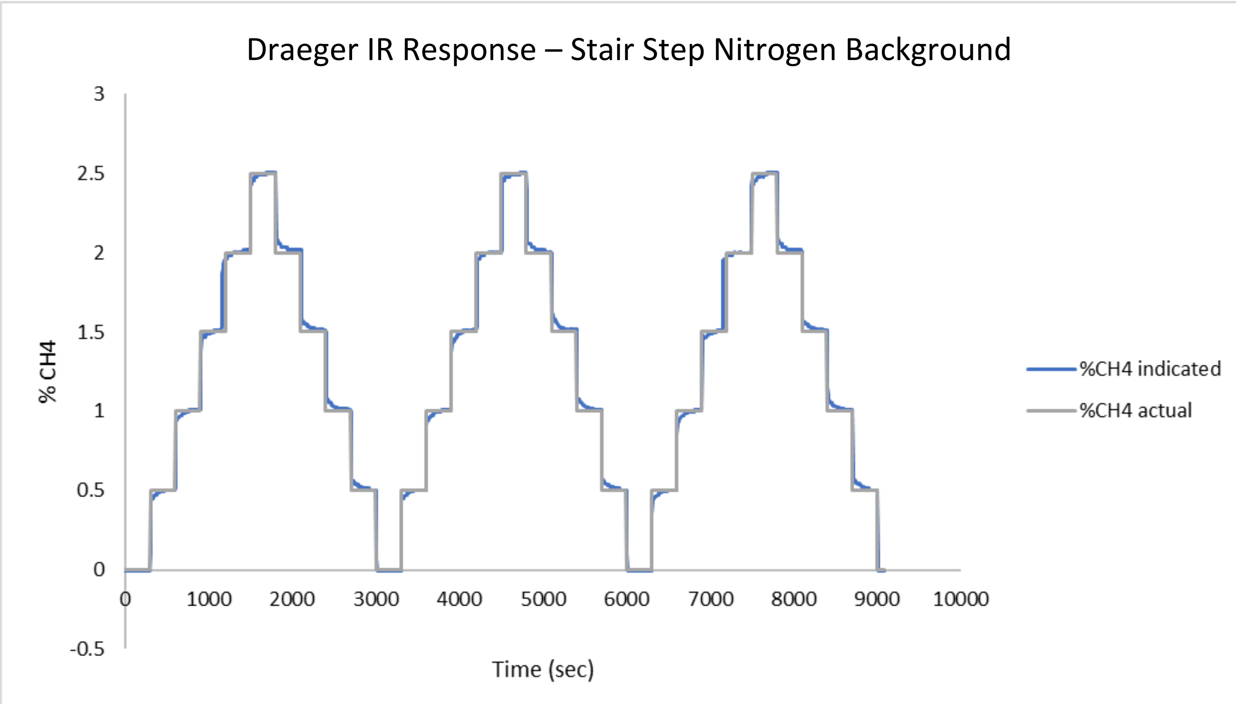

Figure 39: Draeger IR data for the stair step test with a nitrogen background.

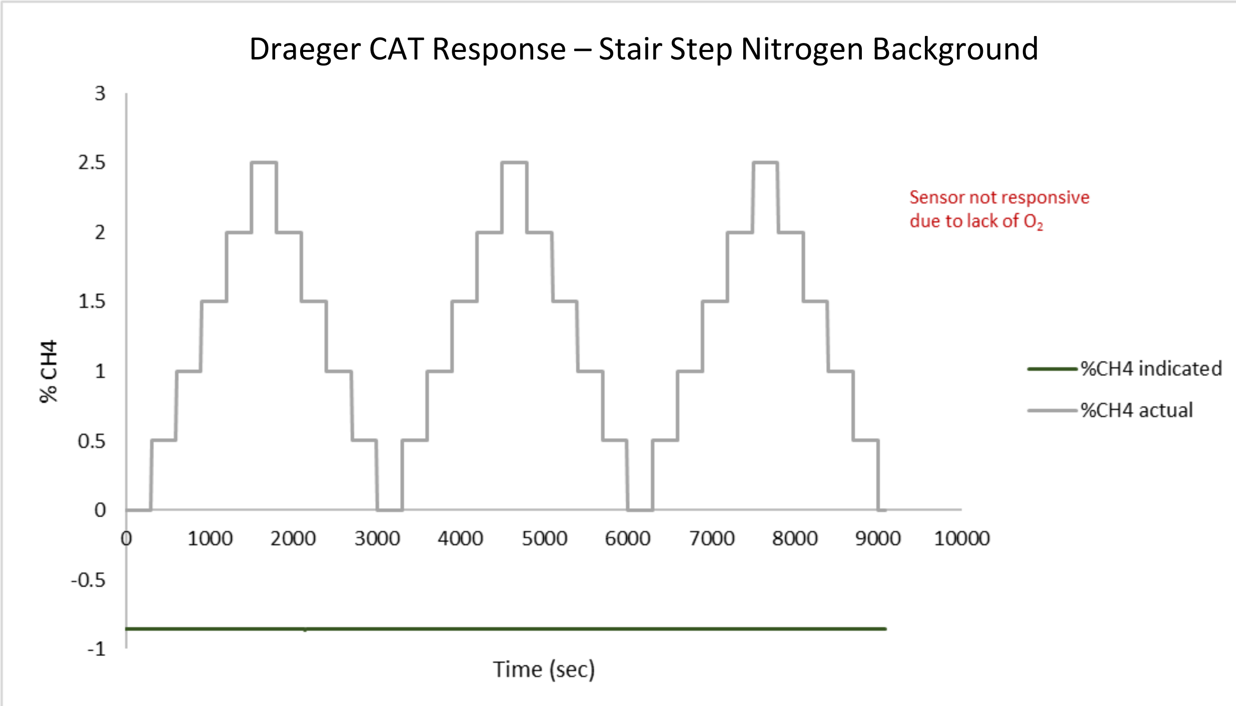

Figure 40: Draeger CAT data for the stair step test with a nitrogen background.

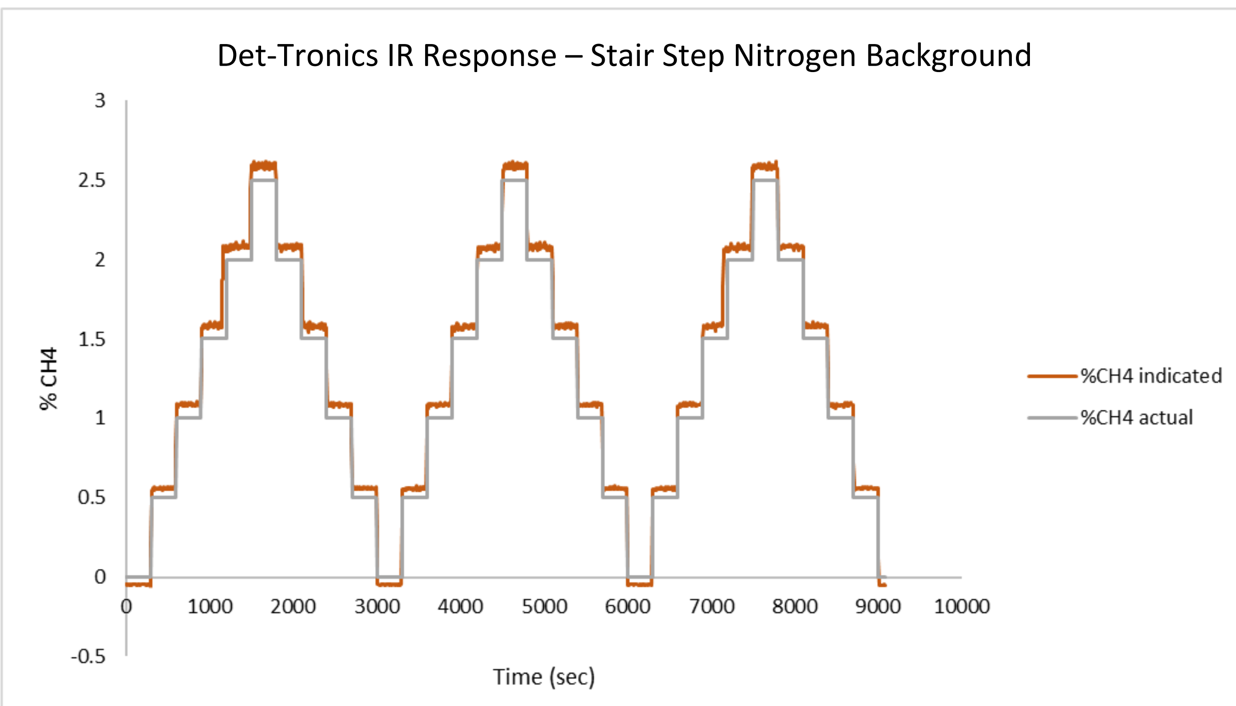

Figure 41: Det-Tronics data for the stair step test with a nitrogen background.

Table 18 lists the average output value for each time the sensor reached a particular "step," along with the average accuracy and precision calculated for those steps. Missing accuracy and precision values are cases of division by zero errors or values not collected. Accuracies for each sensor and value are also represented graphically in **Figure 42** and **Figure 43**.

The accuracy values for the Draeger IR were all less than 1.5% and were the lowest for the sensors tested. The accuracy values for the Det-Tronics IR were all less than 12%, with the measured values consistently higher than the test values.

In most cases, the precision values were very low, which is good. In one instance, the Draeger IR had a precision of 1.29% due to the sensor output toggling between 1.00% and 1.03% for a 1.00% methane concentration.

For most sensors and methane concentrations, the outputs were very similar across the three repetitions of the stair step pattern. Small variations were typically the outputs settling at one value for steps which resulted from an increased methane concentration and another for steps which resulted from a decreased methane concentration.

These individual accuracy values were averaged for each sensor, not including the ~0% values for accuracy, which are skewed exceptionally large due to the very small concentrations. The Draeger IR has an average accuracy of 0.73% and the Det-Tronics IR has an average accuracy of 6.69%. The vendors' specifications for accuracy for each sensor are as follows: Draeger IR = ≤ ±1% LEL and Det-Tronics IR = ±1% of the full-scale reading.

Table 18: Accuracy and Precision Results – Nitrogen Background.

Sensor	**%CH_4**	**1**	**2**	**3**	**4**	**5**	**6**	**Average Accuracy**	**Average Precision**
Draeger IR	0.0	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-	0%
	0.5	0.50	0.51	0.50	0.51	0.50	0.51	1.00%	0.96%
	1.0	1.00	1.03	1.00	1.02	1.00	1.03	1.33%	1.29%
	1.5	1.51	1.51	1.51	1.52	1.50	1.51	0.67%	0.32%
	2.0	2.01	2.03	2.00	2.02	2.00	2.02	0.67%	0.77%
	2.5	2.50	2.50	2.50	2.50	2.50	2.50	0.00%	0.09%
Det-Tronics IR	0.0	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-	0%
	0.5	0.56	0.56	0.56	0.56	0.56	0.56	12.00%	0.28%
	1.0	1.09	1.09	1.08	1.09	1.09	1.09	8.83%	0.07%
	1.5	1.58	1.58	1.58	1.58	1.58	1.58	5.33%	0.15%
	2.0	2.08	2.08	2.07	2.08	2.07	2.08	3.83%	0.17%
	2.5	2.59	2.59	2.59	2.59	2.58	2.58	3.47%	0.08%

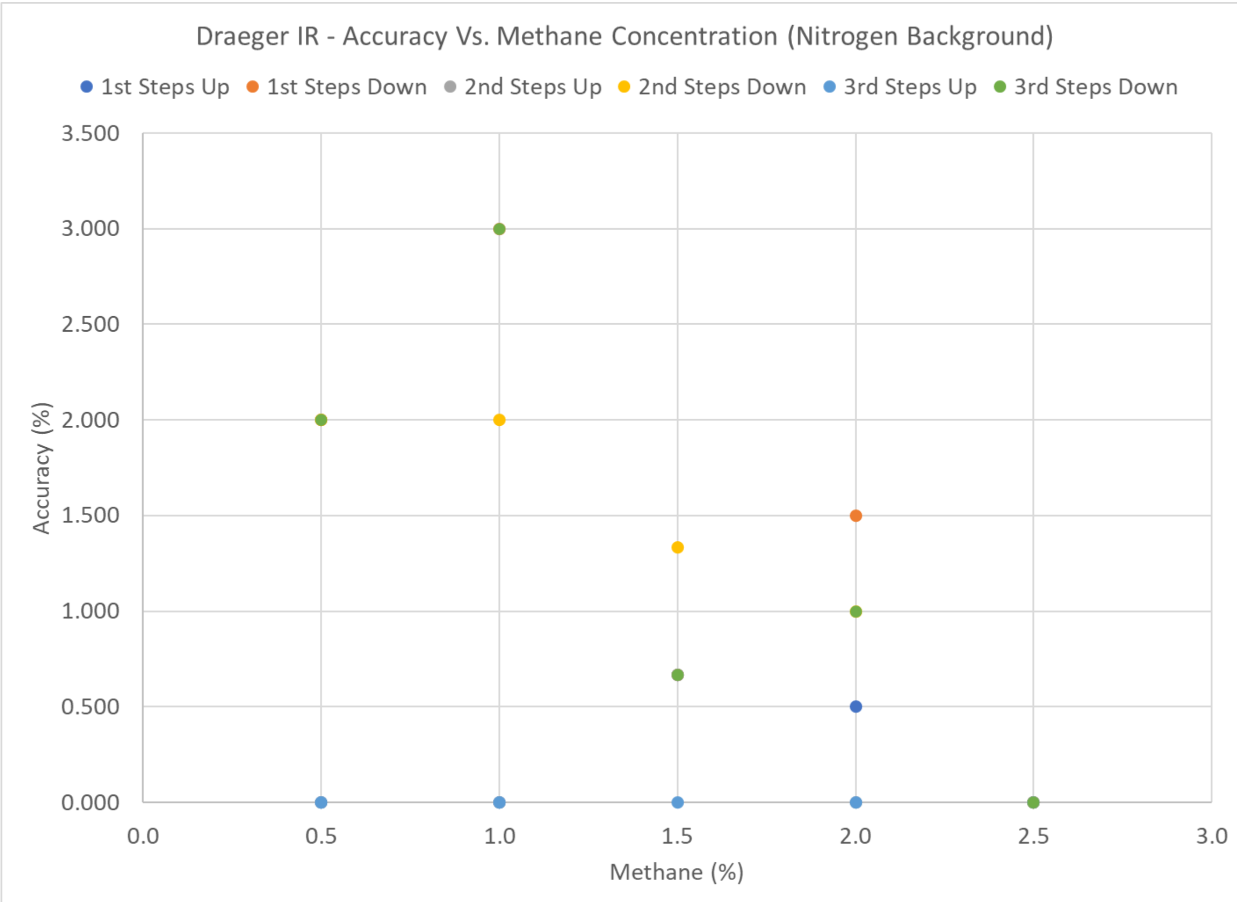

Figure 42: Draeger IR accuracy vs. methane concentration with a nitrogen background.

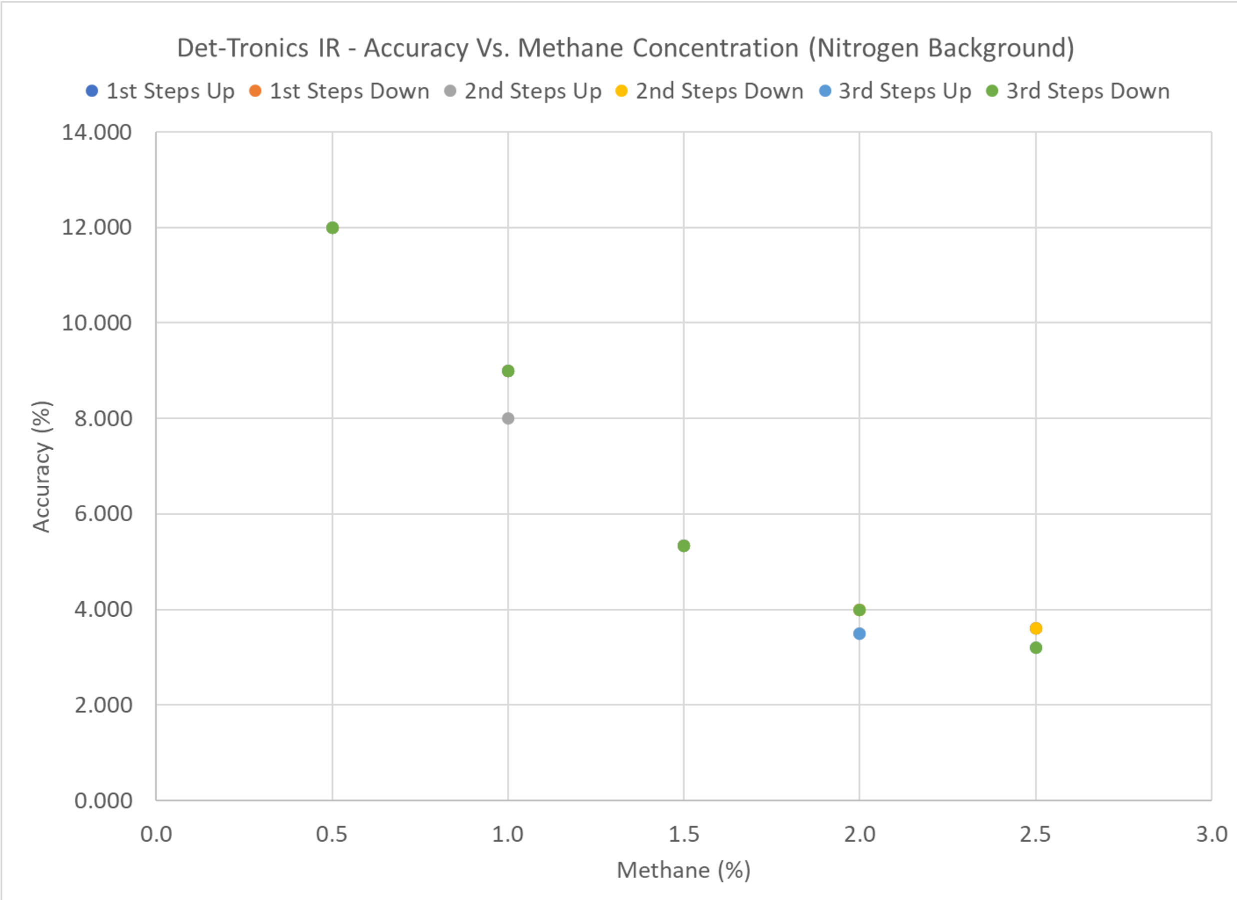

Figure 43: Det-Tronics IR accuracy vs. methane concentration with a nitrogen background.

Square Wave Test

This test was used to determine the repeatability of the sensors. Methane concentrations were changed in a series of square waves, from ~0% to a given methane concentration and back to ~0% again. Each concentration was repeated three times. The sensor outputs for each of the three repetitions were compared to one another to determine how repeatable each sensor's outputs were.

Procedure

1. Connect methane gas mixture and appropriate background gas to the test system.
2. Power on the sensors.
3. Allow appropriate warm-up time, per manufacturer specification, prior to continuing.
4. Begin data collection.
5. Begin flow of appropriate background gas to provide ~0% methane.
6. Allow outputs to stabilize.
7. Adjust gas flows for a methane concentration of 0.5%.
8. Allow outputs to stabilize.
9. Adjust gas flows for a methane concentration of ~0%.
10. Allow outputs to stabilize.
11. Repeat steps 7 through 10 for two more cycles at 0.5%.
12. Repeat this process, with three cycles per concentration, increasing methane concentrations by 0.5% (or similar value that is appropriate for available gas concentrations) each time until the maximum available gas concentration is reached.

Determining Repeatability

For the purpose of this evaluation, repeatability is defined as the maximum change in sensor output over three repetitions of the same methane concentration change. Repeatability is given in terms of the difference in methane concentrations reported by the sensors, $\%CH_4$. The average sensor output values after stabilization were used to eliminate the impact of any system noise.

Repeatability was calculated as follows:

$$Repeatabilty = output_{maximum} - output_{minimum}$$

where:

$output_{maximum}$ = the maximum average sensor output, after stabilization, for the three cycles at a given methane concentration.

$output_{minimum}$ = the minimum average sensor output, after stabilization, for the three cycles at a given methane concentration.

The flow settings for the square wave test are shown in **Table 19**. All flow rates are in standard cubic centimeters per minute (sccm).

Table 19: Flow settings for square wave test (methane gas changed first throughout test).

$\%CH_4$ Setpoint	Time	FC1 (methane gas)	FC2 (dilution gas)
0.00	0:00	0	6556
0.50	0:05	730	5826
0.00	0:10	0	6556

0.50	0:15	730	5826
0.00	0:20	0	6556
0.50	0:25	730	5826
0.00	0:30	0	6556
1.00	0:35	1460	5096
0.00	0:40	0	6556
1.00	0:45	1460	5096
0.00	0:50	0	6556
1.00	0:55	1460	5096
0.00	1:00	0	6556
1.50	1:05	2190	4366
0.00	1:10	0	6556
1.50	1:15	2190	4366
0.00	1:20	0	6556
1.50	1:25	2190	4366
0.00	1:30	0	6556
2.00	1:35	2920	3636
0.00	1:40	0	6556
2.00	1:45	2920	3636
0.00	1:50	0	6556
2.00	1:55	2920	3636
0.00	2:00	0	6556
2.50	2:05	3650	2906
0.00	2:10	0	6556
2.50	2:15	3650	2906
0.00	2:20	0	6556
2.50	2:25	3650	2906
0.00	2:30	0	6556

<u>Results – Air Background</u>

Figure 44 through **Figure 46** show the data collected for the square wave test with an air background.

In each case, the three repetitions of each methane concentration had very similar responses, indicating good repeatability.

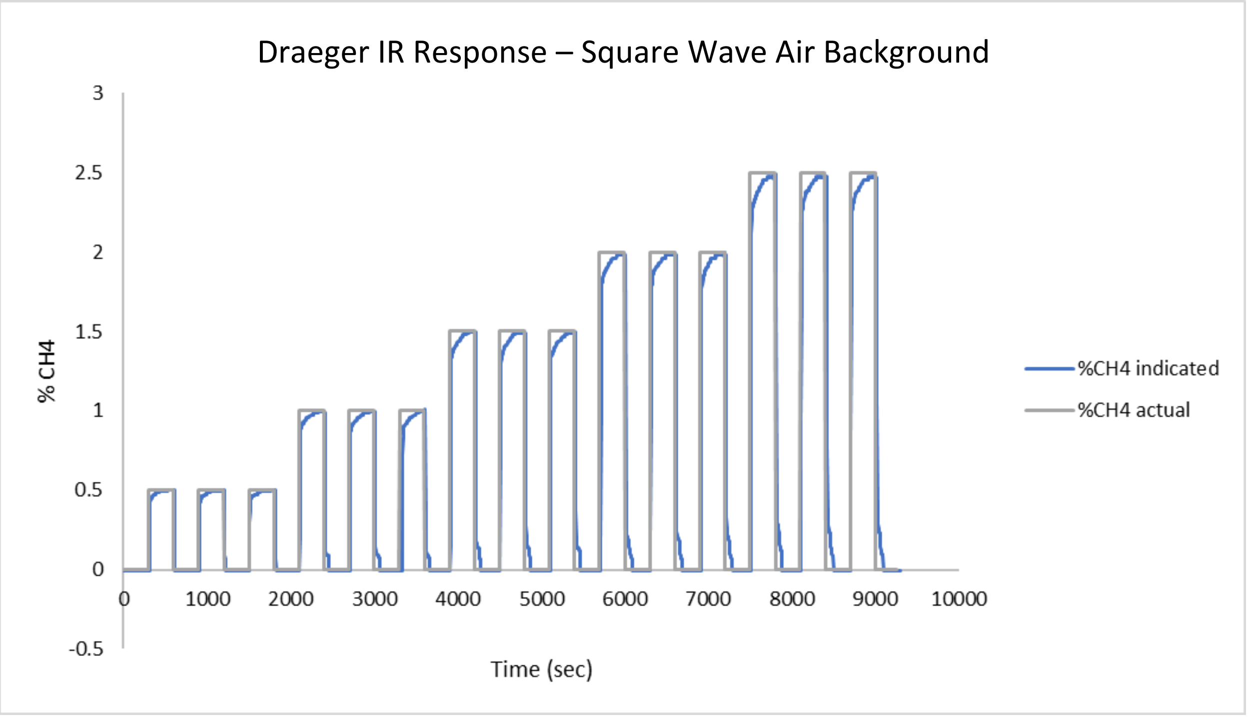

Figure 44: Draeger IR data for the square wave test with an air background.

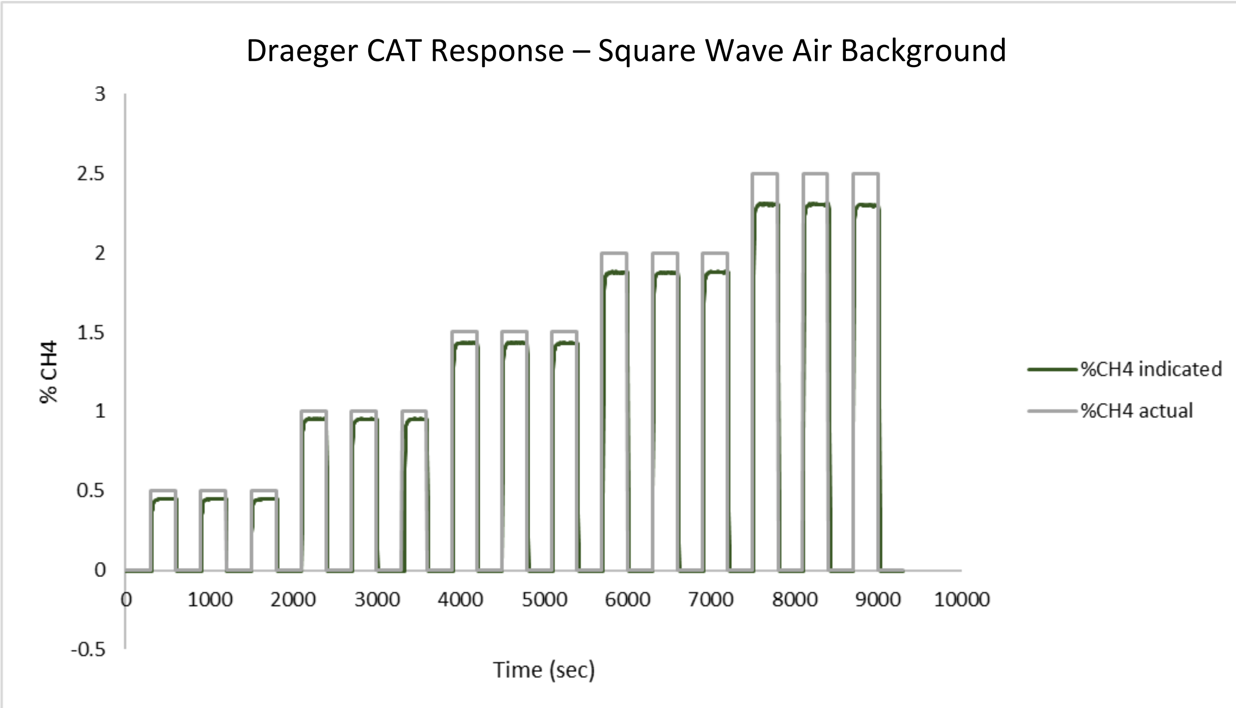

Figure 45: Draeger CAT data for the square wave test with an air background.

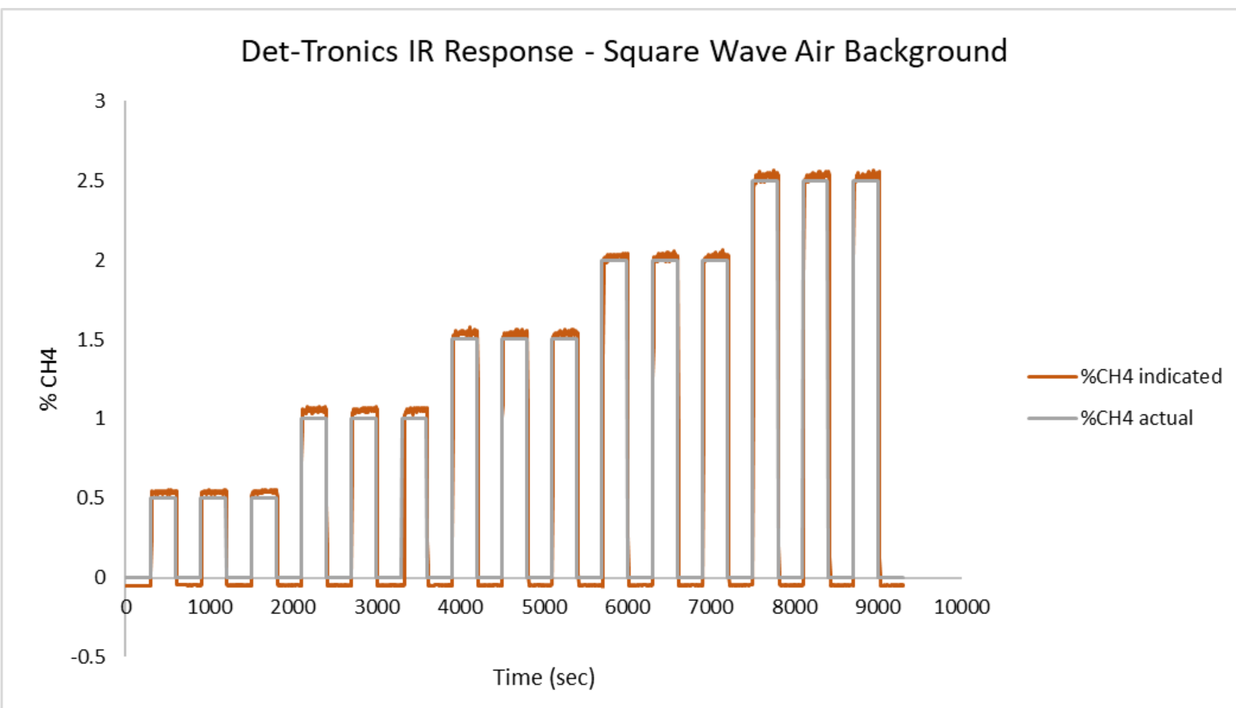

Figure 46: Det-Tronics data for the square wave test with an air background.

For each methane concentration, the average sensor outputs after they had stabilized were calculated. Those values, as well as the repeatability (the difference between the maximum and minimum values for each methane concentration) are given in **Table 20**.

None of the three sensors tested showed a large change between repeated cycling to a given set point. The vendors' specifications for repeatability for each sensor are as follows: Draeger IR = ≤ ±1% LEL; Draeger CAT = ≤ 1% LEL; and Det-Tronics IR = ±1% of the full-scale reading.

Table 20: Repeatability results – air background.

Sensor	%CH_4	Value 1 (%CH_4)	Value 2 (CH_4)	Value 3 (%CH_4)	Repeatability (%CH4)	Average Repeatability
Draeger IR	0.5	0.50	0.49	0.50	0.01	0.01% CH_4
	1.0	0.99	0.99	0.99	0.00	
	1.5	1.49	1.49	1.49	0.00	
	2.0	1.98	1.98	1.98	0.00	
	2.5	2.48	2.47	2.47	0.01	
Draeger CAT	0.5	0.45	0.45	0.45	0.00	0.00% CH_4
	1.0	0.95	0.95	0.95	0.00	
	1.5	1.43	1.43	1.43	0.00	
	2.0	1.88	1.88	1.88	0.00	
	2.5	2.31	2.31	2.30	0.01	
Det-Tronics IR	0.5	0.54	0.54	0.54	0.00	0.00% CH_4
	1.0	1.05	1.06	1.06	0.01	
	1.5	1.54	1.54	1.54	0.00	
	2.0	2.02	2.02	2.02	0.00	
	2.5	2.53	2.53	2.53	0.00	

<u>Results – Nitrogen Background</u>

Figure 47 through **Figure 49** show the data collected for the square wave test with a nitrogen background.

In each case, the three repetitions of each methane concentration had very similar responses, indicating good repeatability. The Draeger CAT did not respond due to the lack of oxygen in the test samples.

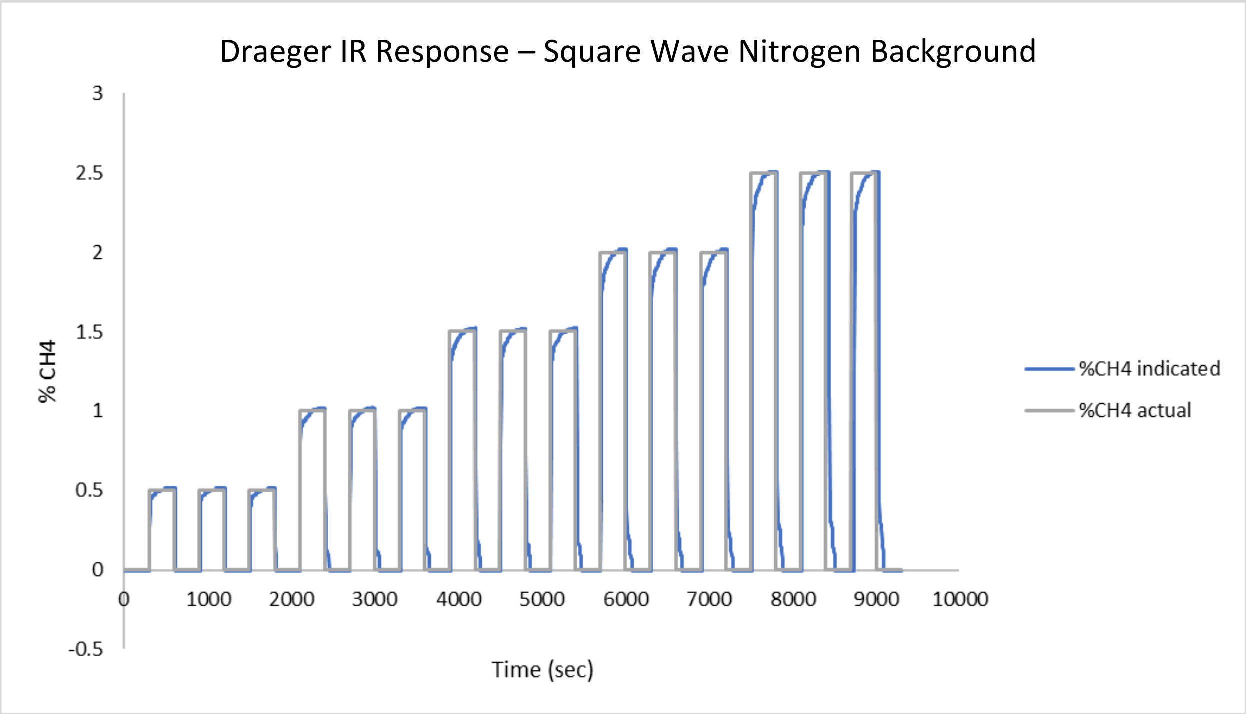

Figure 47: Draeger IR data for the square wave test with a nitrogen background.

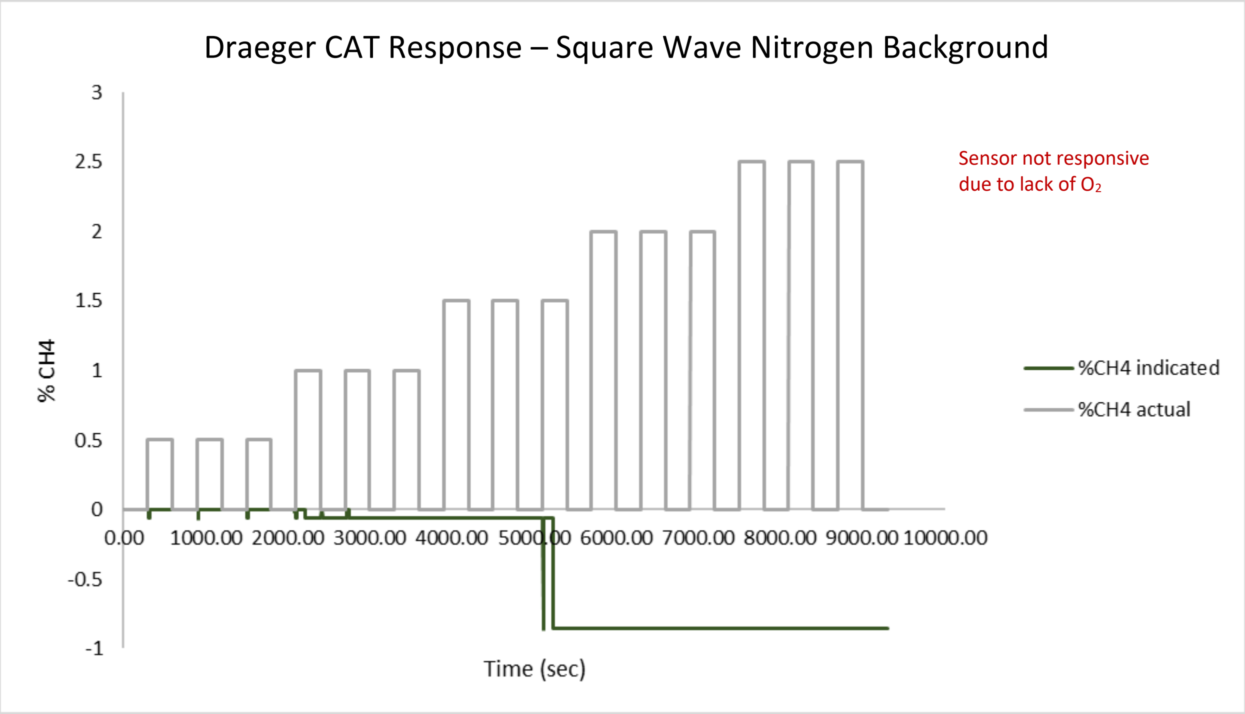

Figure 48: Draeger CAT data for the square wave test with a nitrogen background.

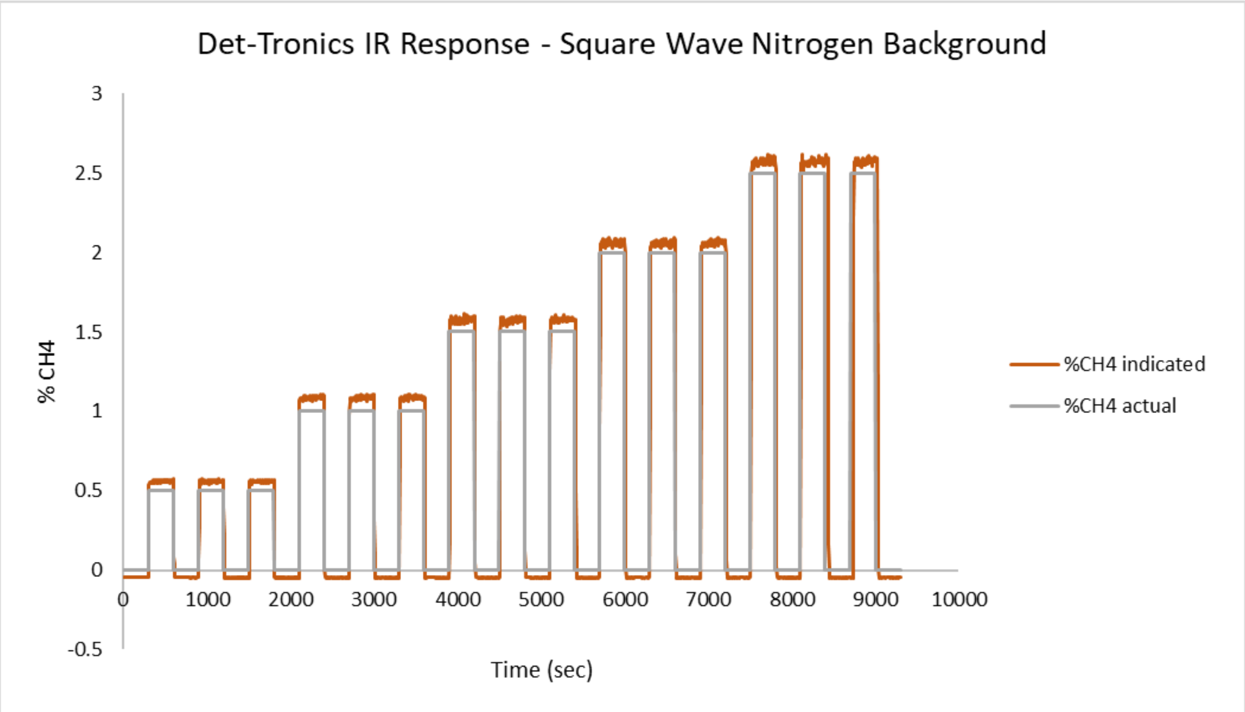

Figure 49: Det-Tronics data for the square wave test with a nitrogen background.

For each methane concentration, the average sensor outputs after they had stabilized were calculated. Those values, as well as the repeatability (the difference between the maximum and minimum values for each methane concentration) are given in **Table 21**.

None of the two sensors tested showed a large change between repeated cycling to a given set point. The vendors' specifications for repeatability for each sensor are as follows: Draeger IR = ≤ ±1% LEL and Det-Tronics IR = ±1% of the full-scale reading.

Table 21: Repeatability results – nitrogen background.

Sensor	**%CH_4**	**Value 1 (%CH_4)**	**Value 2 (CH_4)**	**Value 3 (%CH_4)**	**Repeatability (%CH4)**	**Average Repeatability**
Draeger IR	0.5	0.51	0.51	0.51	0.00	0.00% CH_4
	1.0	1.01	1.01	1.01	0.00	
	1.5	1.51	1.51	1.51	0.00	
	2.0	2.01	2,01	2.01	0.00	
	2.5	2.50	2.50	2.50	0.00	
Det-Tronics IR	0.5	0.56	0.56	0.56	0.00	0.00% CH_4
	1.0	1.08	1.09	1.08	0.01	
	1.5	1.57	1.57	1.58	0.01	
	2.0	2.06	2.06	2.06	0.00	
	2.5	2.57	2.57	2.57	0.00	

Response Tests

This test was used to determine how quickly the sensors respond to the presence or absence of methane. Data for this test were collected in a manner very similar to the one used for the square wave test but using a single gas concentration and higher sample rate for increased granularity for timing. Test data were used to calculate response time – the times it took for the sensor outputs to begin to change following changes in methane concentration, and the T-90 and T-10 times – the times it took for the sensor outputs to be within 10% of their final values following changes in methane concentration.

Procedure

1. Connect methane gas mixture and appropriate background gas to the test system.
2. Power on the sensors.
3. Allow appropriate warm-up time, per manufacturer specification, prior to continuing.
4. Begin data collection with a sample rate of 10 Hz.
5. Begin flow of appropriate background gas to provide ~0% methane.
6. Allow outputs to stabilize.
7. Adjust gas flows for a methane concentration of 1%.
8. Allow outputs to stabilize.
9. Adjust gas flows for a methane concentration of ~0%.
10. Allow outputs to stabilize.
11. Repeat steps 7 through 10 for two more cycles at 1%.

Determining Response Time

For this evaluation, response time is defined as the time that is takes for the sensor output to begin to change following a change in methane concentration. This information is useful because it indicates how quickly a leak can be detected, even if its exact concentration is not yet known.

Response time was calculated for each change in methane concentration as follows.

For increasing gas concentrations:

$$\textit{Response time} = t_{rise} - t_{change}$$

where:

t_{rise} = the time at which the sensor output first rose above the previous methane concentration's stabilized output.

t_{change} = the time at which the provided methane concentration changed

For decreasing gas concentrations:

$$\textit{Response time} = t_{drop} - t_{change}$$

where:

t_{drop} = the time at which the sensor output first fell below the previous methane concentration's stabilized output.

t_{change} = the time at which the provided methane concentration changed

The flow settings for the recovery test are shown in **Table 22**. All flow rates are in standard cubic centimeters per minute (sccm).

Table 22: Flow settings for recovery response test.

$\%CH_4$ Setpoint	Time	FC1 (methane gas)	FC2 (dilution gas)
0	0:00	0	5800
0.05	0:05	100	5800
1.00	0:07	2975	5800
0.05	0:09	100	5800
1.00	0:11	2975	5800
0.05	0:13	100	5800
1.00	0:15	2975	5800
0.05	0:17	100	5800
STOP	0:19	0	5800

Determining T-90 and T-10 Times

In industry, standard values with regard to a sensor's time to adjust from one concentration to another are its T-90 and T-10 times. T-90 refers to the amount of time that it takes for a detector to reach 90% of its final value for increasing concentrations. Similarly, T-10 refers to the amount of time that it takes for a detector to reach 10% above the final value for decreasing concentrations. Although reaching those levels for the expected gas concentration are typically used, this test evaluates the sensors against their settled outputs because the sensors had not been calibrated.

The T-90 and T-10 times for these tests were calculated as follows.

For increasing concentrations:

$$T\text{-}90 = t_{90\%} - t_{change}$$

where:

$t_{90\%}$ = the time at which the sensor first reached 90% of its settled output

t_{change} = the time at which the provided methane concentration changed

For decreasing concentrations:

$$T\text{-}10 = t_{10\%} - t_{change}$$

where:

$t_{10\%}$ = the time at which the sensor first reached 10% above its settled output

t_{change} = the time at which the methane concentration changed

Results – Air Background

Values for flow rates were chosen that required only the methane MFC to be changed between the high (1%) and low (~0%) methane concentrations to reduce the delay in gas concentration changes. Due to the system setup, however, there could be some delay between the gas concentration value (reported by the MFC) and the actual concentrations present down-line at the various sensors due to the time required for the gas to physically travel down the tubing, in spite of its length being minimized.

Figure 50 through **Figure 52** show the data collected for this test.

In each test, once the Draeger IR responded, the output increased quickly following an increase in gas concentration, then slowly continued to increase as it gradually approached its final value. When the methane concentration dropped to zero, the Draeger IR's output very quickly dropped to approximately 0.1% methane but never fully returned to zero.

The Draeger CAT responded in a manner very similar to the Draeger IR, although the sensor values did seem to level out after 30-45 seconds of exposure. When the methane concentration dropped to zero, the Draeger CAT's output dropped relatively quickly to zero.

The Det-Tronics IR sensor responded relatively quickly following an increase in the methane concentration and leveled out fairly quickly. When the methane concentration dropped to zero, the Draeger CAT's output dropped relatively quickly to zero.

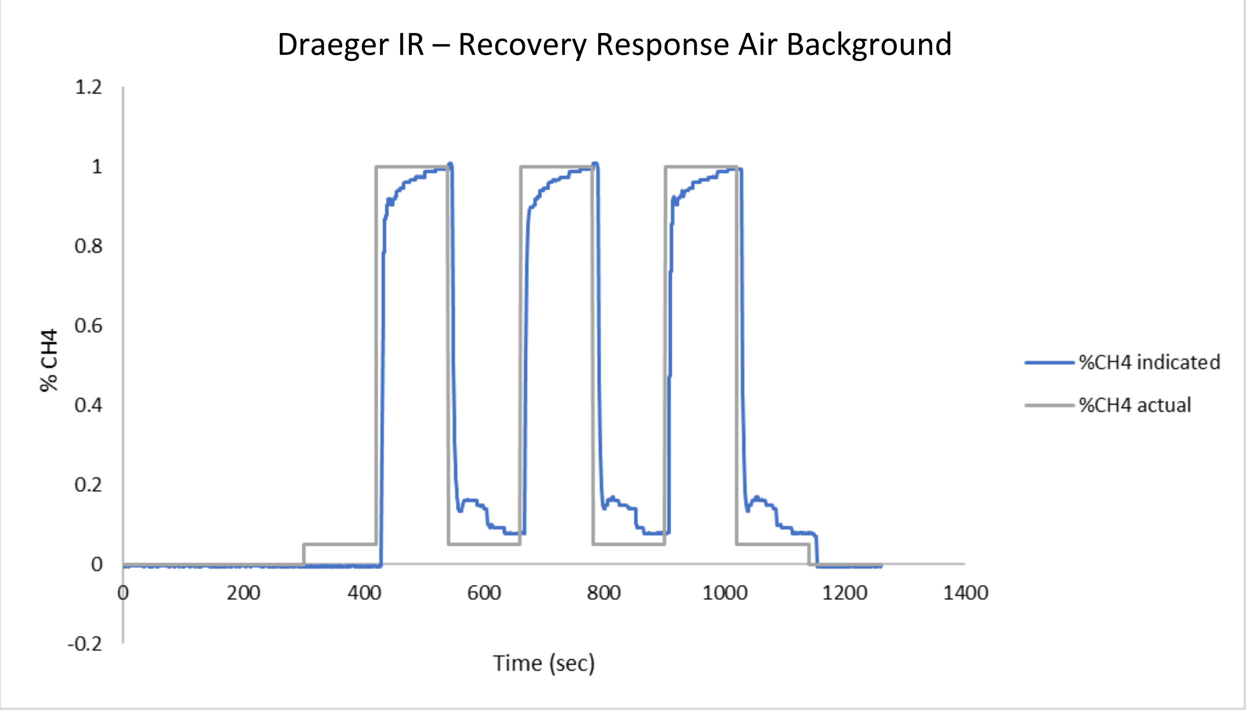

Figure 50: Draeger IR data for the recovery response test with an air background.

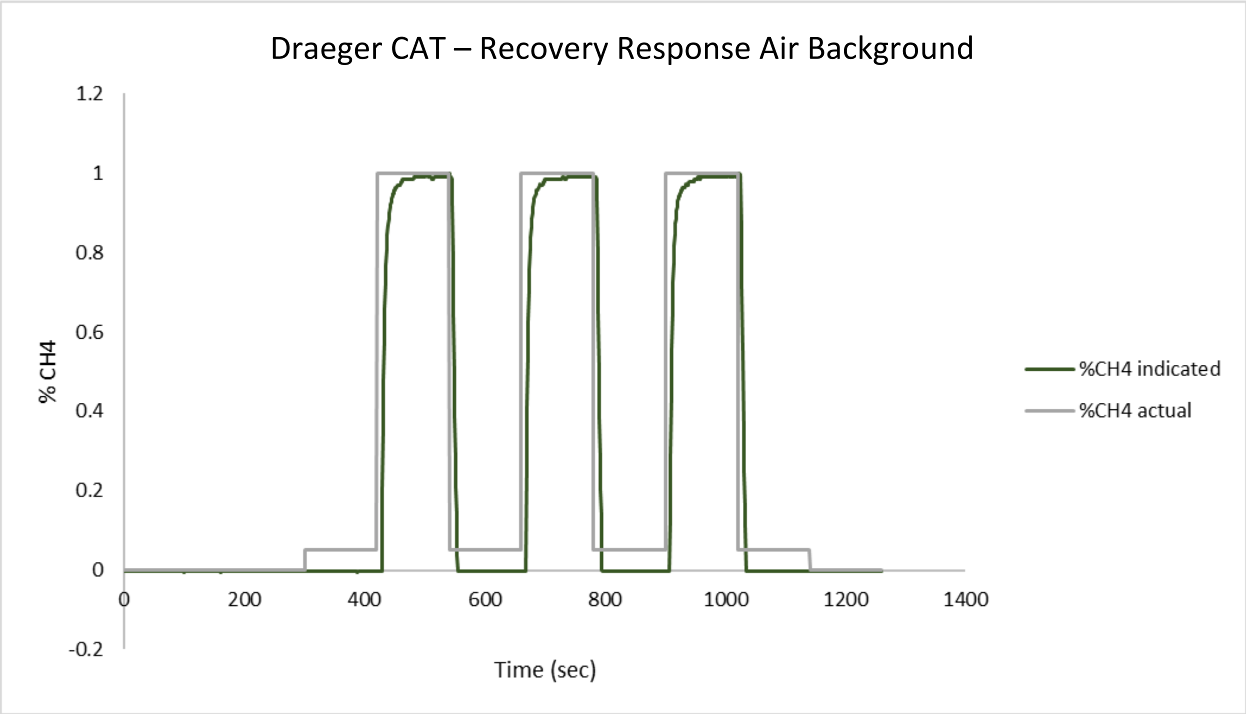

Figure 51: Draeger CAT data for the recovery response test with an air background.

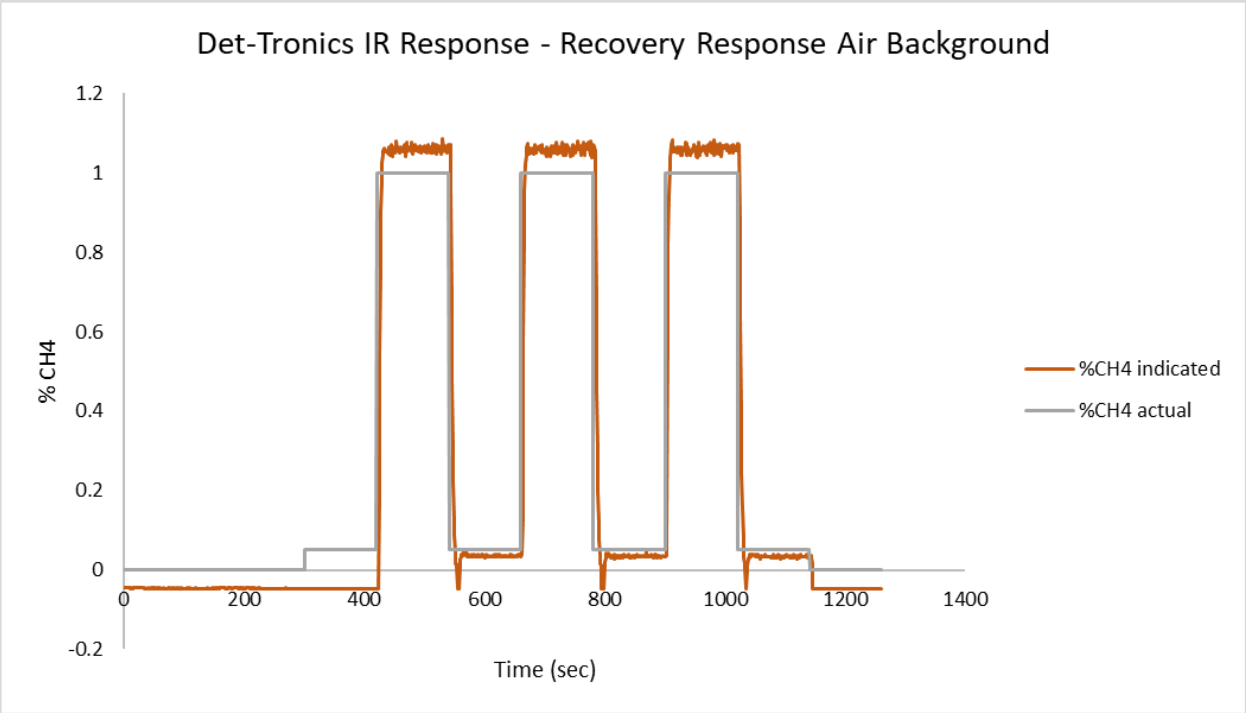

Figure 52: Det-Tronics data for the recovery response test with an air background.

For each test, data was collected in three repetitions. Individual results and the average T-90 and T-10 values are given in **Table 23**.

The Draeger IR responded to a change in methane concentration in about 9 seconds when the methane concentration increased and in about 8 seconds when it decreased. It reached within 90% of its high values in under 20 seconds on average, while lowering to within 10% above its low values under 70 seconds. The vendor's specification for T-90 was 4 seconds (no value for T-10 was provided).

The Draeger CAT responded to a change in methane concentration in about 9 seconds when the methane concentration increased and in about 5 seconds when it decreased. It reached within 90% of its high values in under 20 seconds, while lowering to within 10% above its low values in under 15 seconds. The vendor's specification for T-90 was less than 13 seconds (no value for T-10 was provided).

The Det-Tronics IR responded to a change in methane concentration in about 4 seconds when the methane concentration increased and in about 3 seconds when it decreased. It took about 7 seconds for it to reach within 90% of its high values, while lowering to within 10% above its low values in about 10 seconds. The vendor's specification for T-90 was 7.1 seconds (no value for T-10 was provided).

Table 23: Response times and average T-90 and T-10 values – air background.

Sensor	Response Time Low to High (s)	Response Time High to Low (s)	Average T-90 Time (s)	Average T-10 Time (s)
Draeger IR	9.00	8.00	19.38	68.03
	8.01	10.23		
	7.11	7.79		
Draeger CAT	9.00	4.00	18.43	13.65
	8.01	5.23		
	6.11	5.38		
Det-Tronics IR	4.00	3.00	7.04	9.47
	3.00	4.11		
	2.00	3.15		

Results – Nitrogen Background

Values for flow rates were chosen that required only the methane MFC to be changed between the high (1%) and low (~0%) methane concentrations to reduce the delay in gas concentration changes. Due to the system setup, however, there could be some delay between the gas concentration value (reported by the MFC) and the actual concentrations present down-line at the various sensors due to the time required for the gas to physically travel down the tubing, in spite of its length being minimized.

Figure 53 through **Figure 55** show the data collected for this test.

In each test, once the Draeger IR responded, the output increased quickly following an increase in gas concentration, then slowly continued to increase as it gradually approached its final value. When the methane concentration dropped to zero, the Draeger IR's output very quickly dropped to approximately 0.2% methane but never fully returned to zero.

The Draeger CAT did not respond due to the lack of oxygen present in the test gas.

The Det-Tronics IR sensor responded relatively quickly following an increase in the methane concentration and leveled out fairly quickly. When the methane concentration dropped to zero, the Draeger CAT's output dropped relatively quickly to zero.

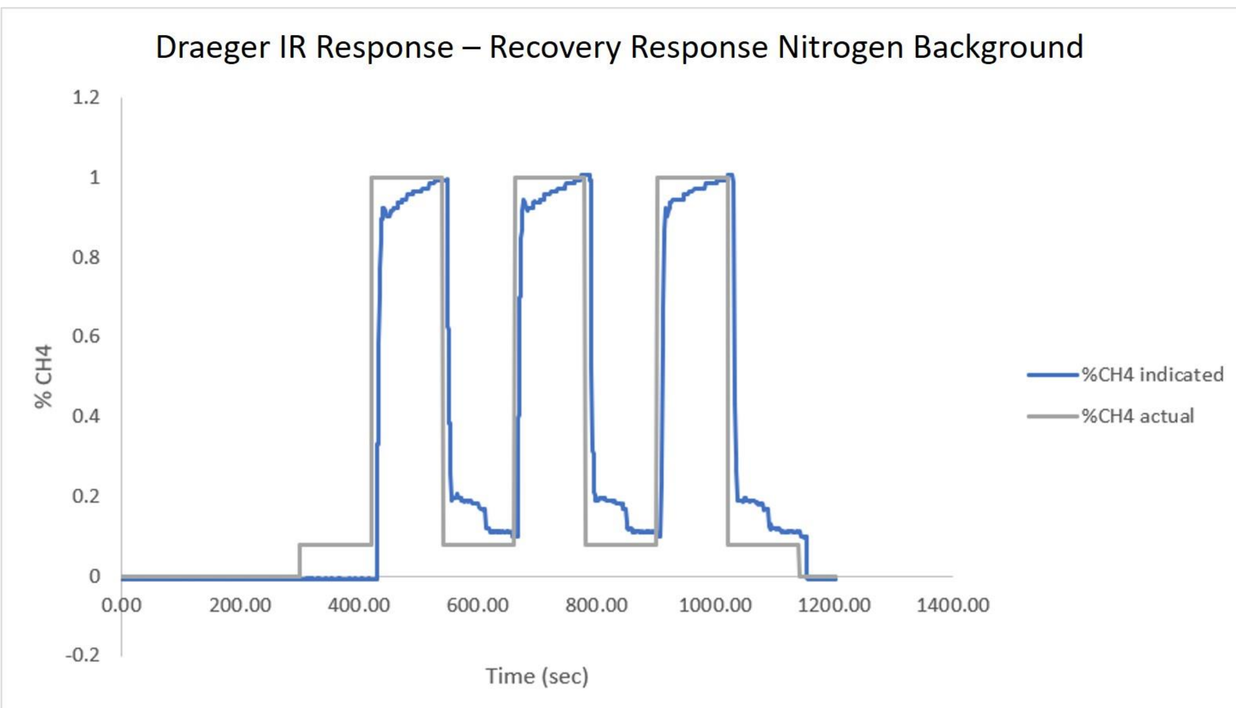

Figure 53: Draeger IR data for the recovery response test with a nitrogen background.

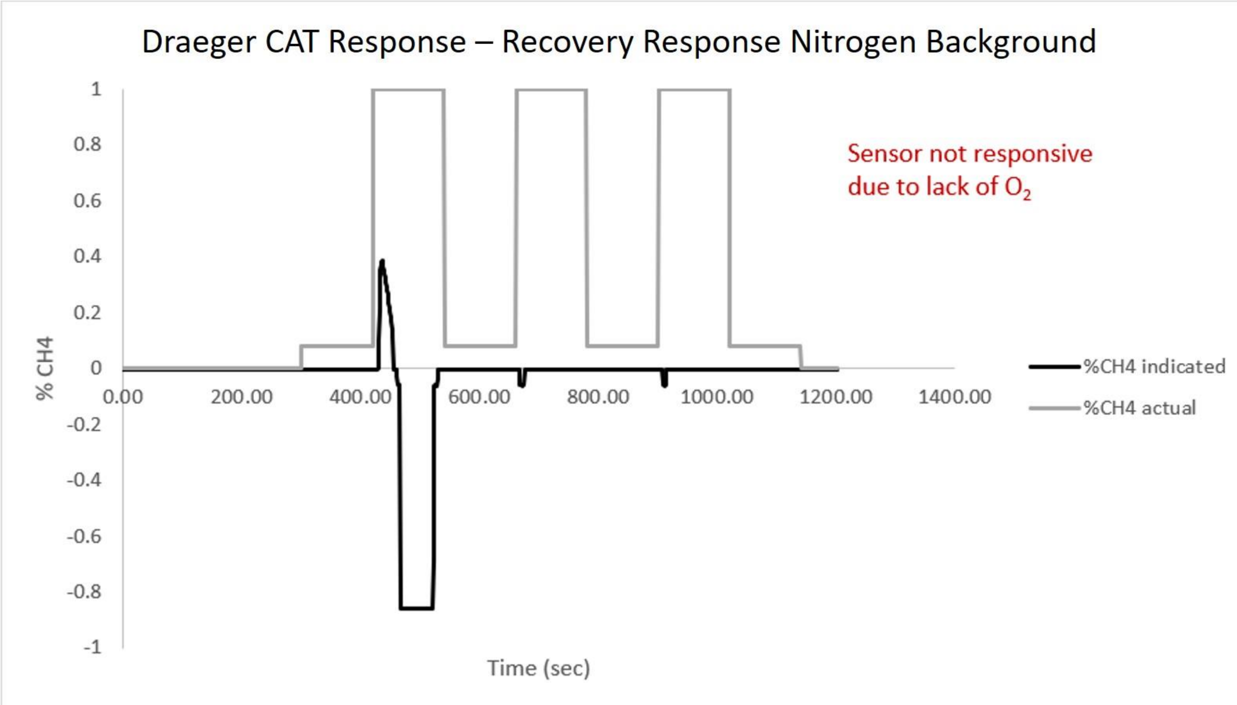

Figure 54: Draeger CAT data for the recovery response test with a nitrogen background.

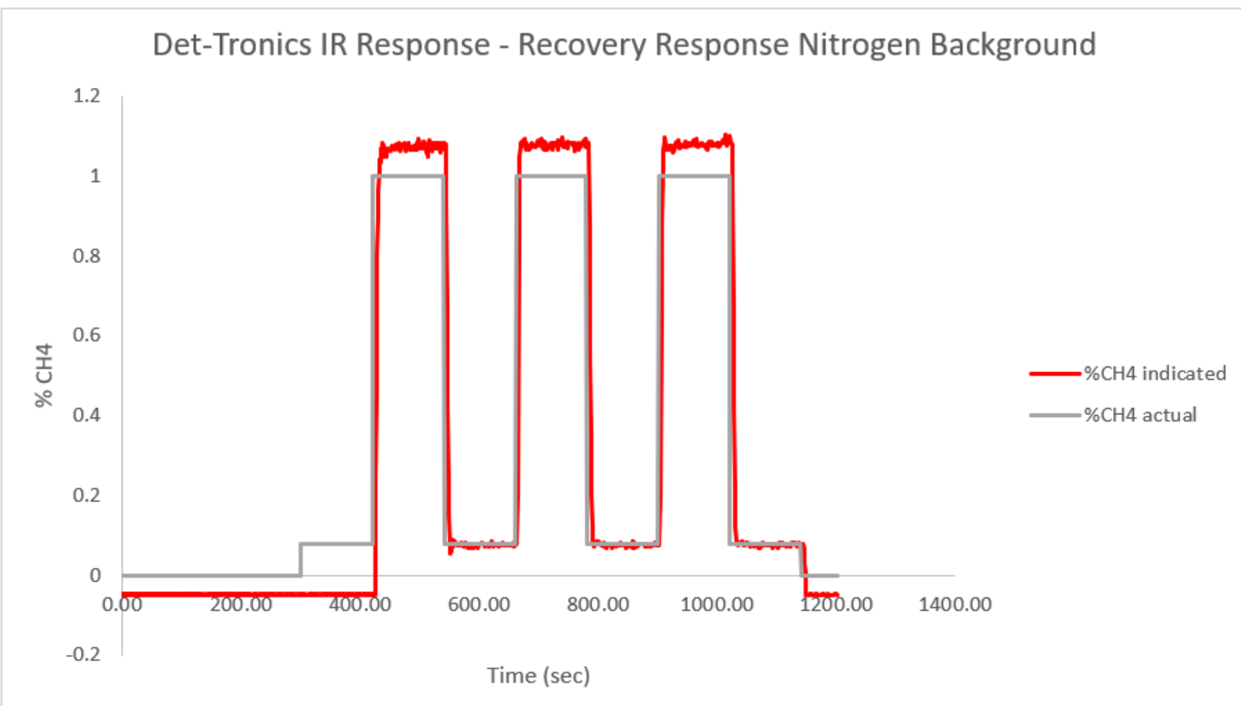

Figure 55: Det-Tronics data for the recovery response test with a nitrogen background.

For each test, data was collected in three repetitions. Individual results and the average T-90 and T-10 values are given in **Table 24**.

The Draeger IR responded to a change in methane concentration in about 9 seconds when the methane concentration increased and in about 7 seconds when it decreased. It reached within 90% of its high values in about 15 seconds on average. The sensor did not reach of value within 10% above its low values while lowering the concentration. It is not clear what caused this issue at this time. The vendor's specification for T-90 is 4 seconds (no value for T-10 was provided).

The Det-Tronics IR responded to a change in methane concentration in about 4 seconds when the methane concentration increased and in about 4 seconds when it decreased. It took about 8 seconds for it to reach within 90% of its high values, while lowering to within 10% above its low values in about 10 seconds. The vendor's specification for T-90 was 7.1 seconds (no value for T-10 was provided).

Table 24: Response times and average T-90 and T-10 values – nitrogen background.

Sensor	Response Time Low to High (s)	Response Time High to Low (s)	Average T-90 Time (s)	Average T-10 Time (s)
Draeger IR	9.81	7.76	14.74	*
	6.97	8.34		
	6.22	8.16		
Det-Tronics IR	4.49	3.13	7.95	10.15
	2.43	4.69		
	2.49	4.15		

* Sensor did not reach 10% value in the time allotted during testing.

15. Summary

Table 25 includes a summary of the results for each test for all sensors.

This testing did include some limitations that could impact results which should be considered when evaluating sensor performances:

- All tests were conducted under general laboratory conditions, without controls over changing humidity, temperature, or barometric pressure.
- Sensors were tested as received, with no on-site zeroing or calibrations performed.
- "Actual" values are based on reported outputs of the MFCs, which may happen slightly before any change in methane concentration occurs at the sensors.
- Gas concentration changes are not instantaneous. The methane gas flow is changed separately from the dilution gas flow, which can lead to a small delay before the actual concentration is achieved due to flow stabilization between the two mass flow controllers.
- Most of these sensors have pressure requirements that limit allowable gas flows and prevent pressure testing per PVS (pressure vessels and pressurized systems).
- The methane gas vendor was limited in the maximum concentration which they could provide due to safety constraints, so performance at higher concentrations could not be evaluated.

Draeger Polytron® 8700 IR

All tests were conducted using a single sensor. **Table 25** gives the average values over repeat tests using this sensor as an overall summary. This sensor was tested as received. This sensor performed in backgrounds of air and nitrogen.

Draeger Polytron® 8200 CAT

All tests were conducted using a single sensor. **Table 25** gives the average values over repeat tests using this sensor as an overall summary. This sensor was tested as received. This sensor performed in a background of air but did not perform in a background of nitrogen.

Det-Tronics PIRECLA11A1T2 Detector

All tests were conducted using a single sensor. **Table 25** gives the average values over repeat tests using this sensor as an overall summary. This sensor was tested as received. This sensor performed in backgrounds of air and nitrogen.

Table 25. Test results summary for all sensors evaluated.

Test	Background Gas	Draeger IR Average Result	Draeger CAT Average Result	Det-Tronics IR Average Result
0% Drift	Air	0.00% CH_4	0.00% CH_4	0.00% CH_4
	Nitrogen	0.00% CH_4	0.00% CH_4	0.00% CH_4
2% Drift	Air	0.02% CH_4	0.00% CH_4	0.00% CH_4
	Nitrogen	0.05% CH_4	**	0.02% CH_4
LDL Increasing %CH_4	Air	0.09% CH_4	0.18% CH_4	0.09% CH_4
	Nitrogen	0.13% CH_4	**	0.13% CH_4
LDL Decreasing %CH_4	Air	0.07% CH_4	0.23% CH_4	0.05% CH_4
	Nitrogen	0.07% CH_4	**	0.08% CH_4
Accuracy	Air	0.65%	-9.72%	5.10%
	Nitrogen	0.73%	**	6.69%
Precision	Air	0.91%	0.72%	0.32%
	Nitrogen	0.57%	**	0.13%
Repeatability	Air	0.01% CH_4	0.00% CH_4	0.00% CH_4
	Nitrogen	0.00% CH_4	**	0.00% CH_4
Response Time – Low to High	Air	8.04 s	7.71 s	3.00 s
	Nitrogen	7.67 s	**	3.14 s
Response Time – High to Low	Air	8.67 s	4.87 s	3.42 s
	Nitrogen	8.09 s	**	3.99 s
T-90 Time	Air	19.38 s	18.43 s	7.04 s
	Nitrogen	14.74 s	**	7.95 s
T-10 Time	Air	68.03 s	13.65 s	9.47 s
	Nitrogen	*	**	10.15 s

* Sensor did not reach 10% value in the time allotted during testing.
** Sensor did respond due to lack of oxygen in test gas.

16. Acknowledgements

As always, it would have been impossible to complete any testing without the assistance of numerous others. These include:

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Guy Naylor
Nick Spangler

Hardware and Equipment Support
Hazardous Gas Laboratory
Applied Physics Laboratory
Applied Chemistry Laboratory

17. Appendix A – Hydrogen Leak and Fire Detector Locations Space Shuttle Launch Pads

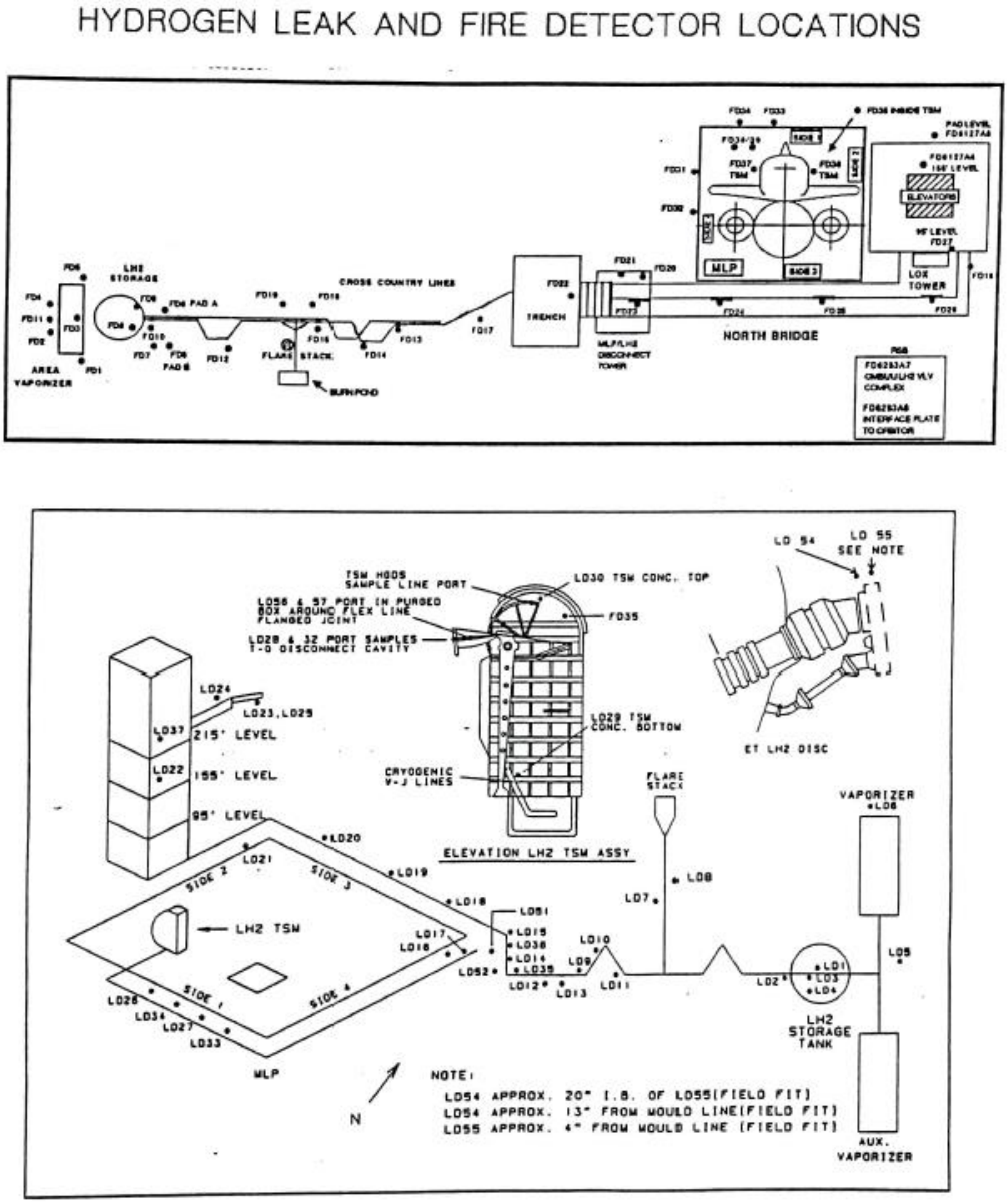

Figure 56: Location of the Space Shuttle launch pad hydrogen leak detectors (LDs) and fire detectors (FDs).