Hydrogen Sensor Test Report

Kennedy Space Center, Applied Chemistry and Applied Physics Laboratories

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Introduction

In order to determine their efficacy and evaluate the possibility of their use as ground support equipment at Kennedy Space Center (KSC), the Applied Chemistry Laboratory tested commercially available hydrogen sensors, including: HY-OPTIMA™ H2scan model 720B, Xensor XEN-5320, NMT Sensors SenseH_2®, and Nissha FIS FH2-HY04.

The hydrogen sensors were purchased and tested using funding from Defense Advanced Research Projects Agency (DARPA), NASA Exploration Ground Systems (EGS), and NASA Engineering & Safety Center (NESC). Testing followed the general methods of the relevant operations in K0000224376-GEN: In-Situ Hydrogen Sensor Characterization Procedure, a test procedure developed for testing of Makel Engineering, Inc. (MEI) hydrogen sensors, with modifications as needed for the current test setup and sensors.

Setup and Equipment

HY-OPTIMA™ H2scan 720B

The H2scan 720B sensors are solid state detectors. They are designed for in-line measurement. Units may be field-calibrated. They have serial communications.

Xensor XEN-5320

The XEN-5320 measures gas concentrations based on the thermal conductivity of the gas. It is also capable of detecting helium in air, oxygen, or nitrogen backgrounds, which likely prevents it from effectively detecting hydrogen in the presence of helium.

This sensor collects three samples per second. Each sensor is zeroed in the factory, but can be zeroed by the user. Gain can also be adjusted to calibrate. The manufacturer recommends calibrating in conditions similar to those in which the sensor will be used with regard to temperature and humidity. There are options for adjusting output for measuring hydrogen or helium in the software. WiFi, serial, and USB outputs are available.

NMT Sensors Sense H_2®

The Sense H_2® sensors are ceramic sensors designed for aerobic use. They provide a 1-5 V analog output corresponding to hydrogen concentrations in 0.5% increments.

Nissha FH2-HY04

The FH2-HY04 is a catalytic combustion sensor designed for use in cars. It is only designed for use in an air background.

Sensor Details

The following sensors were tested in this evaluation:

- HY-OPTIMA™ H2scan
  - Model 720B
  - PN 50000071-2
  - SN B000053
- Xensor XEN-5320
  - XEN-5320 USB
  - Factory IDs 04D192, 04D193, 04D189
- NMT Sensors Sense H_2®
  - PN 241002
  - SNs EC085-011, EC085-009, EC085-010
- Nissha FIS FH2-HY04
  - PN FH2-HY04
  - SNs 200331-302, 200331-301, 200331-303

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

Table 1 lists the sensors tested along with the gases used in their evaluation and manufacturer specified hydrogen detection limits. Additional sensor specifications are provided in Appendix B.

Table 1. Gas blends used in hydrogen sensor testing.

Sensor	**Manufacturer-Specified Background Gases**	**Background Gases Tested**	**Hydrogen Detection Limits (per Manufacturer)**
H2scan 720B	Air, Nitrogen, Oxygen	Air, Nitrogen, Helium	0.4-5%
XEN-5320	Air, Nitrogen	Air, Nitrogen, Helium	0-100%
Sense H_2®	Air	Air, Nitrogen, Helium	0.25%-4%
FH2-HY04	Air	Air, Nitrogen, Helium	0-4%

Figure 1 shows the general test setup for hydrogen sensor testing.

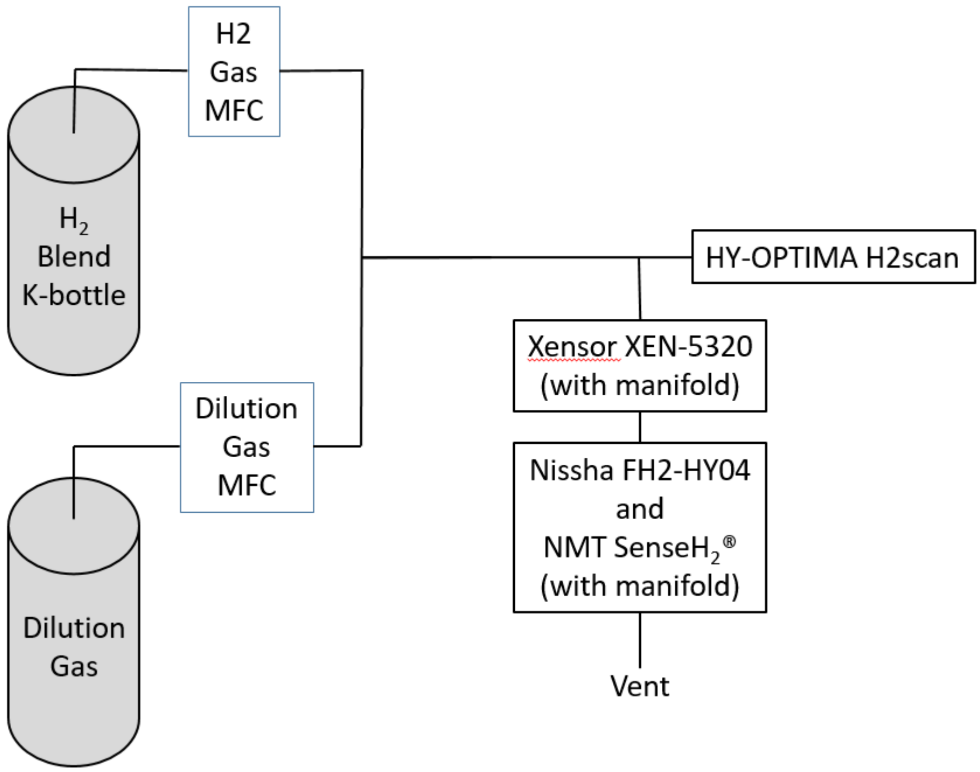

Figure 1. General test setup for hydrogen sensor testing.

Hydrogen gas was provided to all sensors under test from a k-bottle of gas with a known concentration of hydrogen in the desired background gas. The upper hydrogen concentrations were limited by safety constraints from the gas vendor. To provide lower concentrations of hydrogen 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 hydrogen.

The H2scan, shown in Figure 2, was connected to the hydrogen flow setup with a manufacturer-provided connector that put the sensing element adjacent to the flow of gas through the system. To maximize contact between its sensing element and the gas stream, the H2scan was placed at a 90-degree bend in the gas flow line.

Figure 2. HY-OPTIMA™ H2scan

The XEN-5320 was connected to the hydrogen flow setup with a manufacturer-built manifold, designed for use in testing and calibration. This adapter has an o-ring that fits to the XEN-5320's sensing element, sealing it against a flow-through chamber with hose barbs at each end that allow it to be connected to the test setup. Figure 3 shows the XEN-5320 and its manifold.

Figure 3. XEN-5320 sensor and manifold disassembled (left) and configured for testing (right).

The Sense H_2® and FH2-HY04 are both designed for use in hydrogen automobiles and did not have a readily-available option for connecting them to the hydrogen flow setup. To integrate these sensors into the flow-through test system, a manifold similar to the one purchased from Xensor for the XEN-5320 was constructed by a machinist at Kennedy Space Center. This custom manifold consisted of a tube cut through a block of aluminum with 1/8" hose barb attachments at each end. Holes sized for the sensing interfaces of the Sense H_2® and FH2-HY04 were cut from the top of the block down to this tube, allowing the sensing elements of both sensors to be in the flow of gas through the manifold. Figure 4 shows this custom manifold with the sensors.

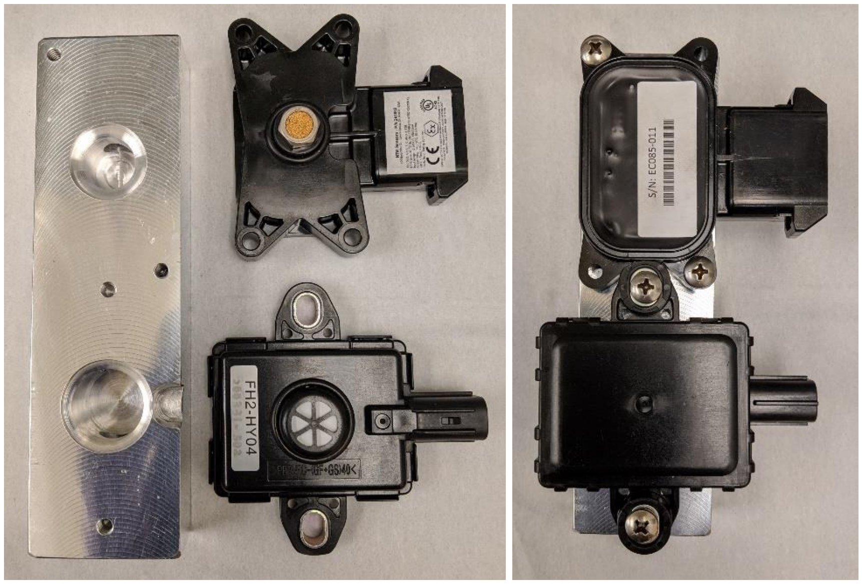

Figure 4. Custom manifold for Sense H_2® and FH2-HY04, shown disassembled (left) and configured for testing (right).

MFC 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 5. 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.

Appendix A lists additional details on equipment and gases used in testing.

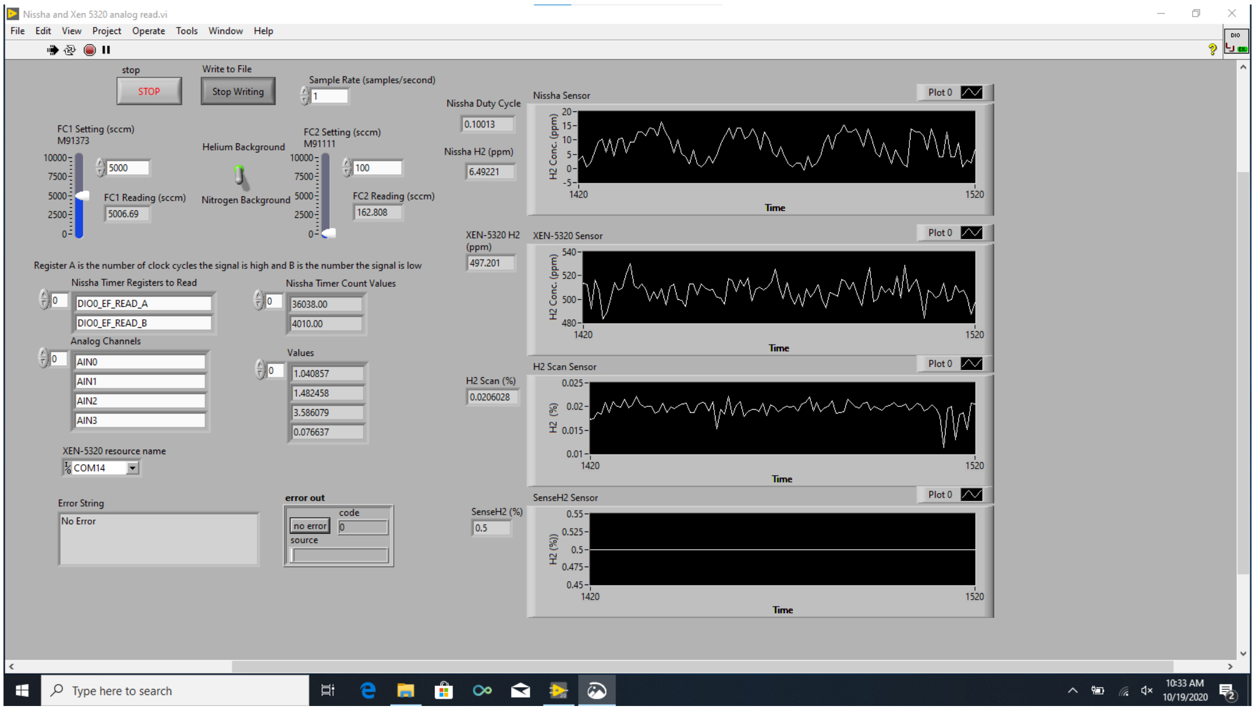

Figure 5. LabVIEW interface for flow control and data collection.

H2scan

The H2scan's output is 4-20 mA. A resistor was added to convert the output to 0-5 V, which was read by the LabVIEW program via a LabJack analog input.

The manufacturer provides the following information for calculating the percent hydrogen detected from the sensor's analog output:

$$H_{2\%} = \frac{I_{meas} - I_{H2lo}}{I_{H2hi} - I_{H2lo}} \cdot (H_{2hi} - H_{2lo}) + H_{2lo}$$

where

I_{meas} = the measured current

I_{H2lo} = Low H_2 current, default value = 4 mA

I_{H2hi} = High H_2 current, default value = 20 mA

H_{2hi} = Low H_2 range, default value = 0%

H_{2lo} = High H_2 range, default value = 100%

Using a 261 Ω resistor to convert from current output to voltage, and considering that the default values provided likely apply to the other sensors referenced in the same manual, which have ranges of 0.5-100% hydrogen, whereas this sensor has a range of 0.4-5.0% hydrogen, this equation was modified for our calculations to:

$$H_{2\%} = \frac{V_{meas} - V_{H2lo}}{V_{H2hi} - V_{H2lo}} \cdot (H_{2hi} - H_{2lo}) + H_{2lo}$$

$$H_{2\%} = \frac{V_{meas} - 1.04\ V}{5.20\ V - 1.04\ V} \cdot (5\%)$$

This sensor does have an option for user calibration, but it was tested as-received for the purpose of this evaluation.

Xensor-5320

The Xensor-5320's output was digital, provided via a USB connection. The LabVIEW program queried the sensor's output and read the sensor's reported hydrogen concentration. The output of this sensor was read as-received. The manufacturer's literature does note that the sensor is sensitive to changes in temperature and humidity and recommends zeroing the unit under ambient conditions at the location in which it will be used.

Sense H_2®

The Sense H_2®'s output is 0-5 V, which was read directly by the LabVIEW program via a LabJack analog input. Figure 6 shows the manufacturer-provided correlation between output voltage and percent hydrogen measured.

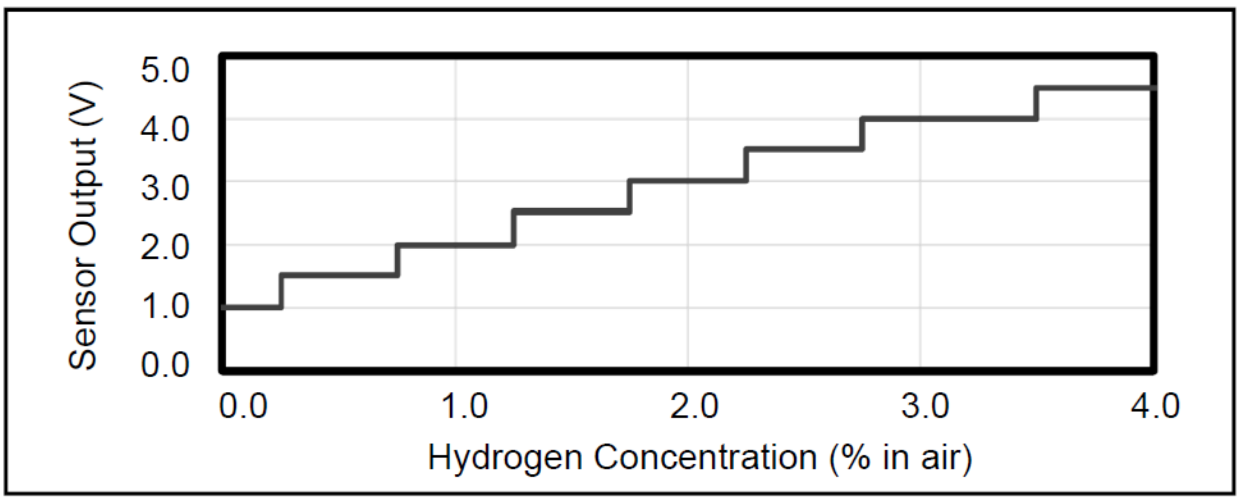

Figure 6. Sensor output vs hydrogen concentration provided by NMT Sensors for the Sense H_2®.

Based on this, the LabVIEW program used the following ranges to determine the percent hydrogen based on output voltage:

- $0.9 \le V \le 1.25 \rightarrow 0\%\ H_2$
- $1.25 < V \le 1.75 \rightarrow 0.5\%\ H_2$
- $1.75 < V \le 2.25 \rightarrow 1.0\%\ H_2$
- $2.25 < V \le 2.75 \rightarrow 1.5\%\ H_2$
- $2.75 < V \le 3.25 \rightarrow 2.0\%\ H_2$
- $3.25 < V \le 3.75 \rightarrow 2.5\%\ H_2$
- $3.75 < V \le 4.25 \rightarrow 3.0\%\ H_2$
- $4.25 < V \le 4.70 \rightarrow 4.0\%\ H_2$

FH2-HY04

The FH2-HY04's output is a pulse width modulation (PWM) function. The manual suggests the following equation for calculating the hydrogen concentration based on the PWM duty cycle:

$$H_{2,ppm} = 500 \times (duty\ percent - 10)$$

Initial testing showed that this was incorrect – the hydrogen concentration actually corresponded to the inverse of the duty cycle. As such, the following equation was used by the LabVIEW program to calculation the hydrogen concentration measured by the sensor:

$$H_{2,ppm} = 500 \times (\frac{1}{duty\ percent} - 10)$$

The output of the sensor was smoothed using a Zener diode across the sensor's output signal wires, which were connected to a LabJack flexible input/output.

Testing and Results

Drift

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

Procedure

1. Connect hydrogen gas mixture and appropriate background gas to the test system.
2. Power on the hydrogen sensors.
3. Allow appropriate warm-up time, per manufacturer specification, prior to continuing.
4. Begin gas flow, set to the desired hydrogen 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

Results – 0% Drift, Air Background

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

Figure 7 through Figure 18 show the data collected for each sensor during the 0% drift tests.

The H2scan held steady at 0.00% H_2 in each run, which is expected because it does not respond below 0.4% H_2.

The XEN-5320 sensors did show small fluctuations, but that could have been due to small shifts in the provided hydrogen concentration or noise.

The Sense H_2® sensors were inconsistent. One output 0.0% H_2, another 0.5% H_2, and the other alternated between 0.5% H_2 and 1.0% H_2. This could have been due to some fluctuations in the signal or hydrogen concentration if the units were operating near one of the cutoffs between their stepwise outputs, but the lower detectible limit for them is expected to be 0.25% H_2, so it is unlikely.

The FH2-HY04 sensors all showed minimal change in output, which could also have been due to noise or small changes in hydrogen concentration for the gas flow. Two of these sensors output values around 0.07% H_2, while the other output 0.0% H_2.

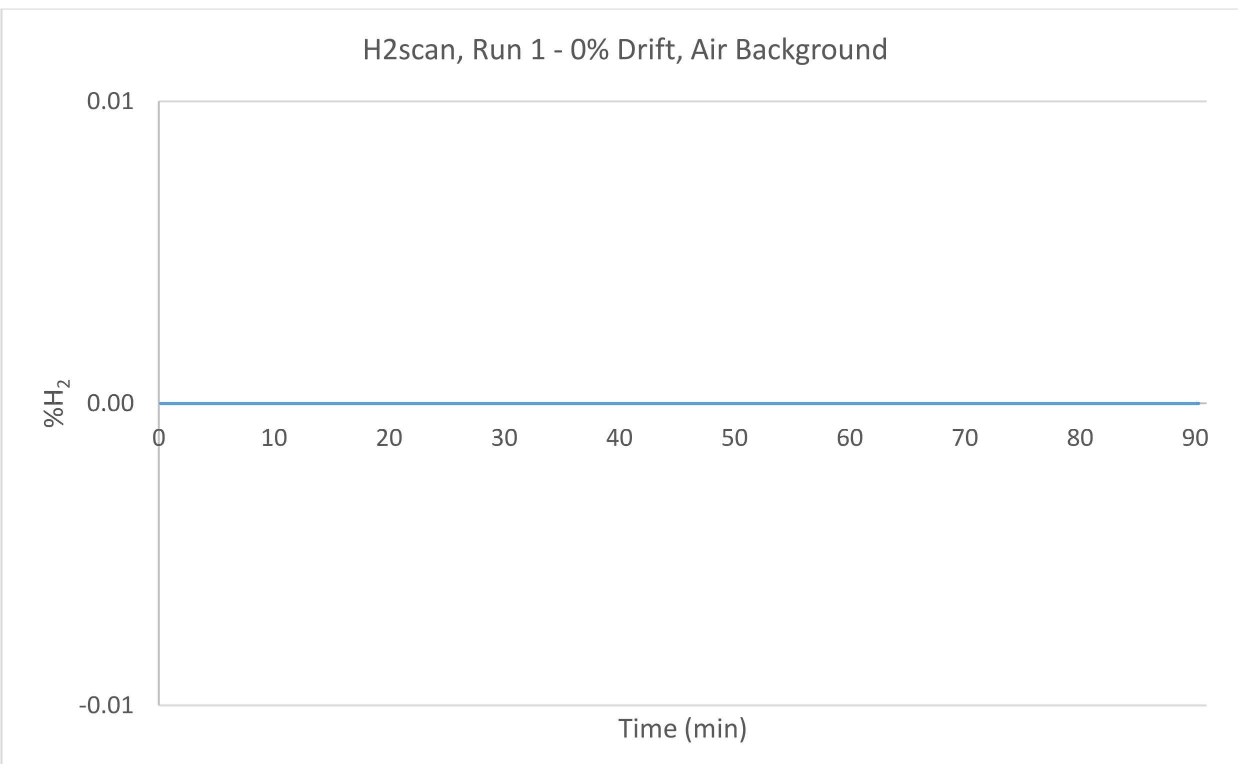

Figure 7. H2scan data for run 1 of the 0% drift test with an air background.

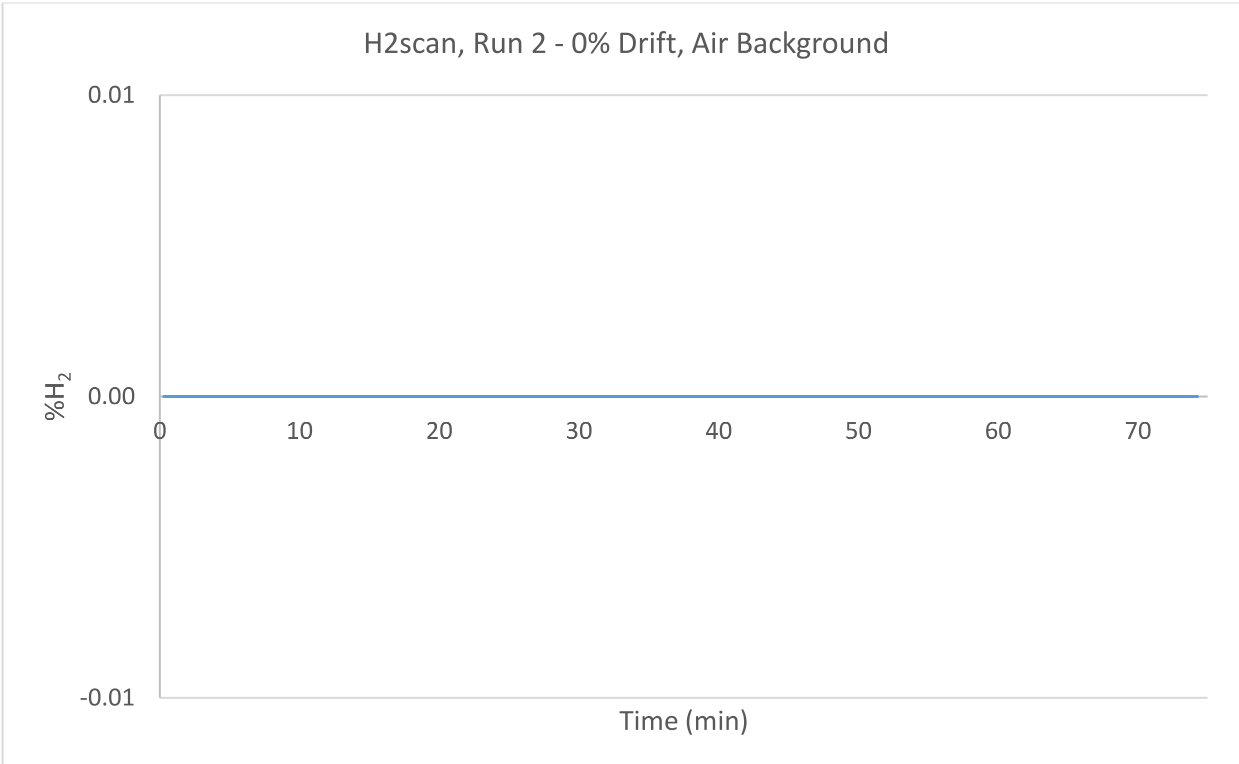

Figure 8. H2scan data for run 2 of the 0% drift test with an air background.

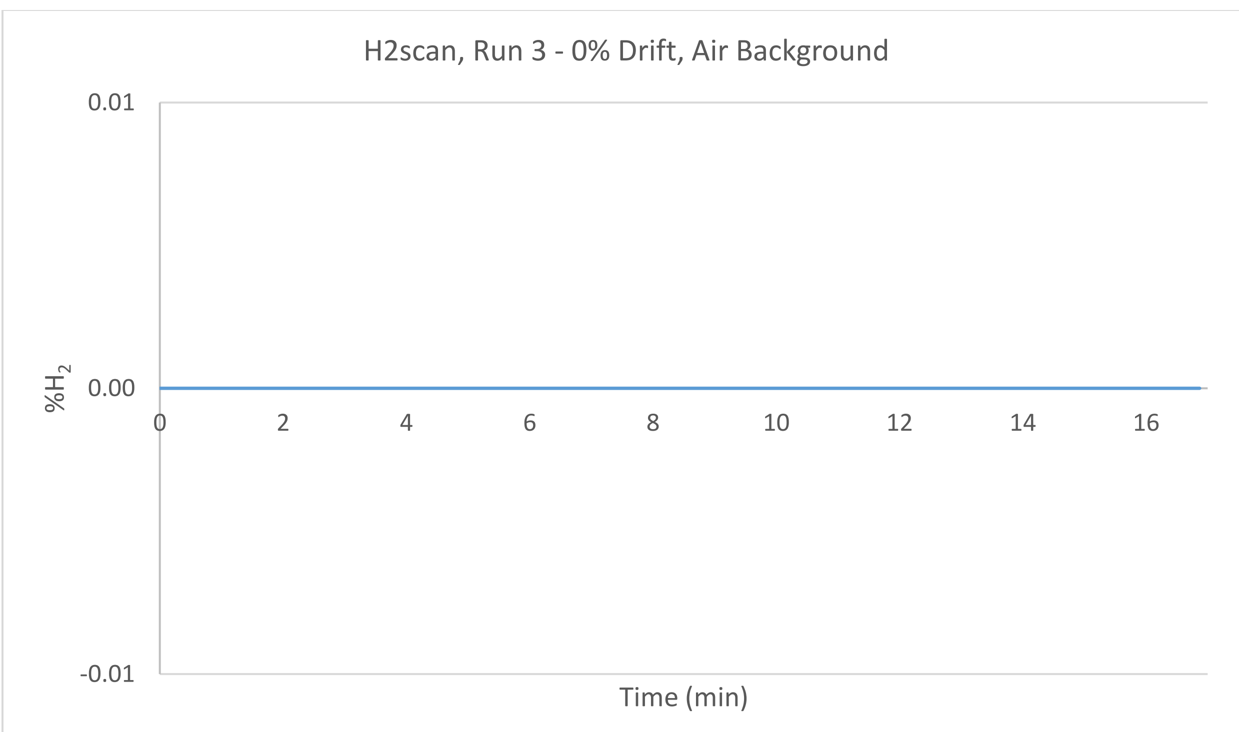

Figure 9. H2scan data for run 3 of the 0% drift test with an air background.

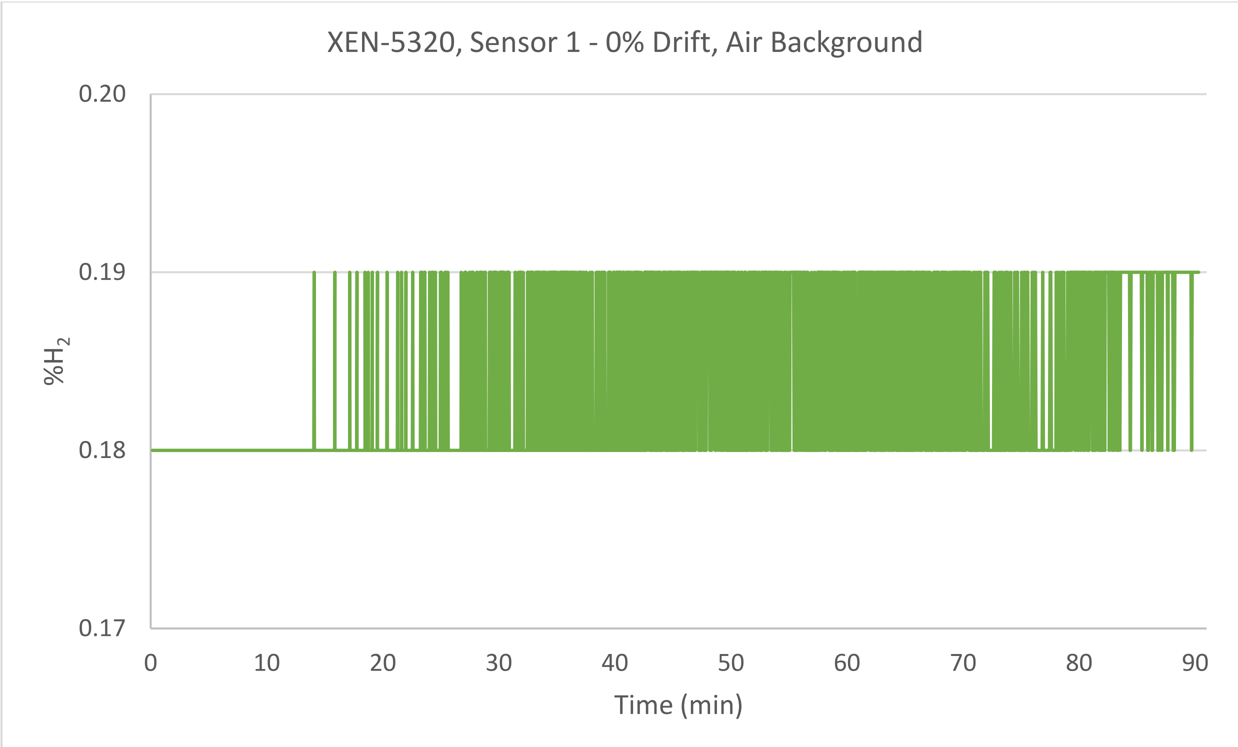

Figure 10. XEN-5320 data for sensor 1 in the 0% drift test with an air background.

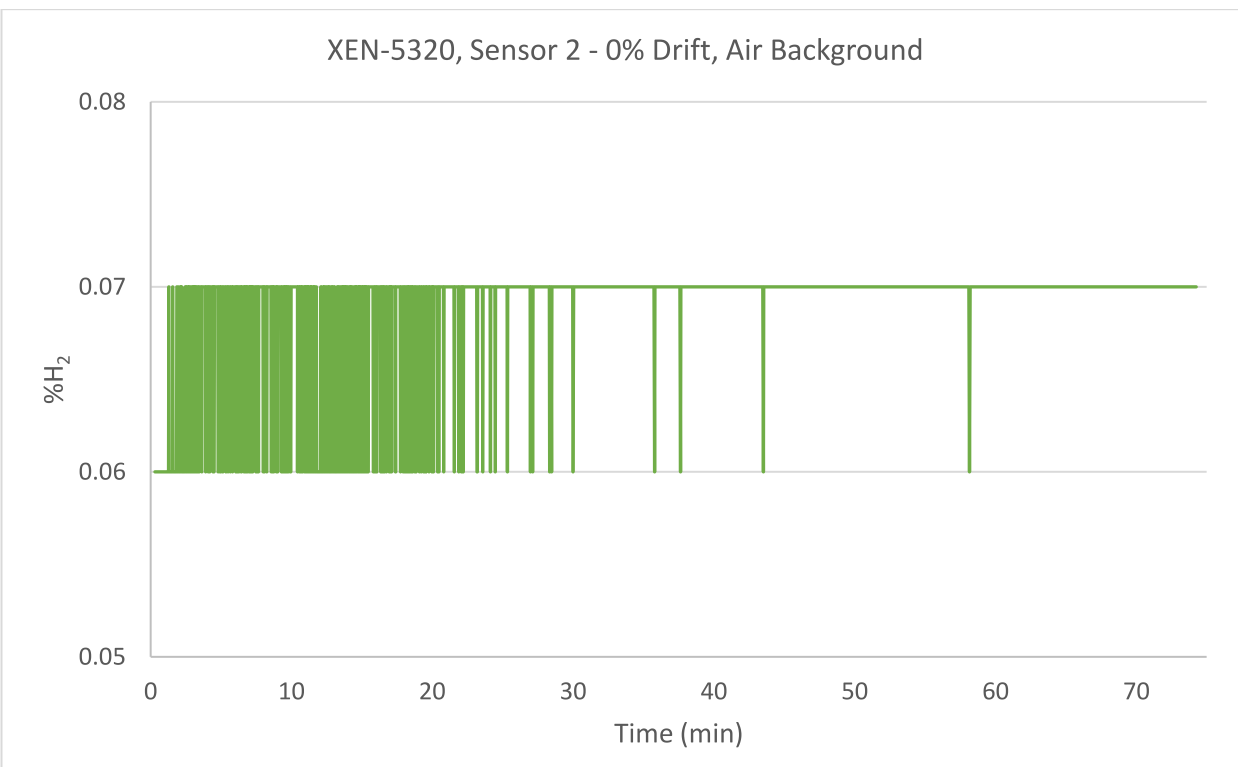

Figure 11. XEN-5320 data for sensor 2 in the 0% drift test with an air background.

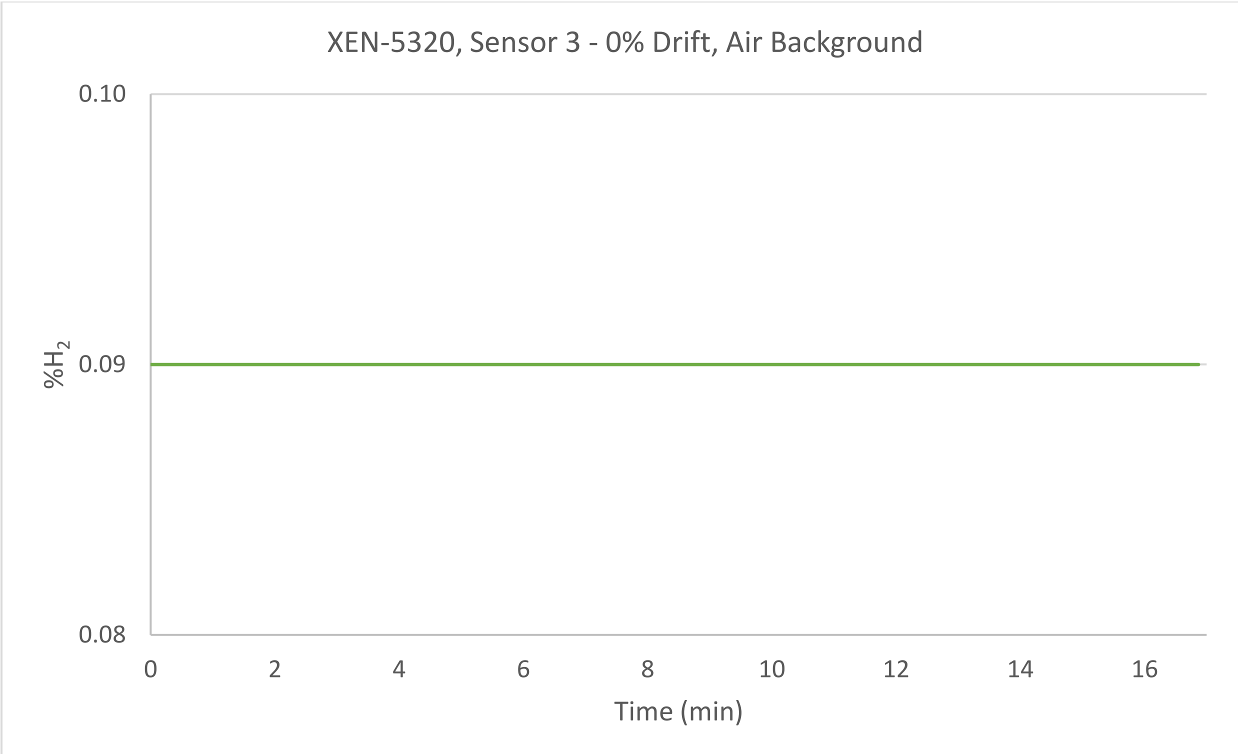

Figure 12. XEN-5320 data for sensor 3 in the 0% drift test with an air background.

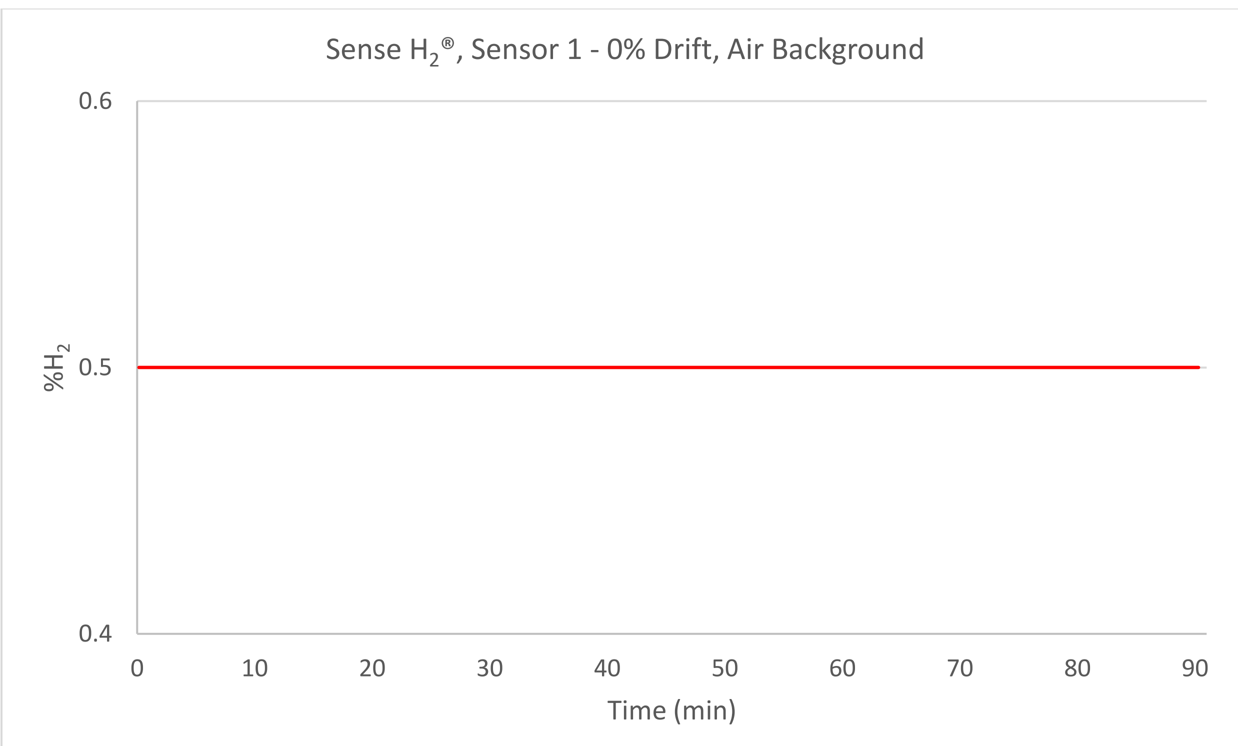

Figure 13. Sense H_2® data for sensor 1 in the 0% drift test with an air background.

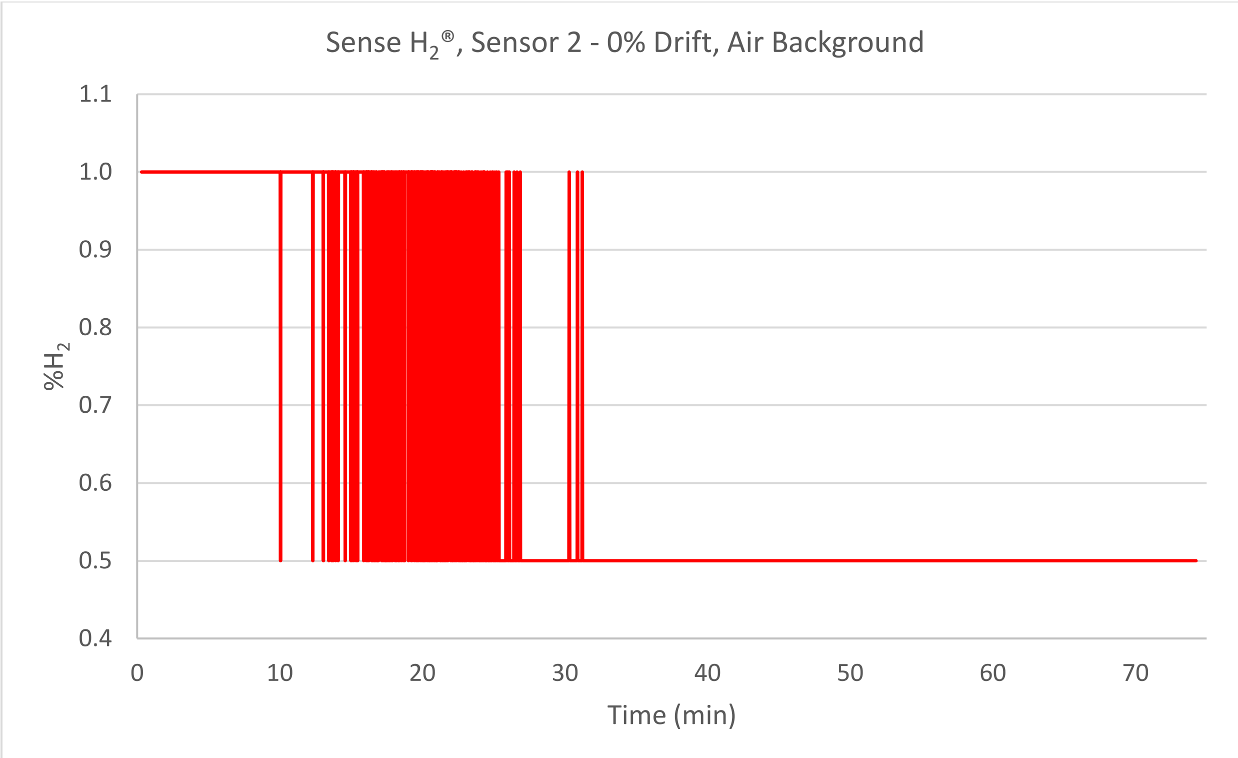

Figure 14. Sense H_2® data for sensor 2 in the 0% drift test with an air background.

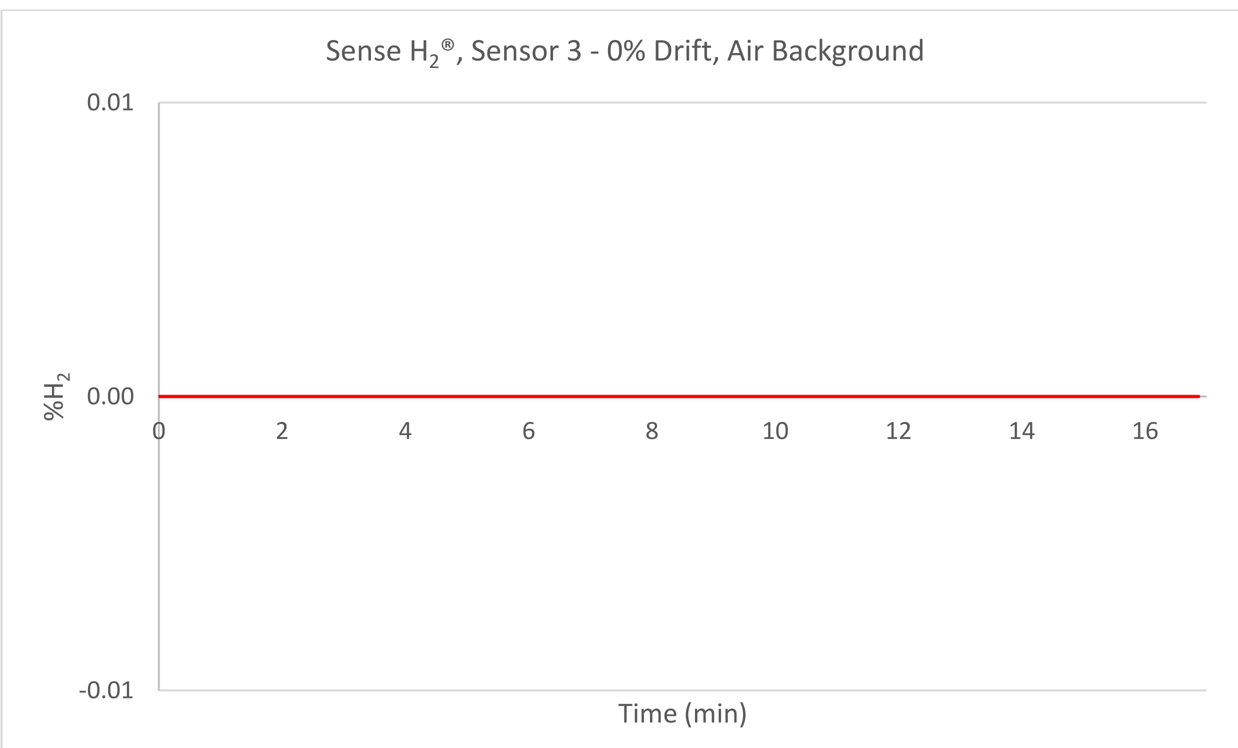

Figure 15. Sense H_2® data for sensor 3 in the 0% drift test with an air background.

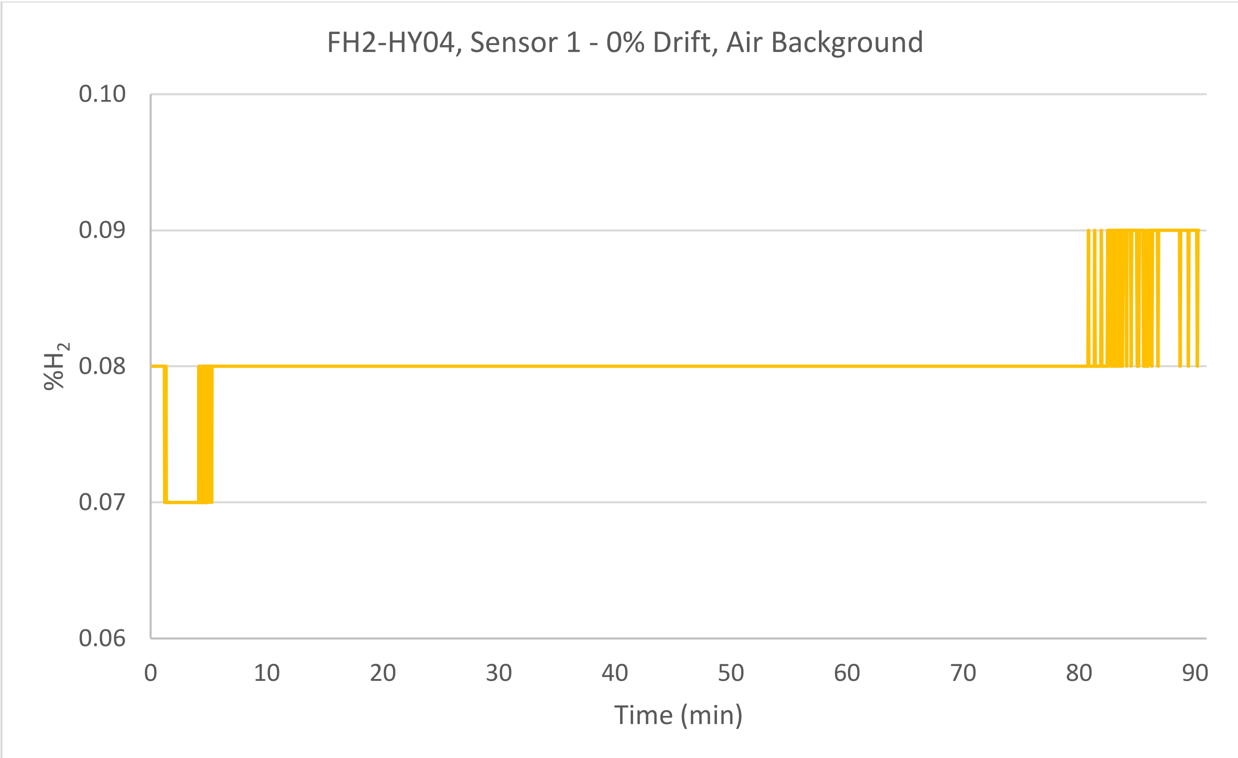

Figure 16. FH2-HY04 data for sensor 1 in the 0% drift test with an air background.

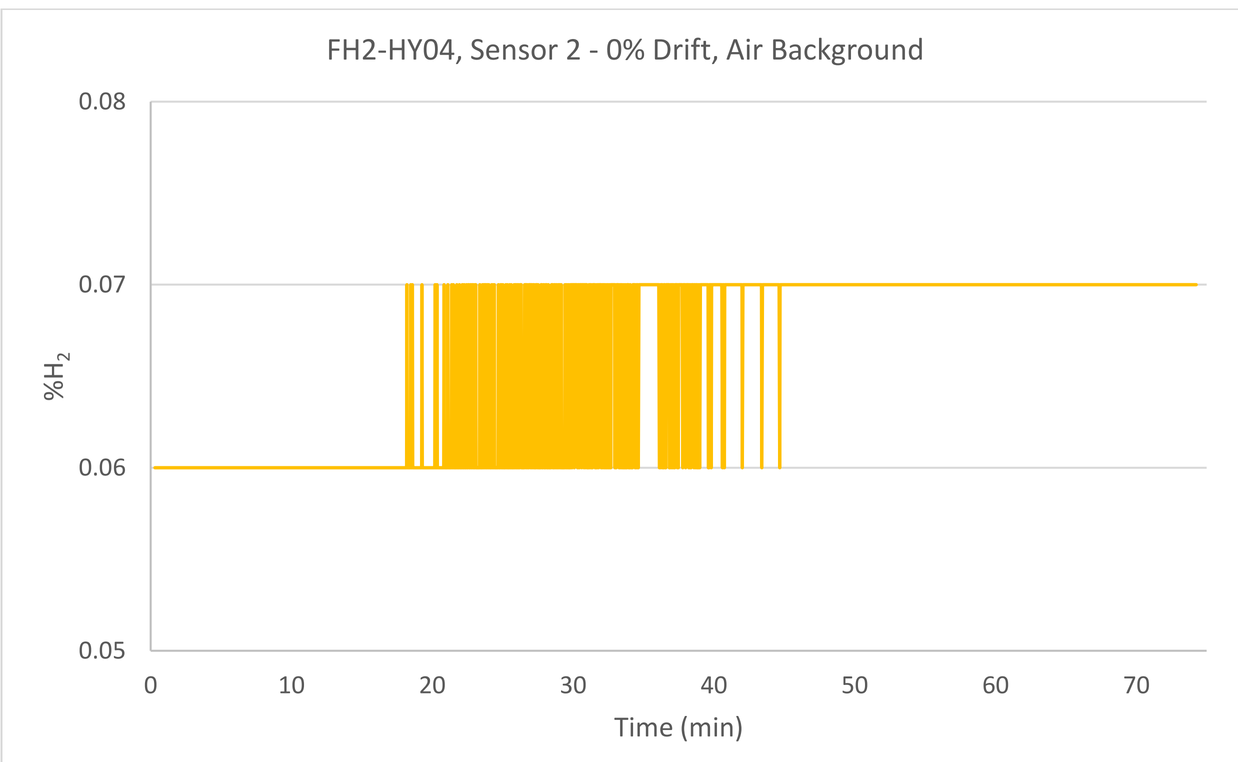

Figure 17. FH2-HY04 data for sensor 2 in the 0% drift test with an air background.

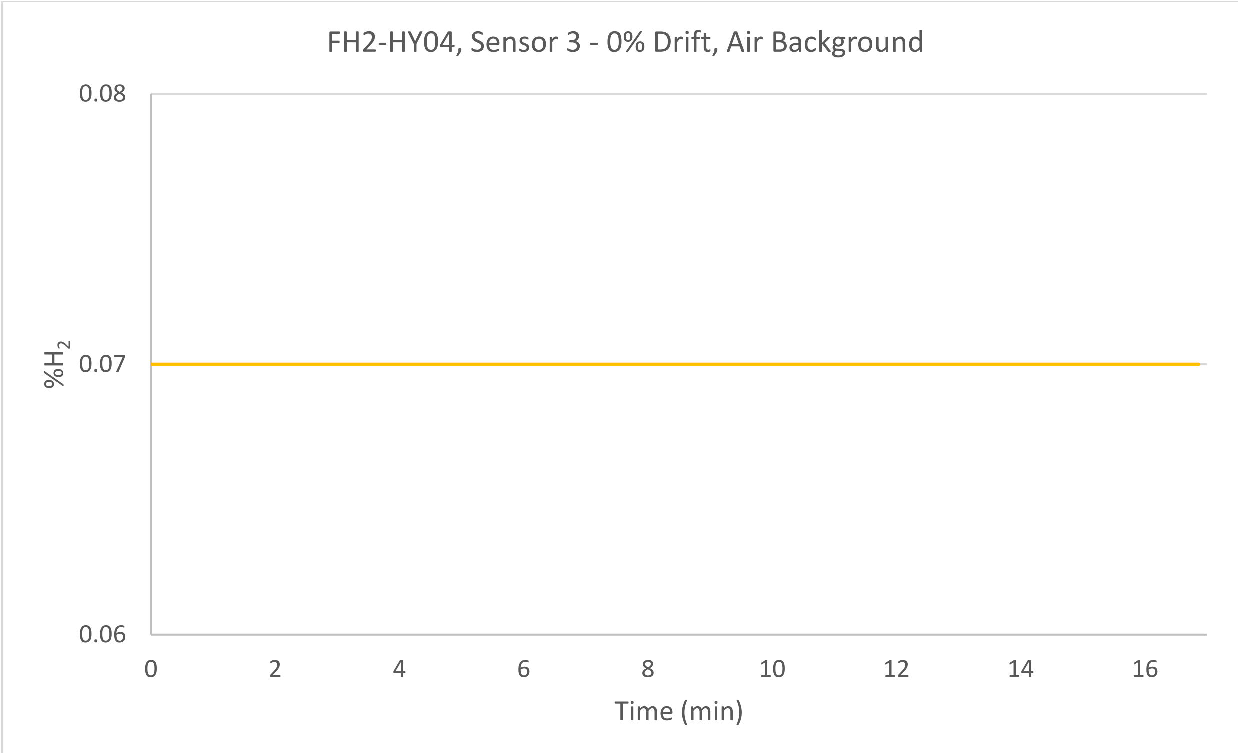

Figure 18. FH2-HY04 data for sensor 3 in the 0% drift test with an air background.

Table 2 gives the results of the 0% drift test with a background of air. Overall, the sensor outputs remained very stable, with the exception of one of the Sense H_2® sensors that jumped by 0.5% H_2.

Table 2. 0% Drift Test Results – Air Background.

Sensor	Sensor/Run	Test Duration (min)	%H_2 Source Drift	Sensor Output Drift (%H_2)
H2scan 720B	1	90.3	0.01	0.00
	2	74.3	0.01	0.00
	3	74.3	0.00	0.00
XEN-5320	1	90.3	0.01	0.01
	2	74.3	0.01	0.01
	3	74.3	0.00	0.00
Sense H_2®	1	90.3	0.01	0.0
	2	74.3	0.01	-0.5
	3	74.3	0.00	0.0
FH2-HY04	1	90.3	0.01	0.02
	2	74.3	0.01	0.01
	3	74.3	0.00	0.00

Results – 0% Drift, Nitrogen Background

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

Figure 19 through Figure 30 show the data collected for each sensor during the 0% drift tests.

Like its performance in air, the H2scan held steady at 0.00% H_2 for every run, which is expected because it does not respond below 0.4% H_2.

The XEN-5320 sensors all performed similarly to their results in the air background as well, showing minimal fluctuations which could have been due to noise or small changes in the hydrogen concentration of the gas provided.

The Sense H_2® sensors all output an error code that is read as -5.0% H_2, indicating a lack of gas. Because these sensors are catalytic, they require oxygen to function, so this response was not surprising.

The FH2-HY04 sensors appeared to be behaving a bit more erratically, with a greater error than they had in the air background. In later tests, it became apparent that these sensors, also not designed to work anaerobically, were not responding in the nitrogen background.

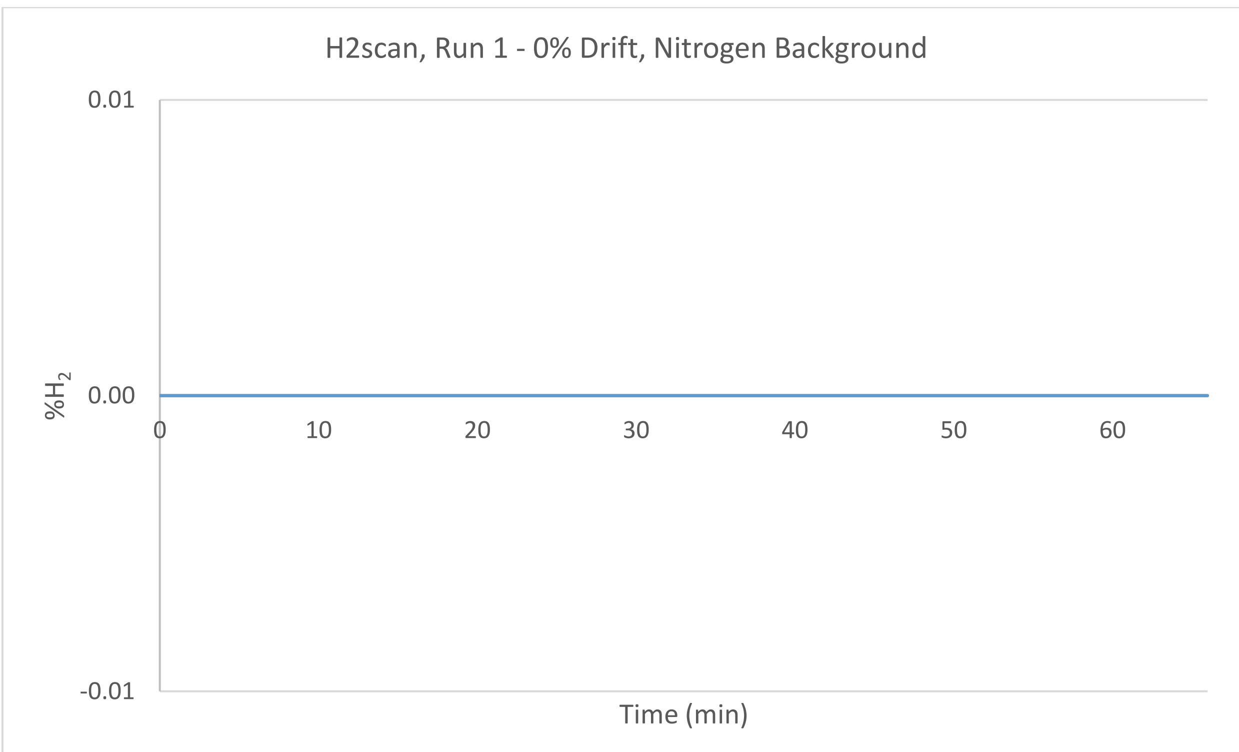

Figure 19. H2scan data for run 1 of the 0% drift test with a nitrogen background.

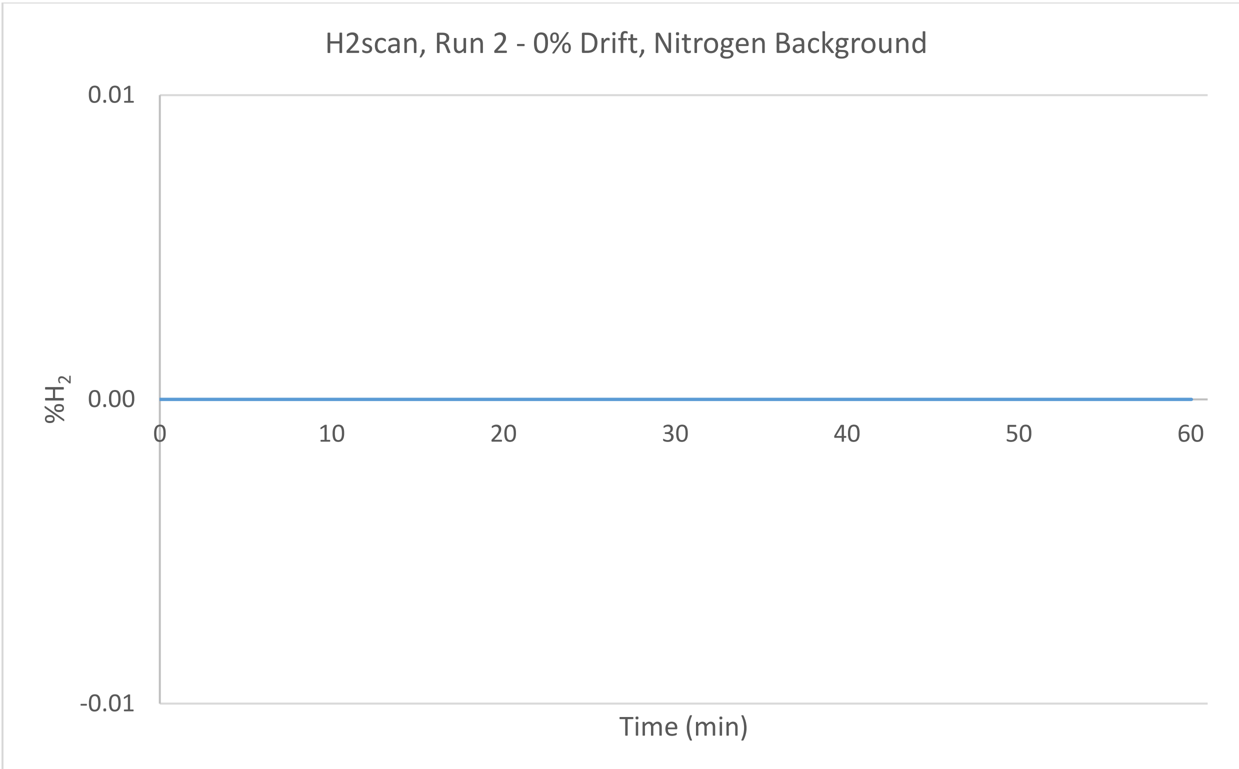

Figure 20. H2scan data for run 2 of the 0% drift test with a nitrogen background.

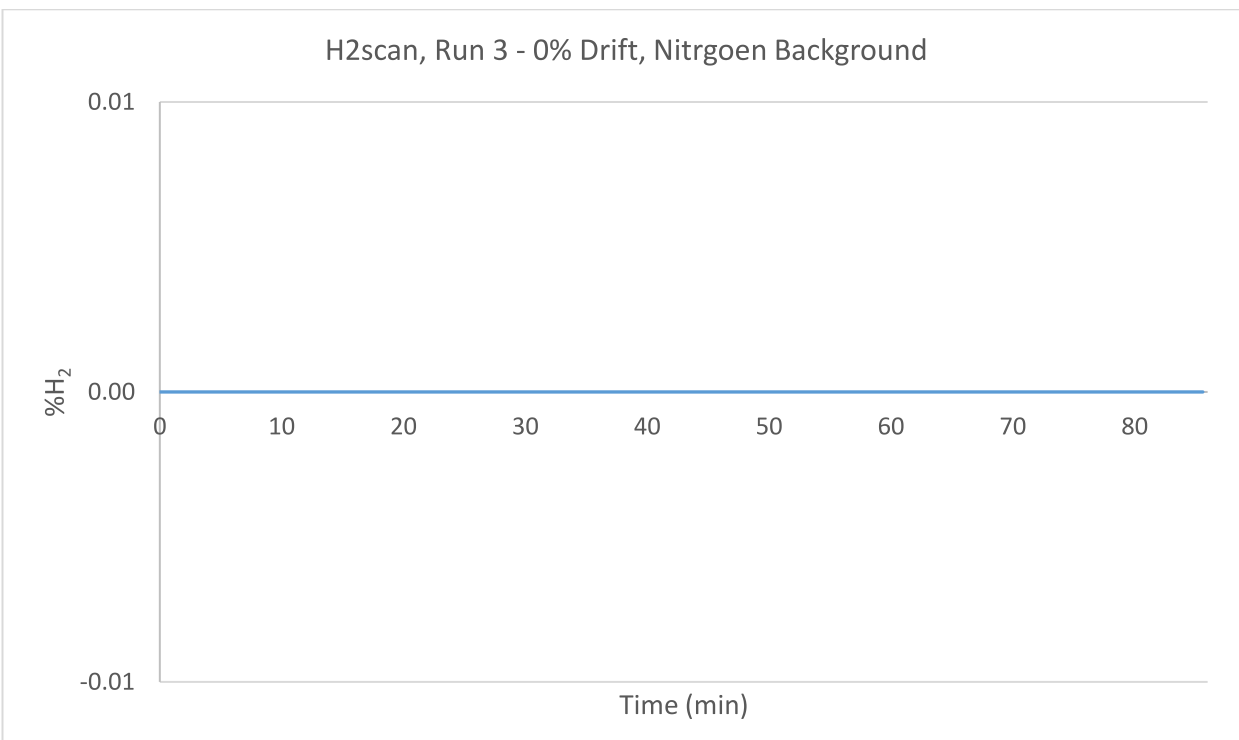

Figure 21. H2scan data for run 3 of the 0% drift test with a nitrogen background.

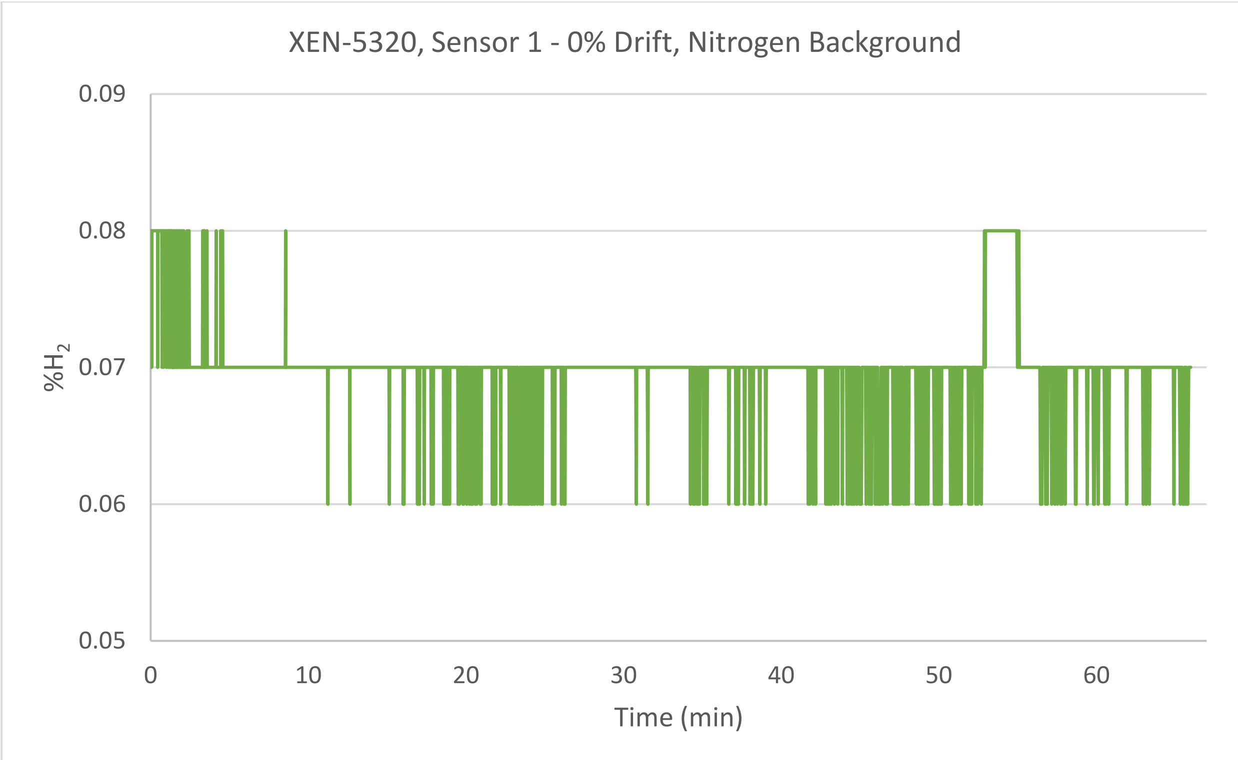

Figure 22. XENSOR-5320 data for sensor 1 in the 0% drift test with a nitrogen background.

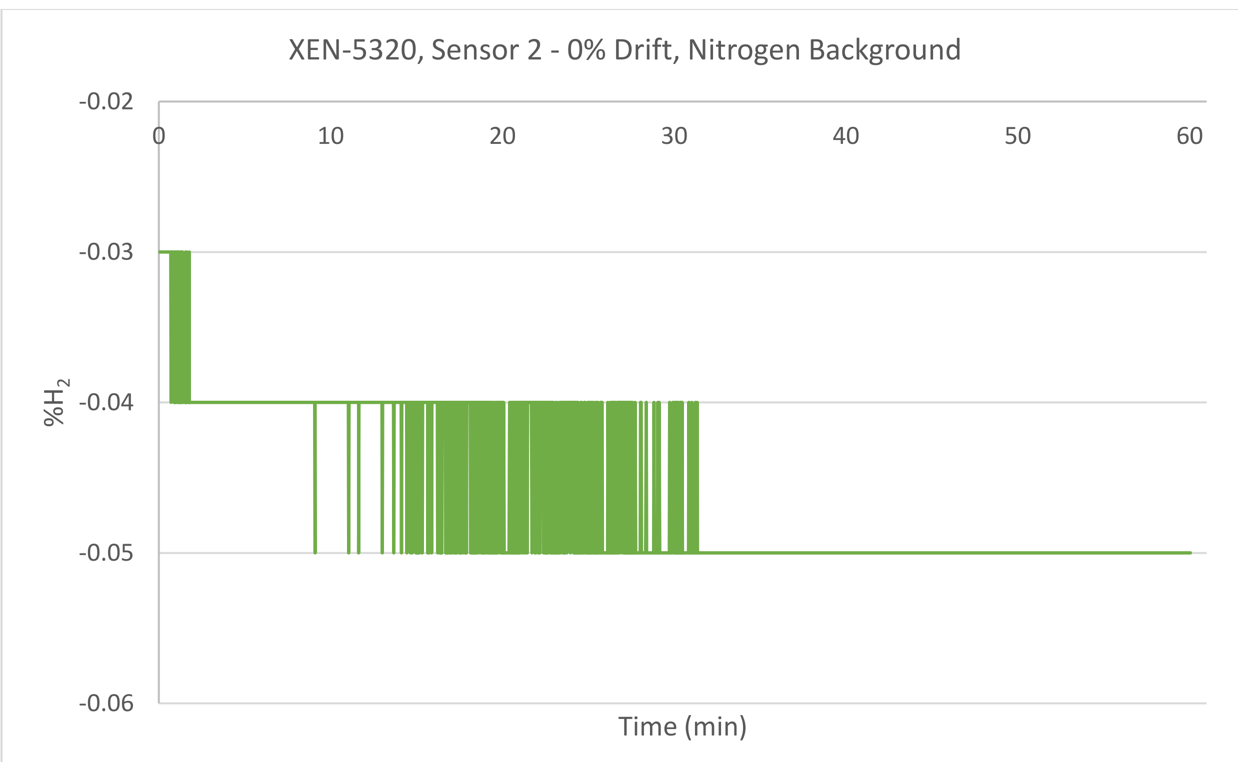

Figure 23. XENSOR-5320 data for sensor 2 in the 0% drift test with a nitrogen background.

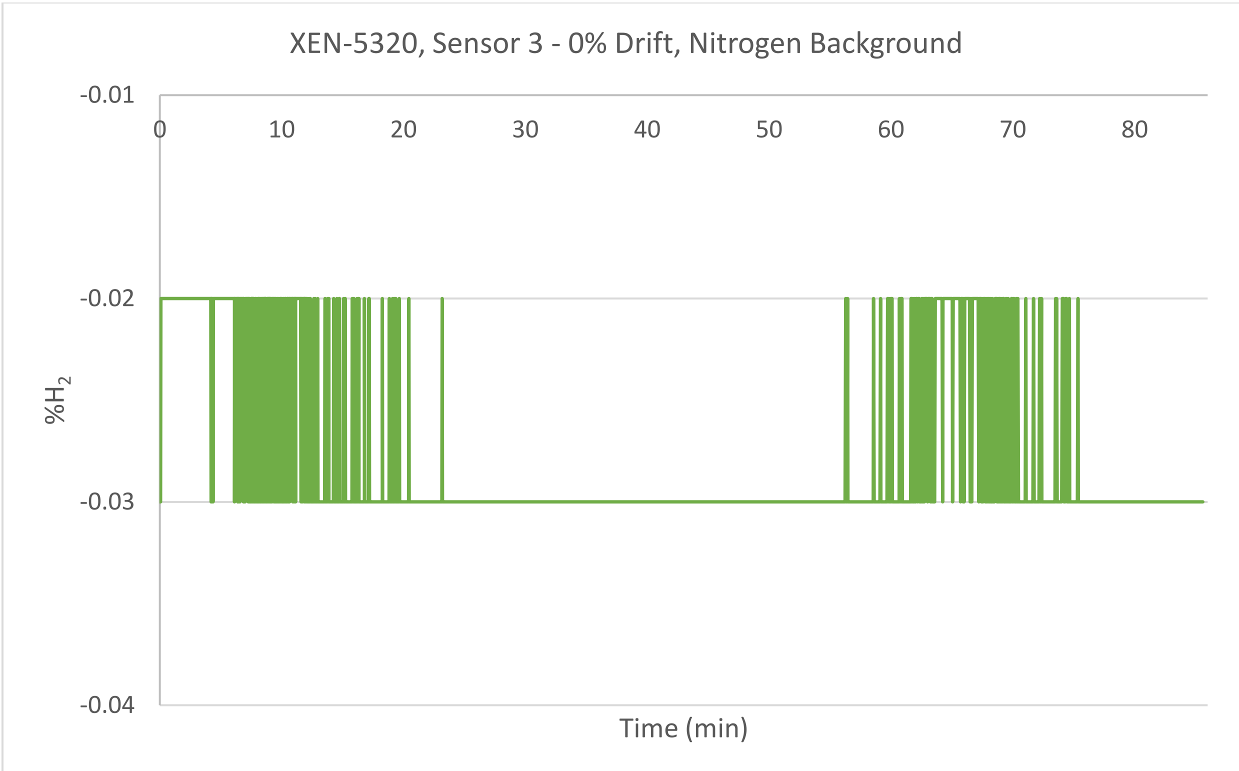

Figure 24. XENSOR-5320 data for sensor 3 in the 0% drift test with a nitrogen background.

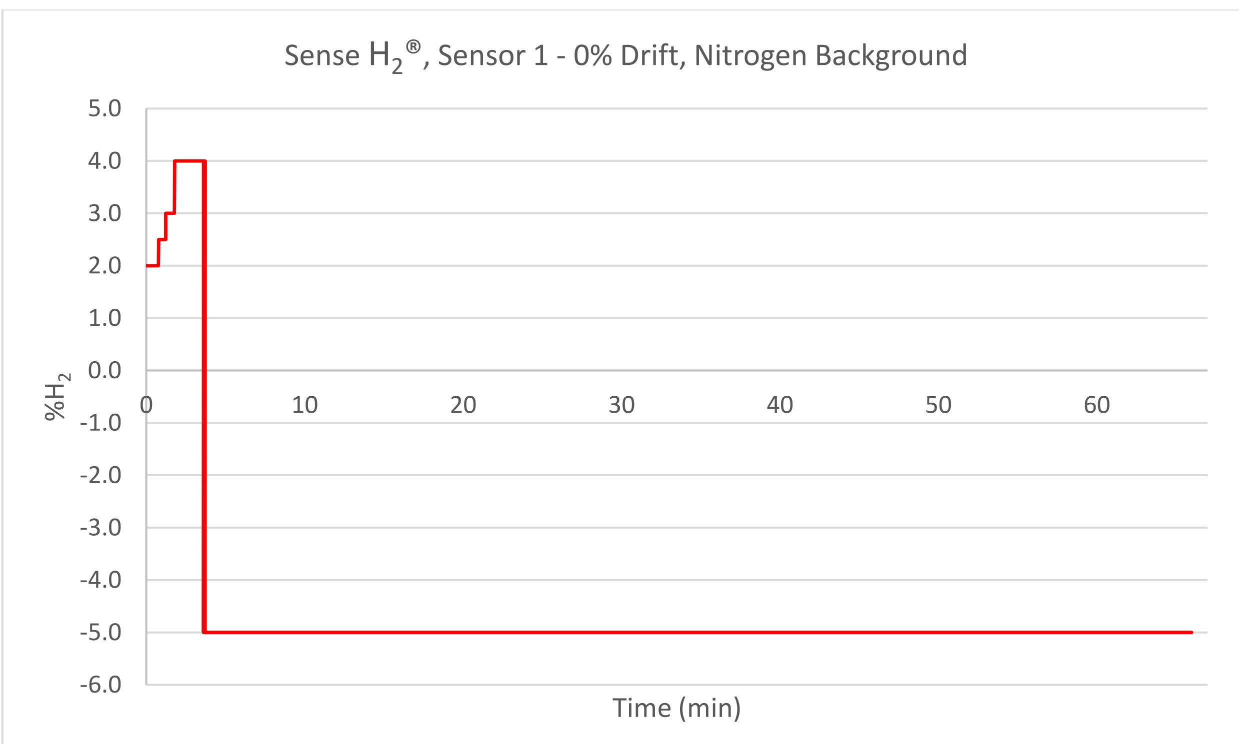

Figure 25. Sense H_2® data for sensor 1 in the 0% drift test with a nitrogen background.

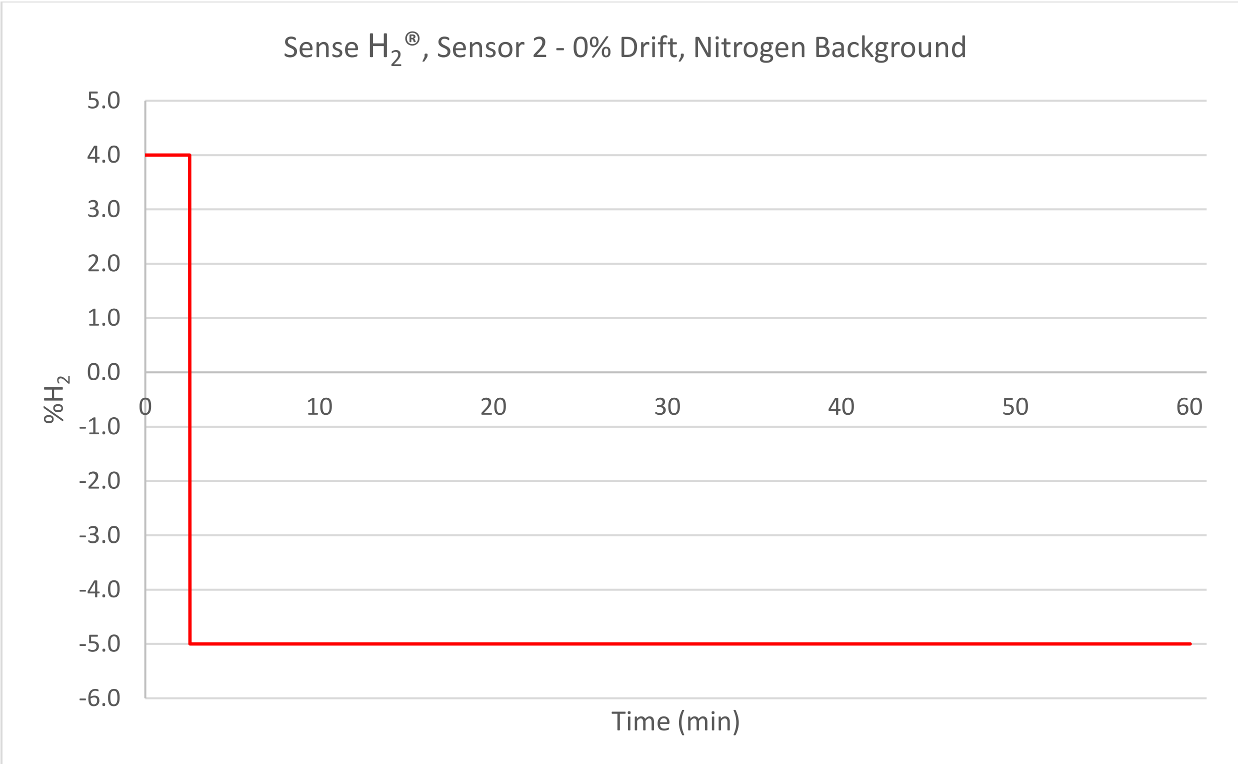

Figure 26. Sense H_2® data for sensor 2 in the 0% drift test with a nitrogen background.

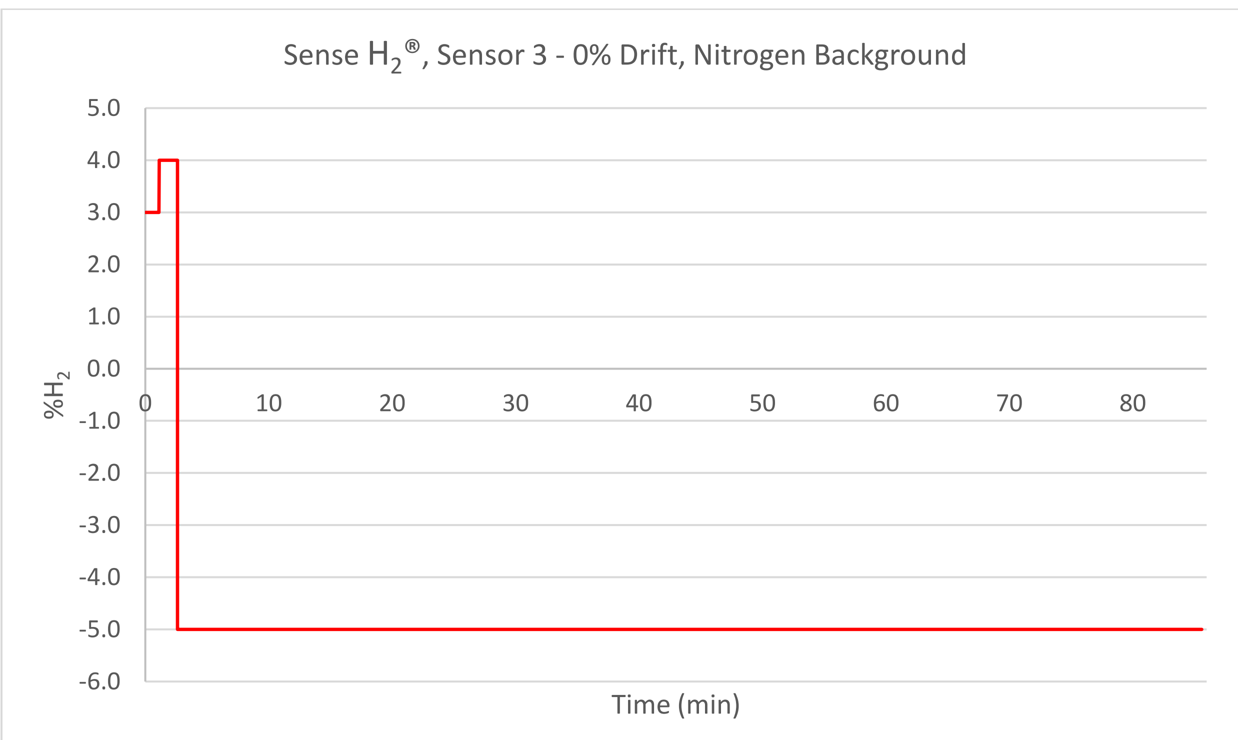

Figure 27. Sense H_2® data for sensor 3 in the 0% drift test with a nitrogen background.

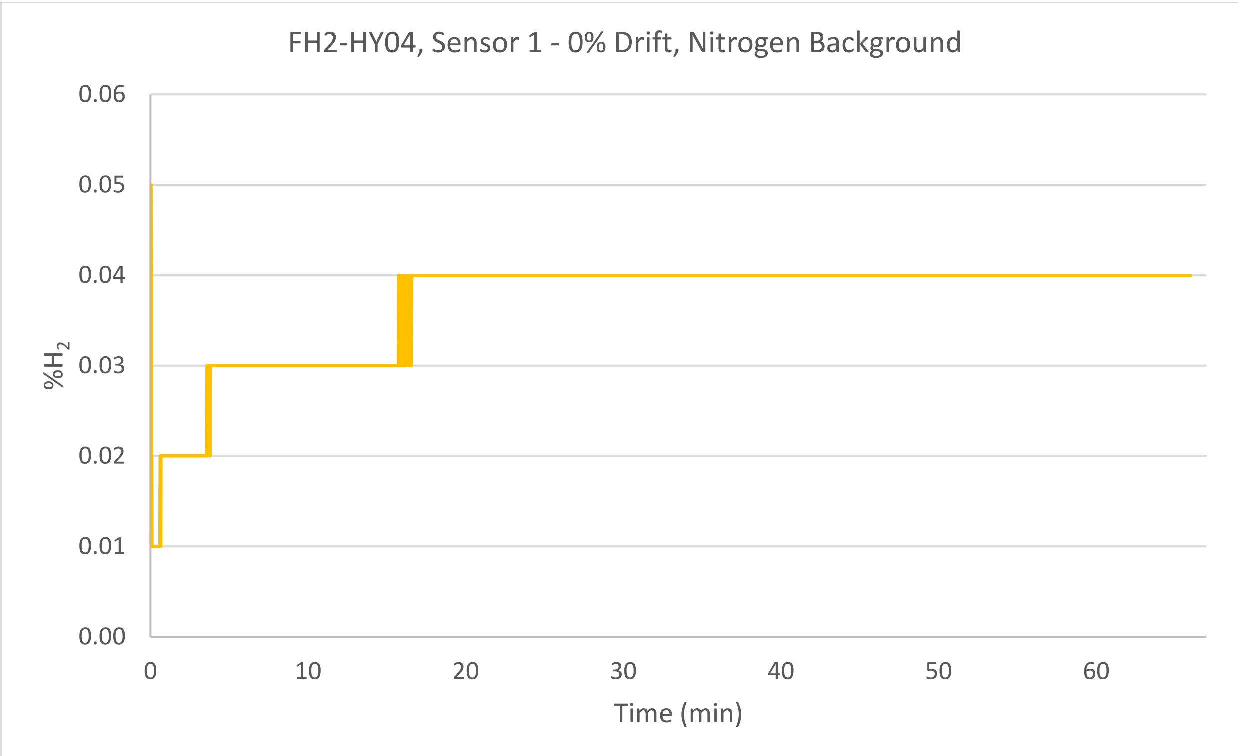

Figure 28. FH2-HY04 data for sensor 1 in the 0% drift test with a nitrogen background.

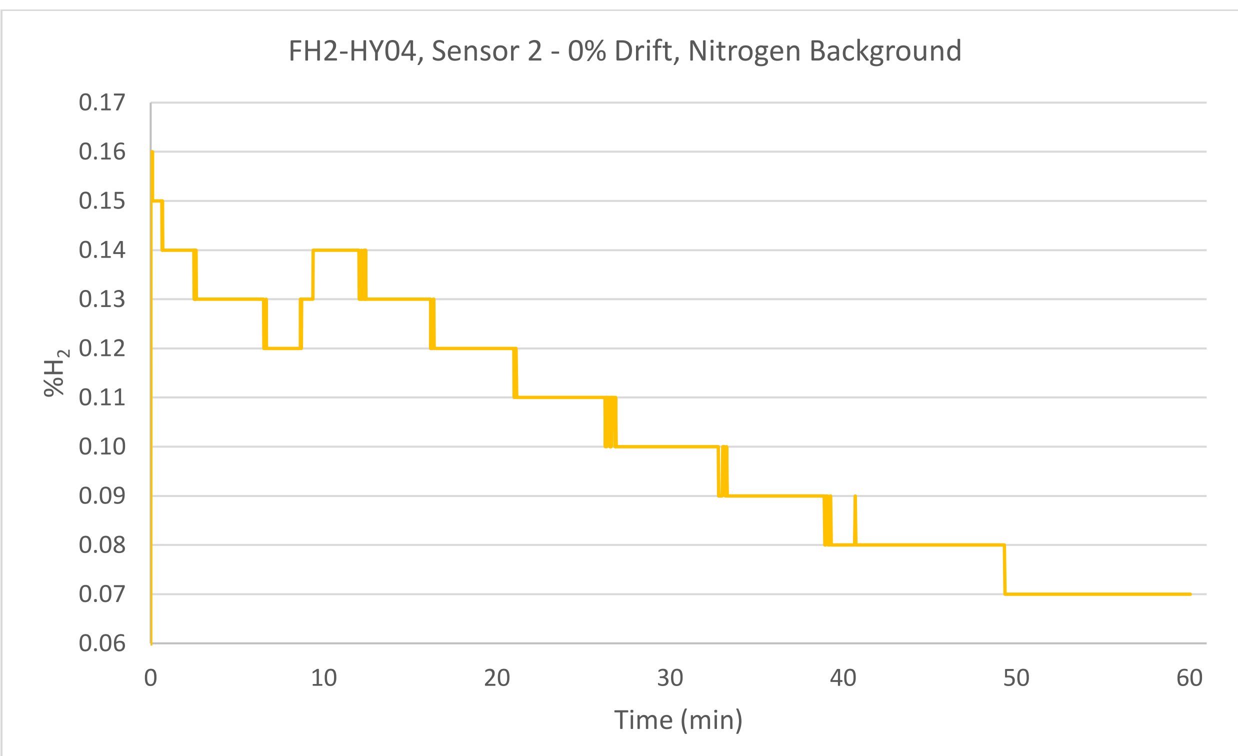

Figure 29. FH2-HY04 data for sensor 2 in the 0% drift test with a nitrogen background.

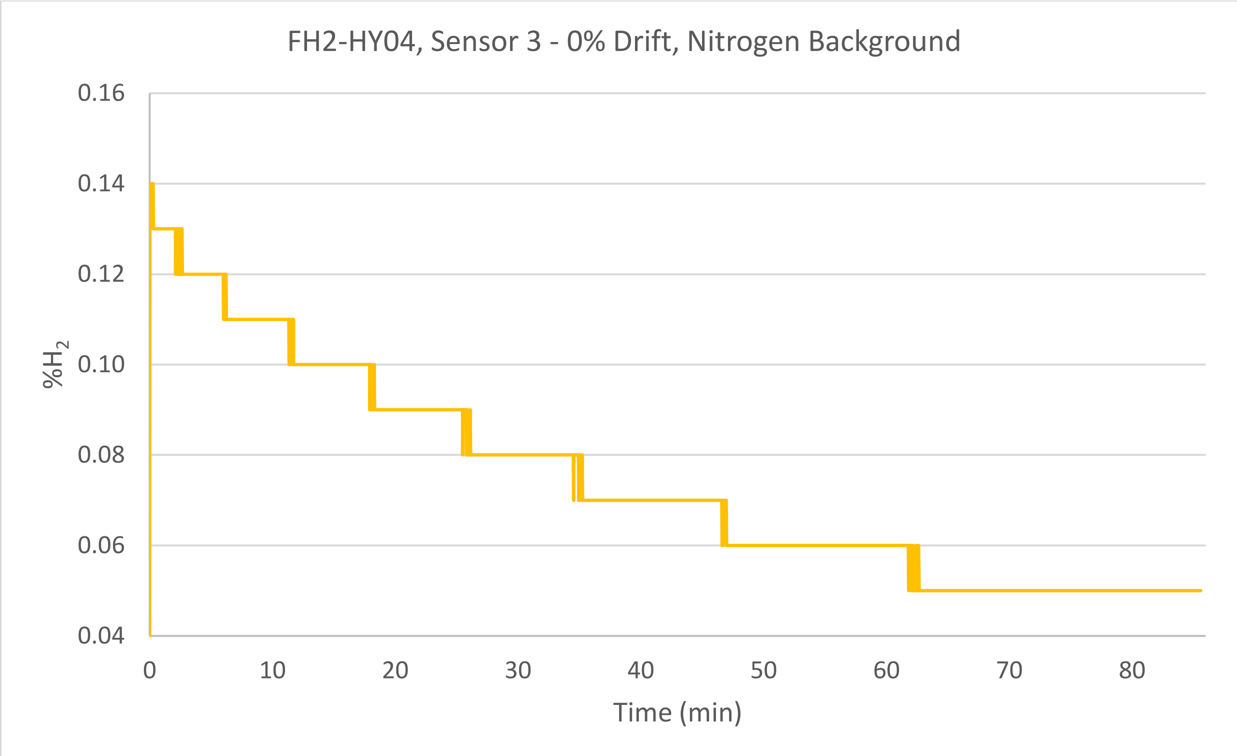

Figure 30. FH2-HY04 data for sensor 3 in the 0% drift test with a nitrogen background.

Table 3 gives the results of the 0% drift test with a background of nitrogen. The Sense H_2® and FH2-HY04 sensors did not function properly in a nitrogen background, so their results have been omitted from the table. Both functioning sensors remained stable throughout the test.

Table 3. 0% Drift Test Results – Nitrogen Background.

Sensor	Sensor/Run	Time Duration (min)	%H_2 Source Drift	Sensor Output Drift (%H_2)
H2scan 720B	1	66.0	-0.02	0.00
	2	60.1	-0.01	0.00
	3	85.6	-0.01	0.00
XEN-5320	1	66.0	-0.02	-0.01
	2	60.1	-0.01	-0.01
	3	85.6	-0.01	-0.01

Results – 0% Drift, Helium Background

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

Figure 31 through Figure 34 show the data collected for each sensor during the 0% drift tests.

The H2scan continued to yield the same results seen in air and nitrogen backgrounds in a helium background, despite having no indication from the manufacturer that it is expected to perform under that condition.

The XEN-5320, however, did not perform well when detecting hydrogen in a helium background. It indicates a > 90% H_2 concentration throughout this test. This is likely because the sensor also detects helium.

As with their performance in nitrogen, the two sensors designed for aerobic use only, the Sense H_2® and FH2-HY04 did not function in a helium background either.

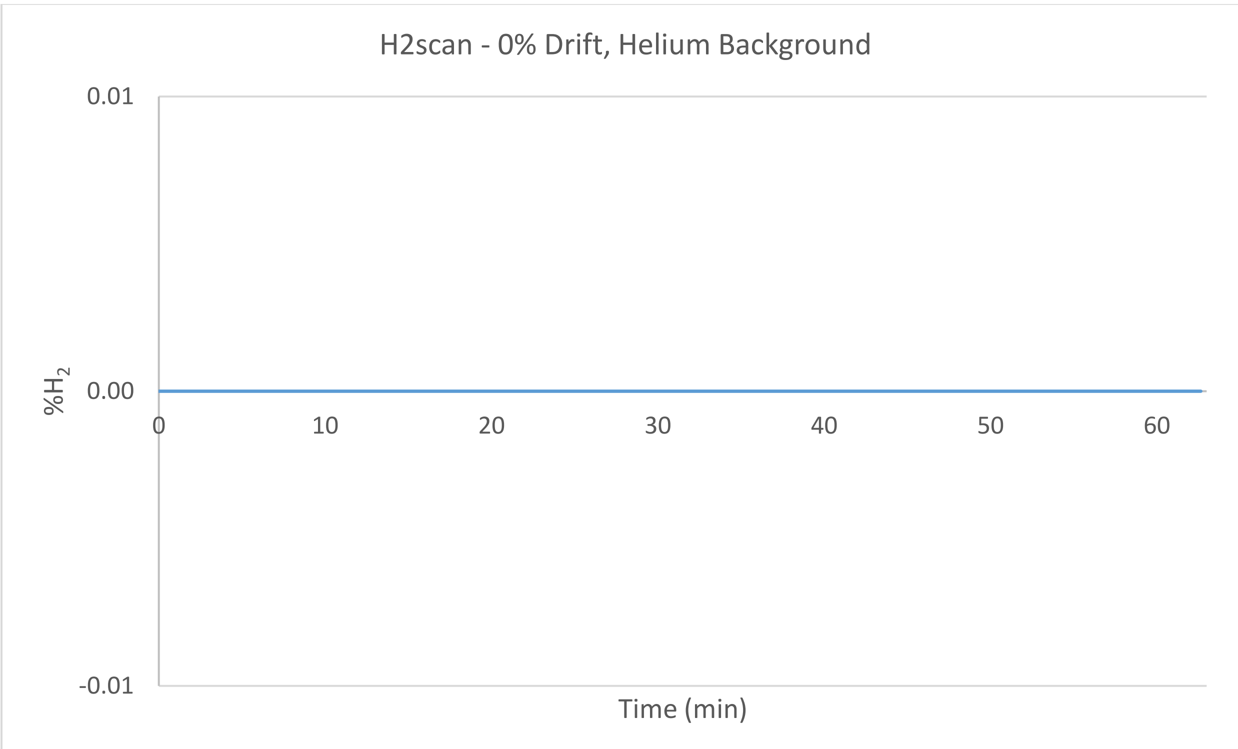

Figure 31. H2scan data for the 0% drift test with a helium background.

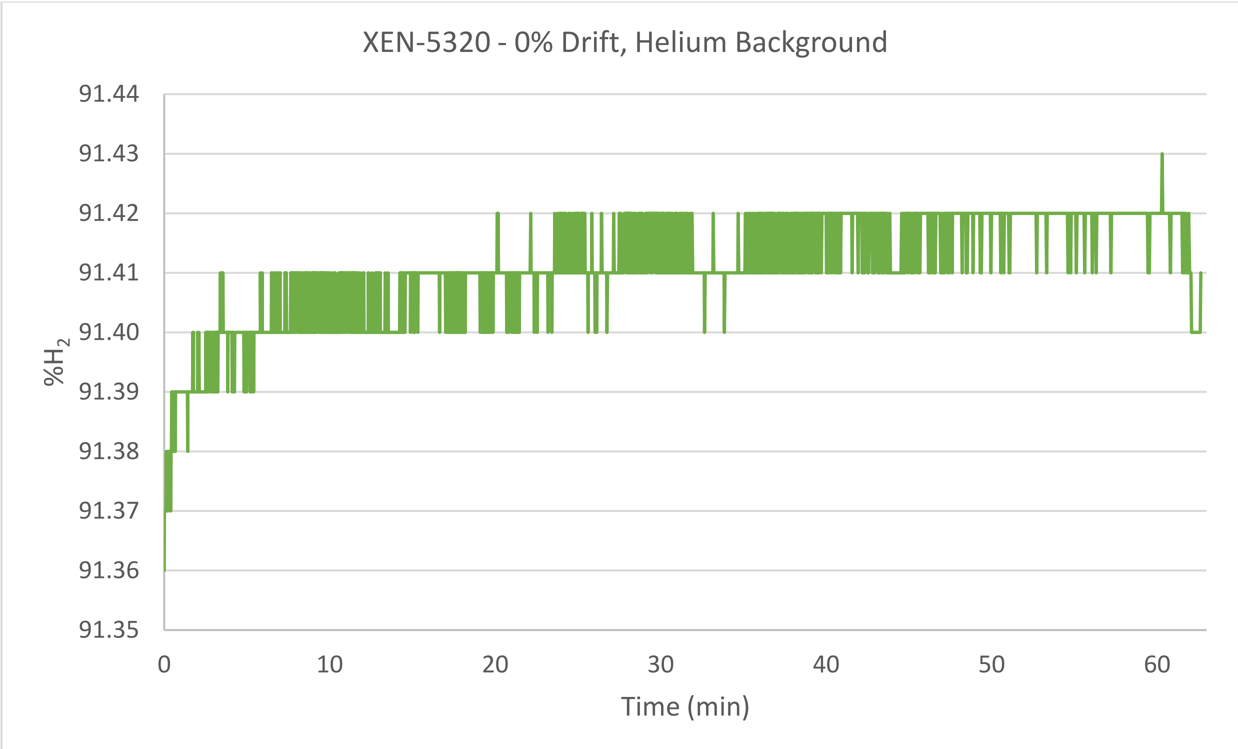

Figure 32. XEN-5320 data for the 0% drift test with a helium background.

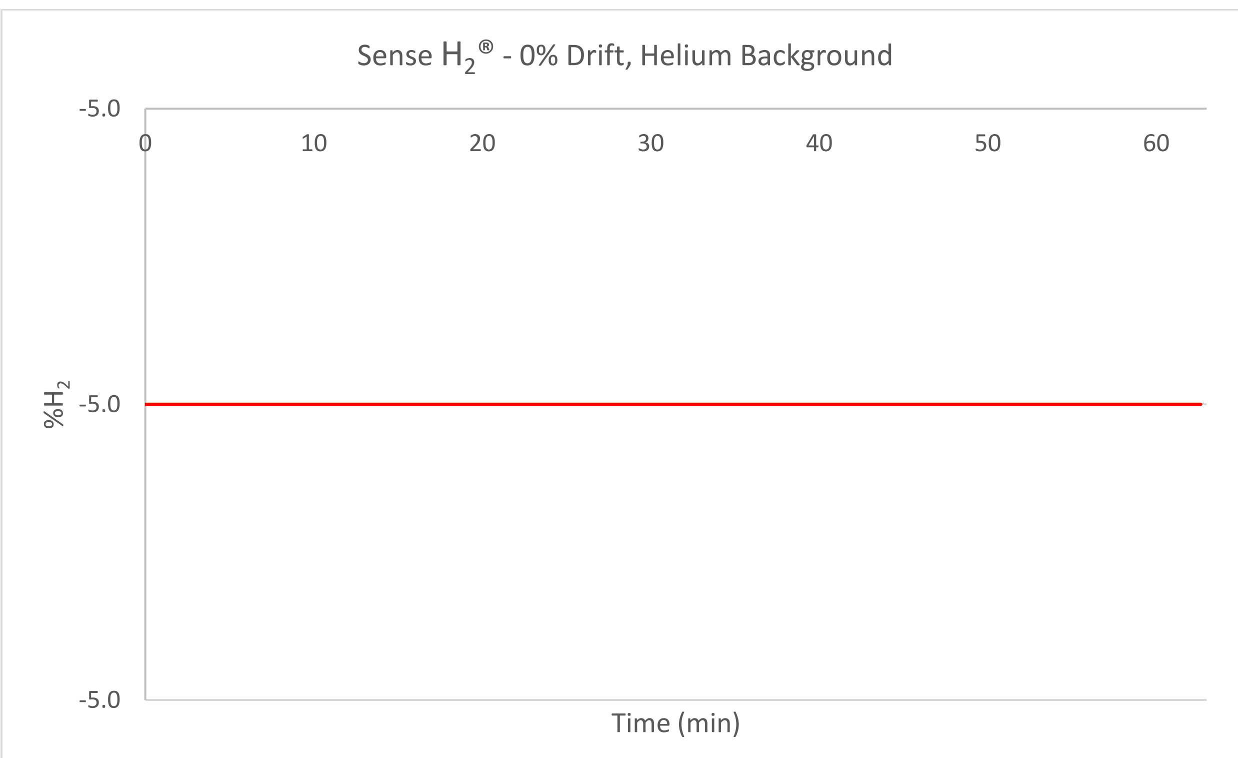

Figure 33. Sense H_2® data for the 0% drift test with a helium background.

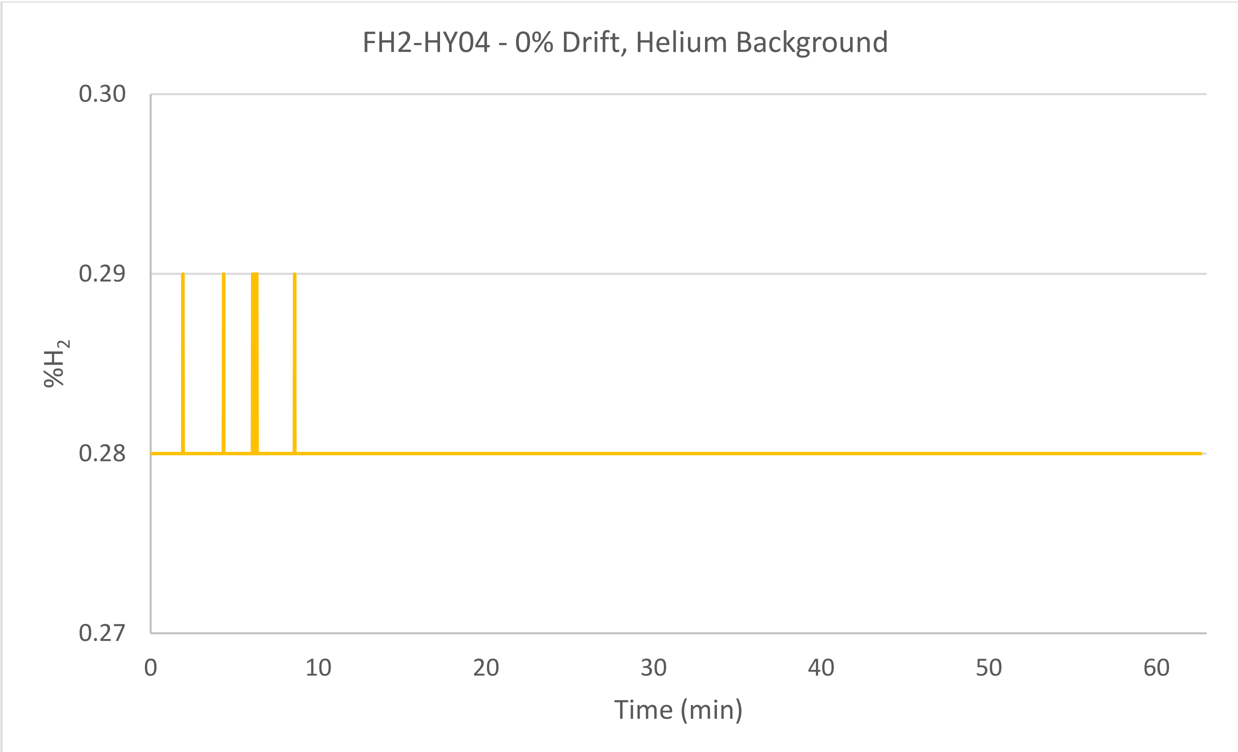

Figure 34. FH2-HY04 data for the 0% drift test with a helium background.

Table 4 gives the results of the 0% drift test with a background of helium. Because the other sensors did not function properly in a helium background, only the H2scan is listed in the table. Its output was stable during the test.

Table 4. 0% Drift Test Results – Helium Background.

Sensor	Test Duration (min)	$\%H_2$ Source Drift	Sensor Output Drift ($\%H_2$)
H2scan 720B	62.6	-0.01	0.00

Results – 2% Drift, Air Background

Figure 35 through Figure 46 show the data collected for each sensor during the 2% drift tests.

The H2scan's values did change throughout these tests. The outputs are also not the same value, even though the same concentration of hydrogen was provided for each test. This is disappointing, since the same sensor was used for each run, but they were similar values. It is also worth noting that, in the first run, the output held fairly steady, with small fluctuations that could be explained by noise or changing hydrogen concentrations, while in the second run, the concentration increased for the first ten minutes, holds steady for about 40 minutes, then began to slowly drop again.

The XEN-5320 had similar results to the 0% drift test, with only minimal fluctuations in output which could have been the result of changing hydrogen concentration in the gas provided or noise.

The Sense H_2® sensors displayed varying outputs in this test. Sensor 1 output 3.0% H_2 throughout its test. Sensor 2 alternated between 2.5% H_2 and 3.0% H_2. Sensor 3 remained primarily at 2.5% H_2.

Similar to the H2scan, the FH2-HY04 had a steadier output for the first test than it did for the later ones, which could indicate that these shifts were due to test conditions for both sensors.

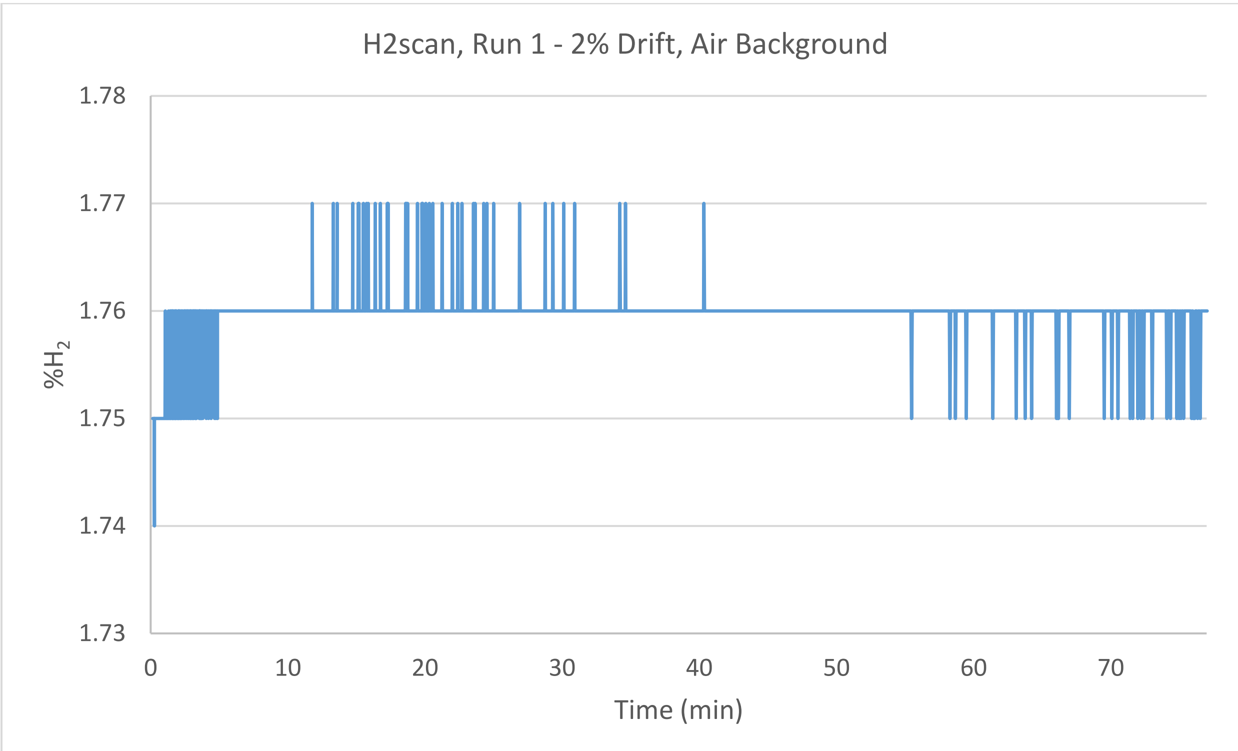

Figure 35. H2scan data from run 1 of the 2% drift test with an air background.

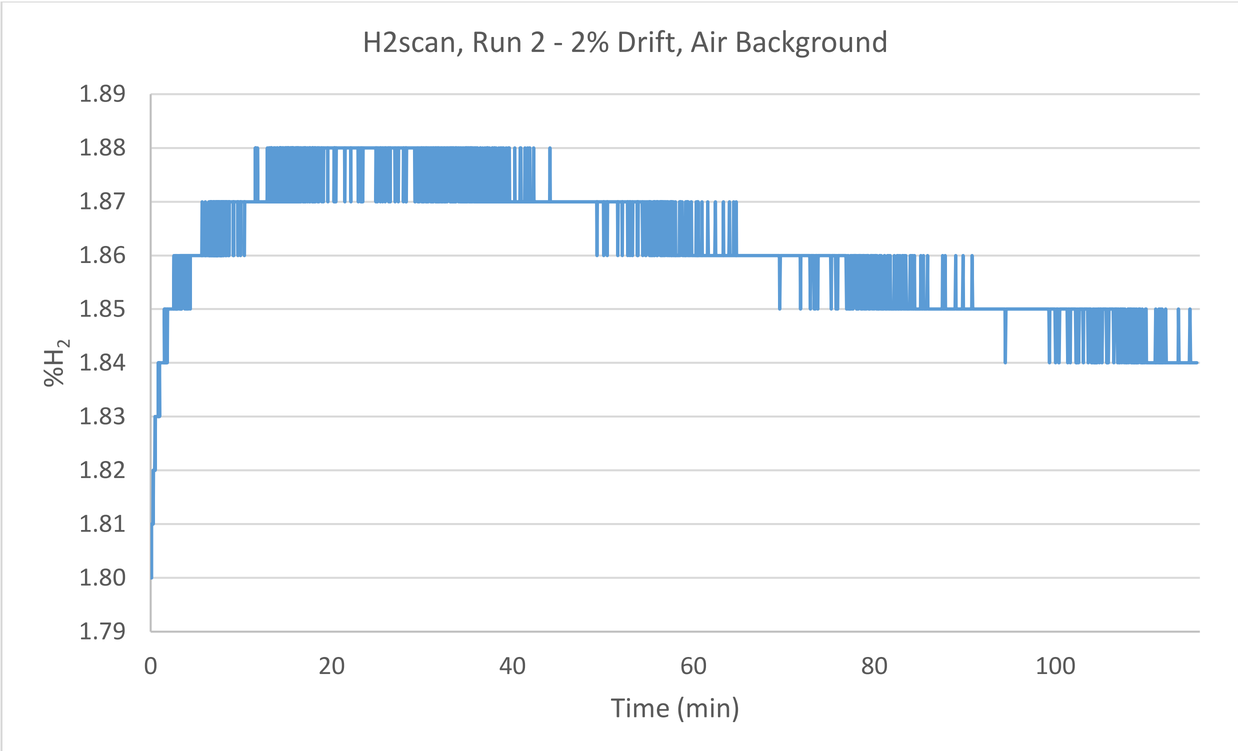

Figure 36. H2scan data from run 2 of the 2% drift test with an air background.

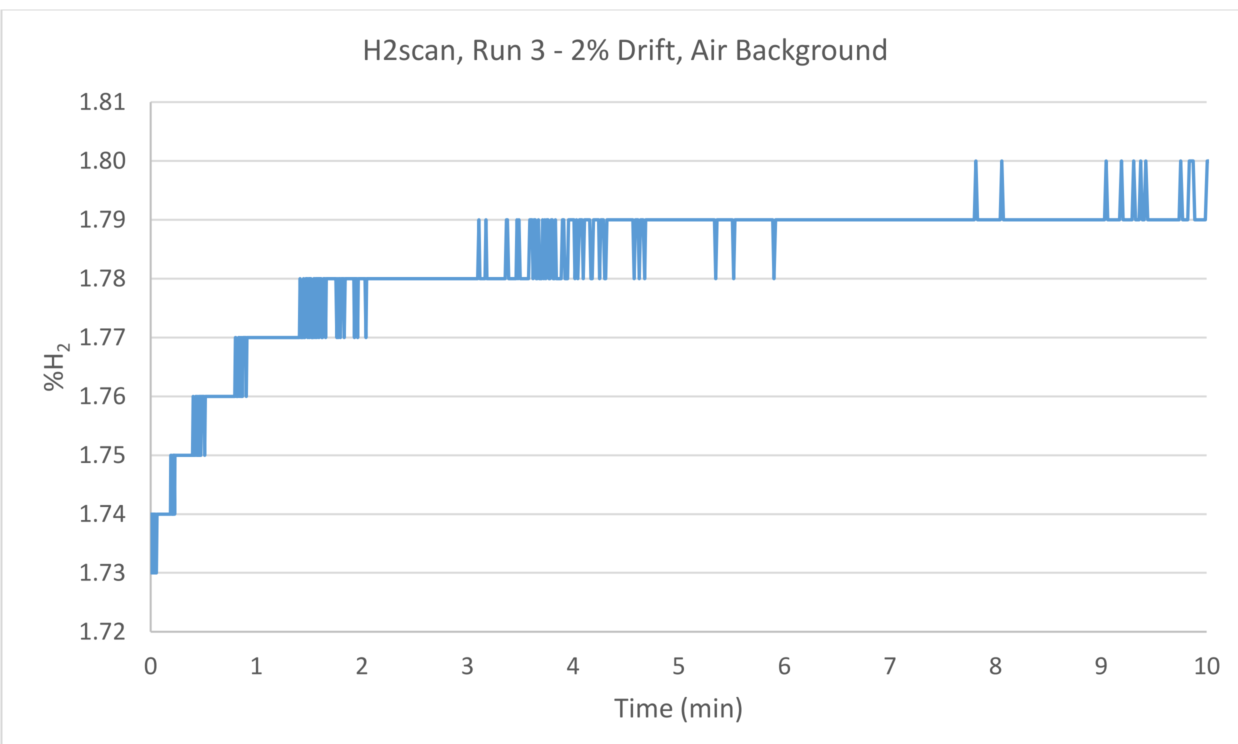

Figure 37. H2scan data from run 3 of the 2% drift test with an air background.

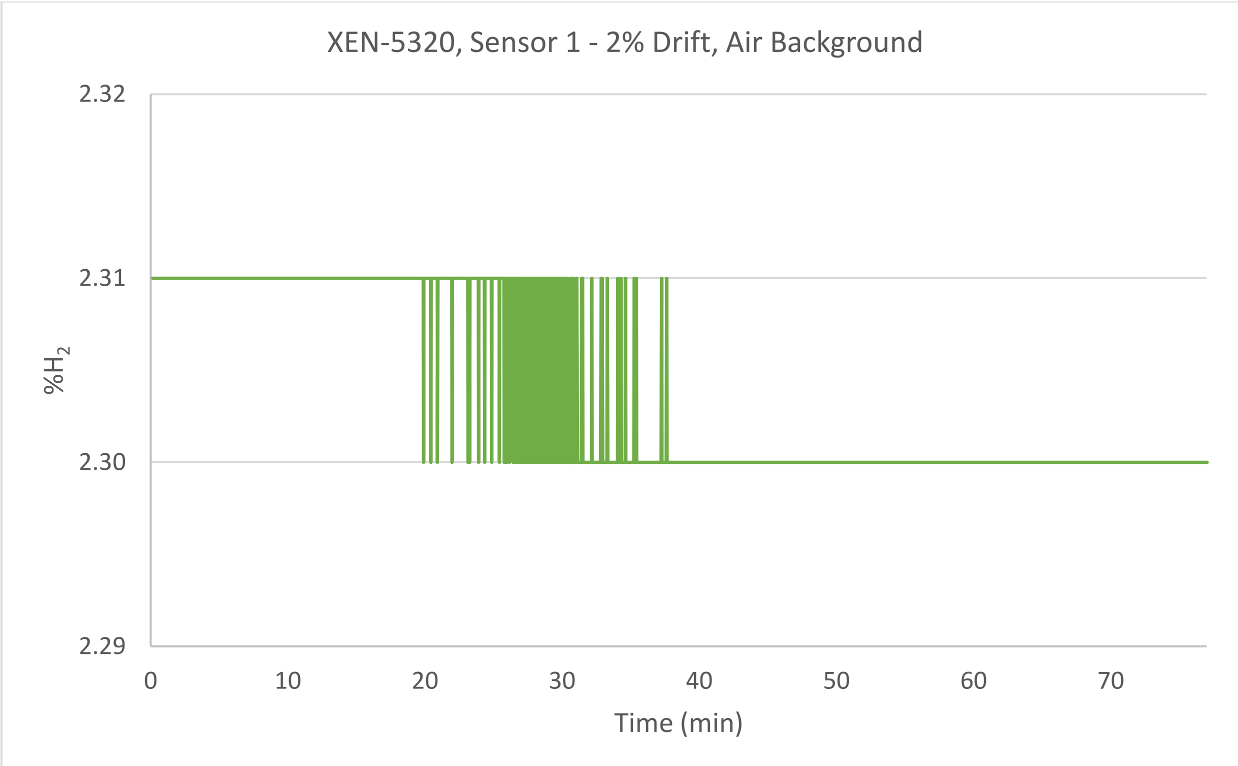

Figure 38. XEN-5320 data from sensor 1 in the 2% drift test with an air background.

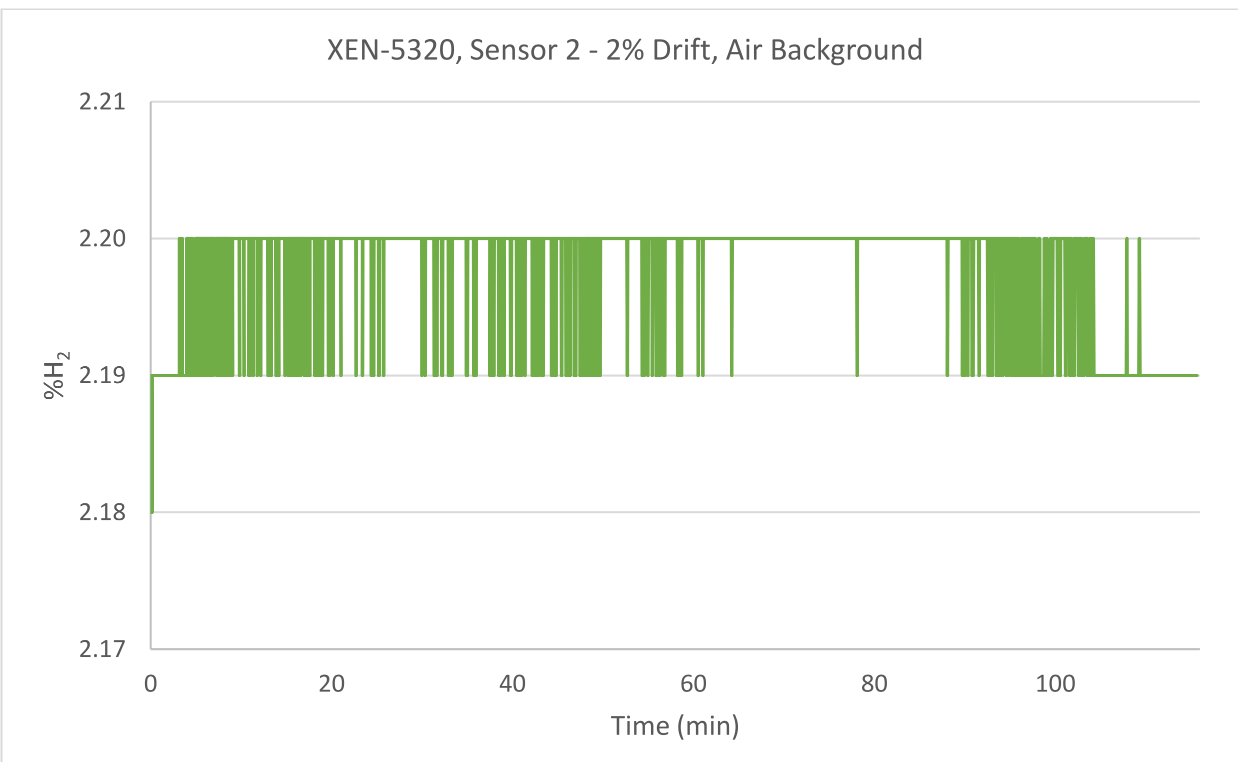

Figure 39. XEN-5320 data from sensor 2 in the 2% drift test with an air background.

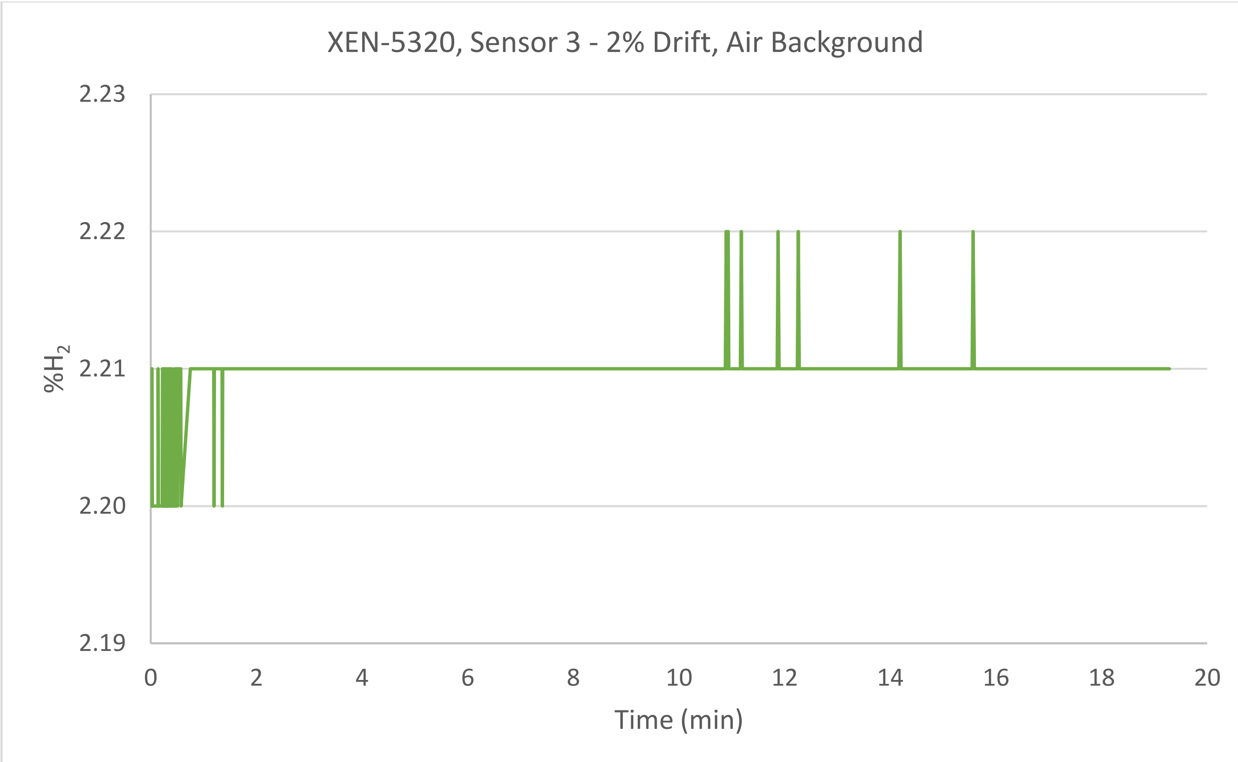

Figure 40. XEN-5320 data from sensor 3 in the 2% drift test with an air background.

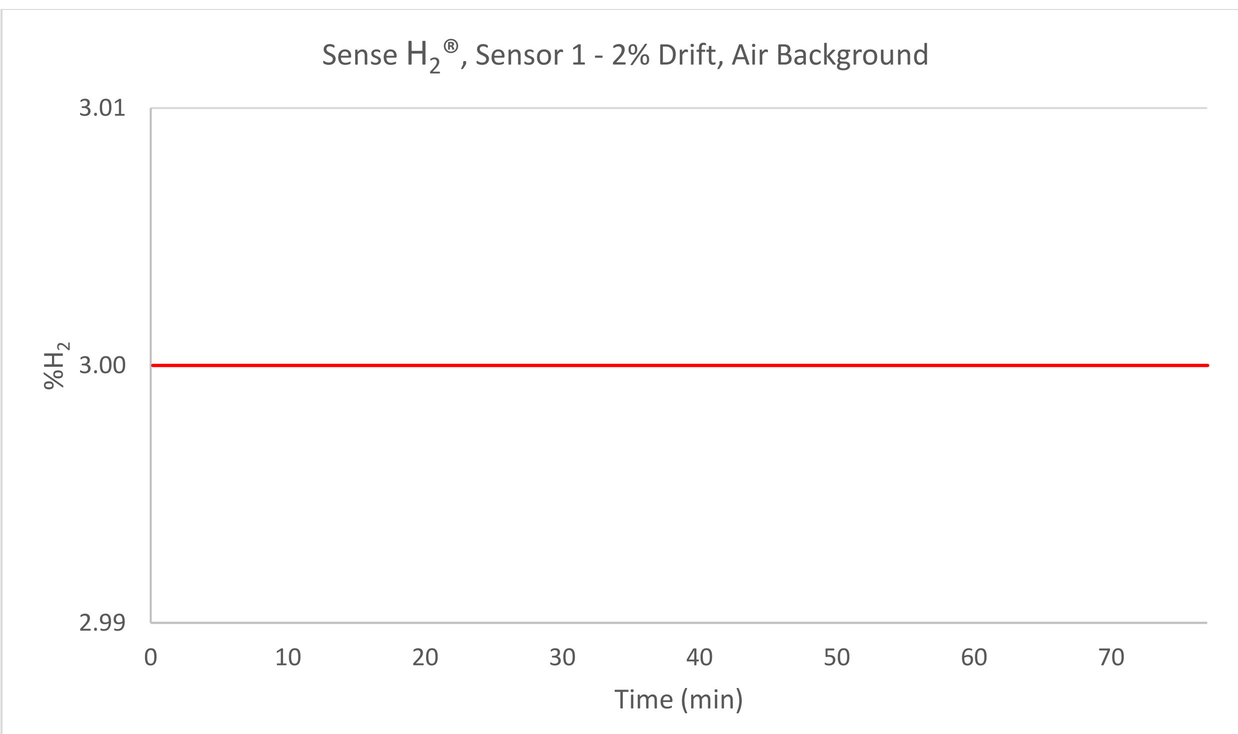

Figure 41. Sense H_2® data from sensor 1 in the 2% drift test with an air background.

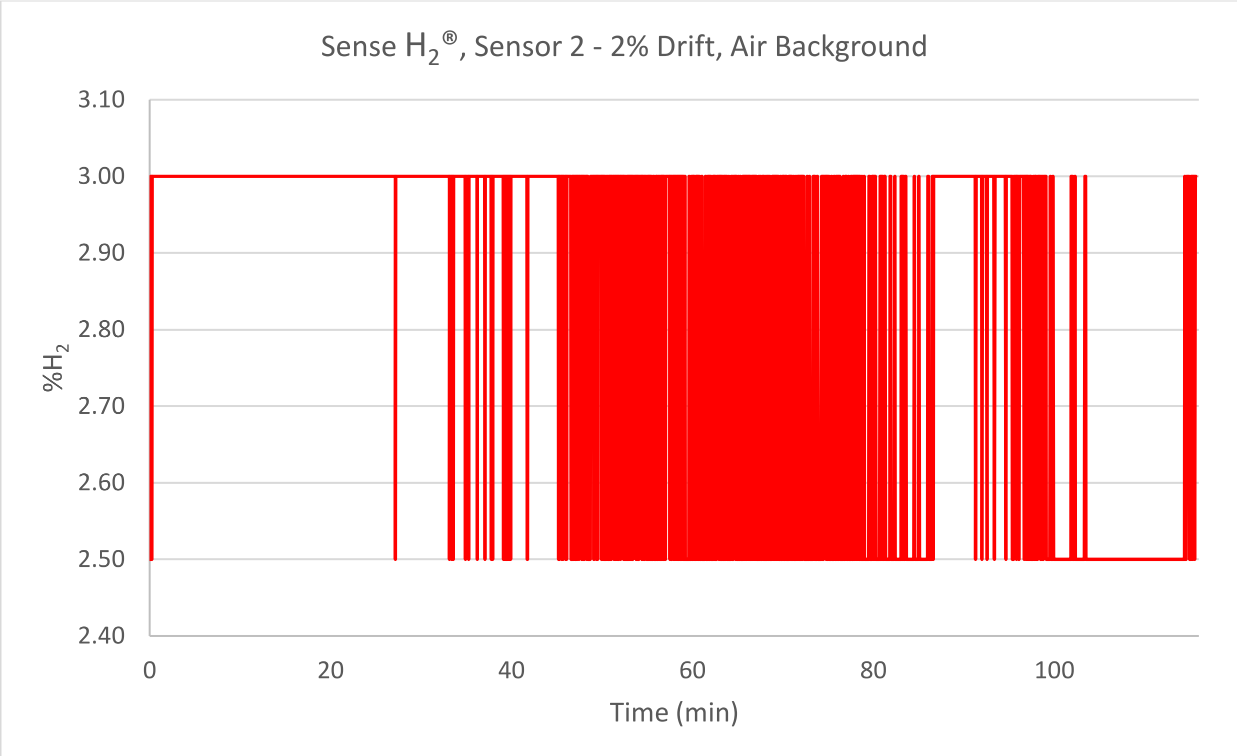

Figure 42. Sense H_2® data from sensor 2 in the 2% drift test with an air background.

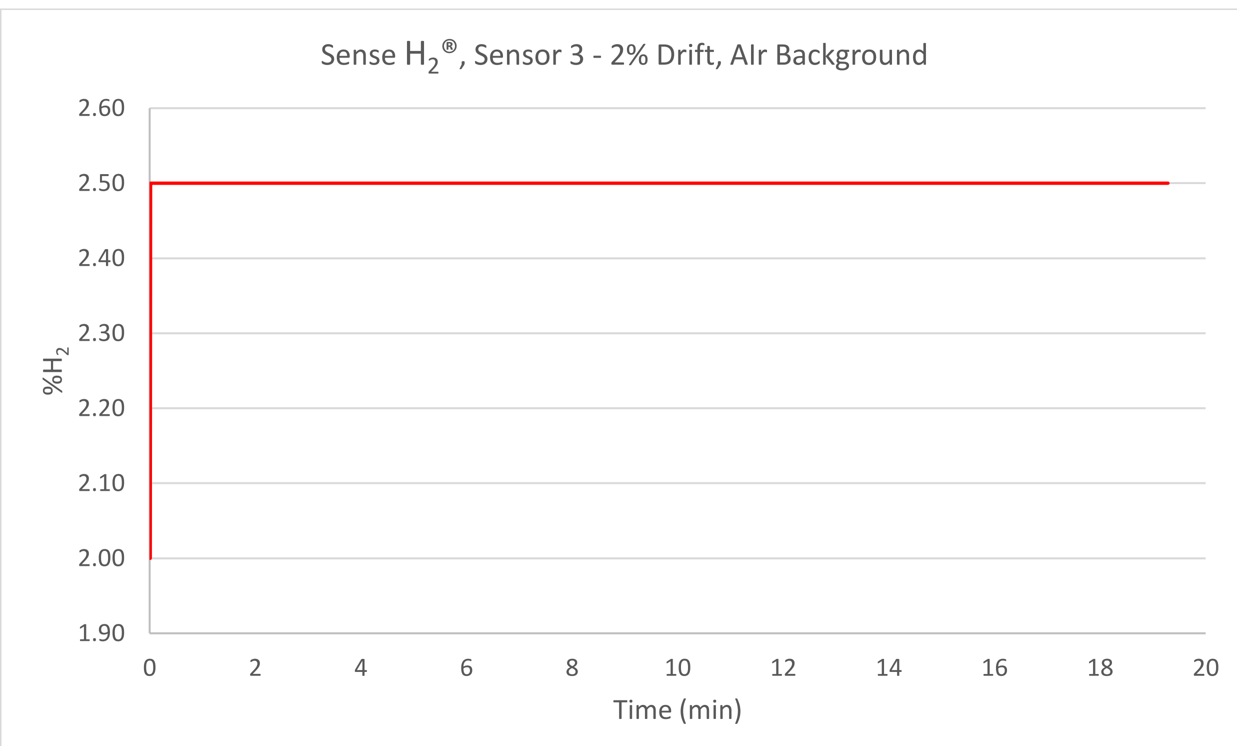

Figure 43. Sense H_2® data from sensor 3 in the 2% drift test with an air background.

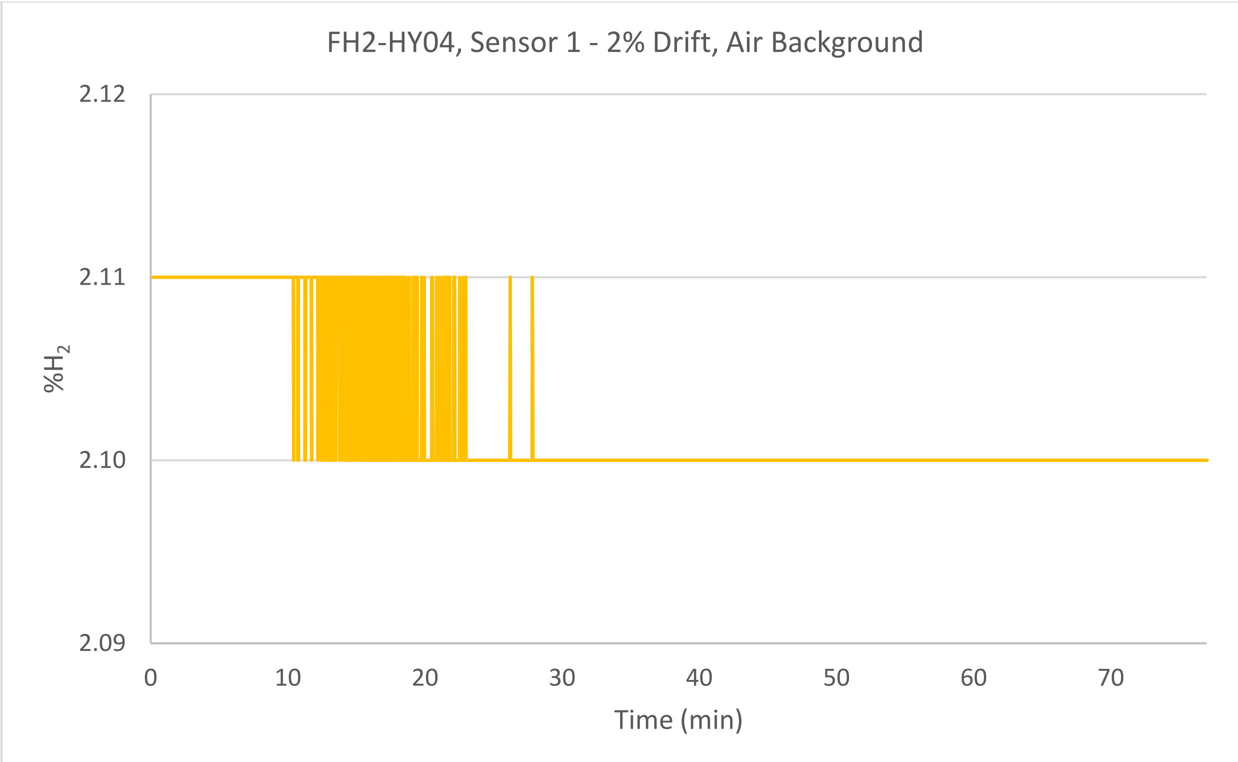

Figure 44. FH2-HY04 data from sensor 1 in the 2% drift test with an air background.

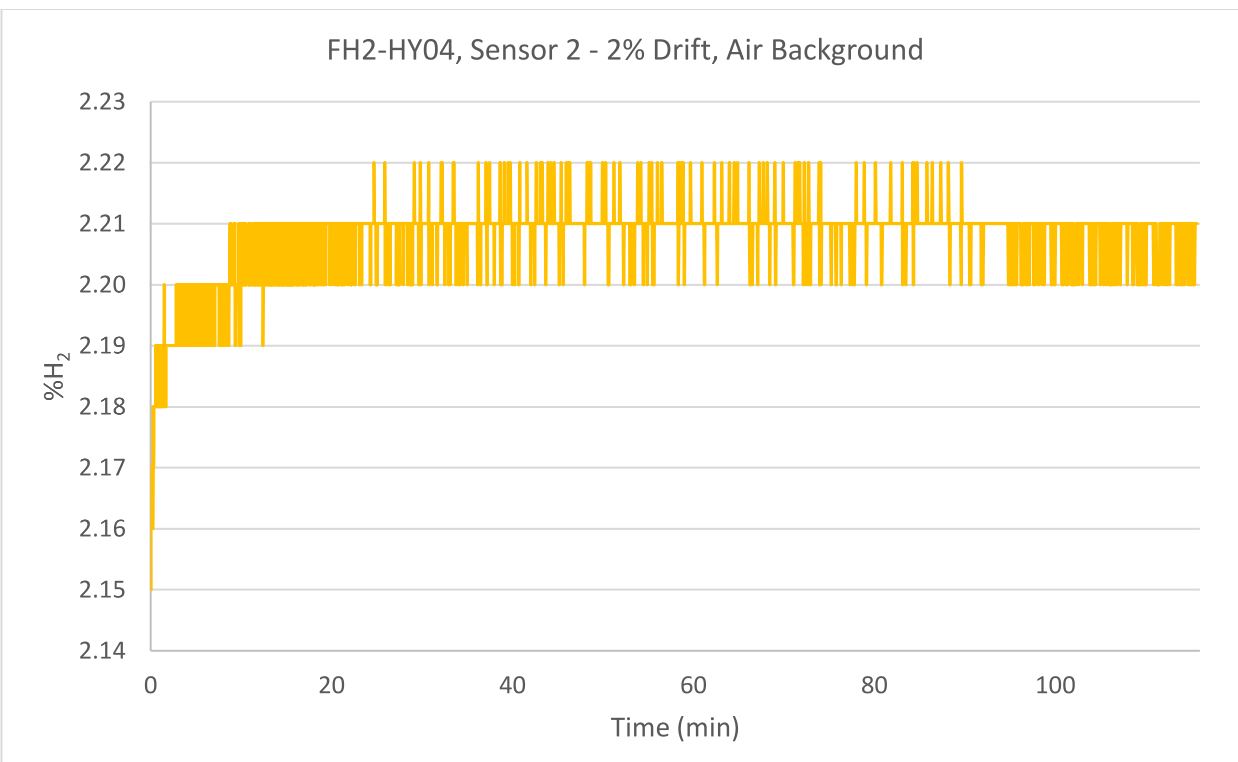

Figure 45. FH2-HY04 data from sensor 2 in the 2% drift test with an air background.

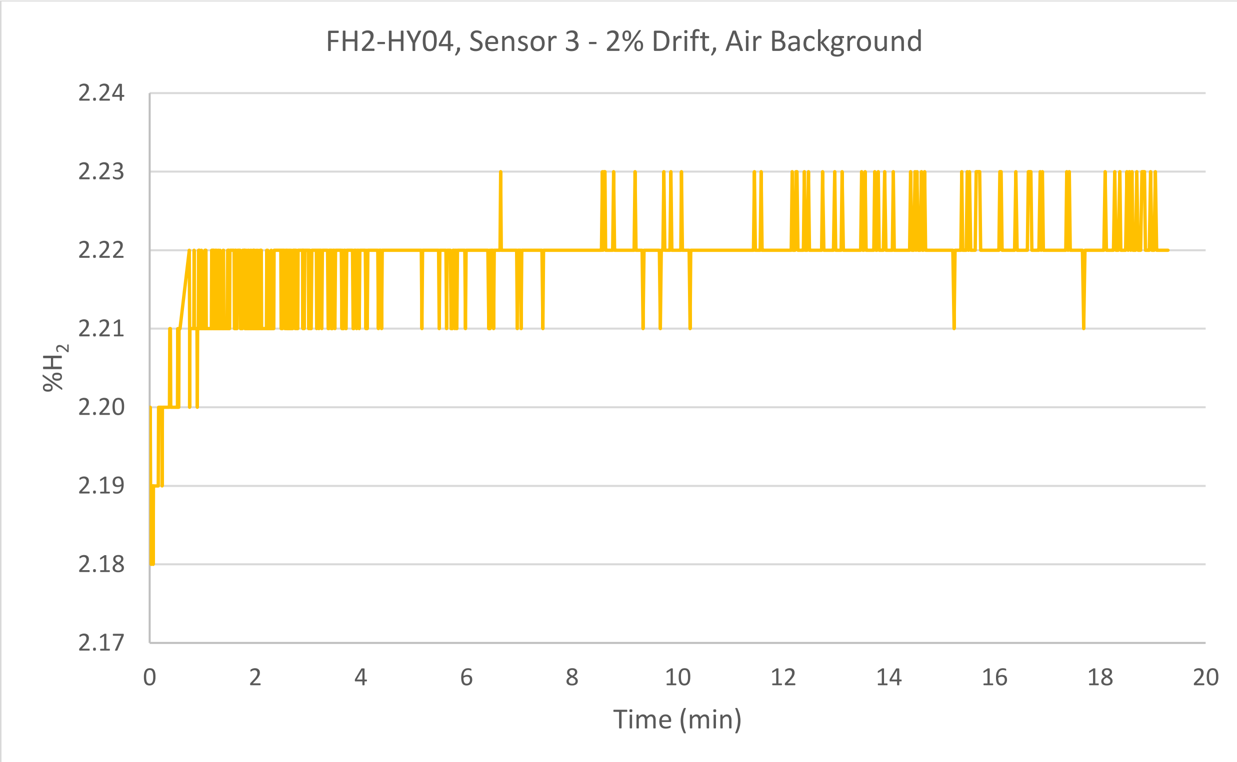

Figure 46. FH2-HY04 data from sensor 3 in the 2% drift test with an air background.

Table 5 gives the results of the 0% drift test with a background of air. With the exception of one Sense H_2® sensor, which was alternating between outputs of 2.5 and 3.0% H_2, the sensors were mostly stable during these tests.

Table 5. 2% Drift Test Results – Air Background.

Sensor	Sensor/Run	Test Duration (min)	%H_2 Source Drift	Sensor Output Drift (%H_2)
H2scan 720B	1	77.0	0.00	0.01
	2	115.7	0.00	0.00
	3	19.3	0.00	0.03
XEN-5320	1	77.0	0.00	-0.01
	2	115.7	0.00	0.00
	3	19.3	0.00	0.00
Sense H_2®	1	77.0	0.00	0.0
	2	115.7	0.00	-0.4
	3	19.3	0.00	0.0
FH2-HY04	1	77.0	0.00	-0.01
	2	115.7	0.00	0.02
	3	19.3	0.00	0.01

Results – 2% Drift, Nitrogen Background

Figure 47 through Figure 58 show the data collected for each sensor during the 2% drift tests.

The H2scan had a similar performance on this test with a nitrogen background to its performance with an air background, with a slight increase throughout the tests.

The XEN-5320 also performed similarly, having only minimal fluctuations in output that could have been the result of noise or small changes in the hydrogen gas provided.

Again, the Sense H_2® and FH2-HY04 did not function anaerobically.

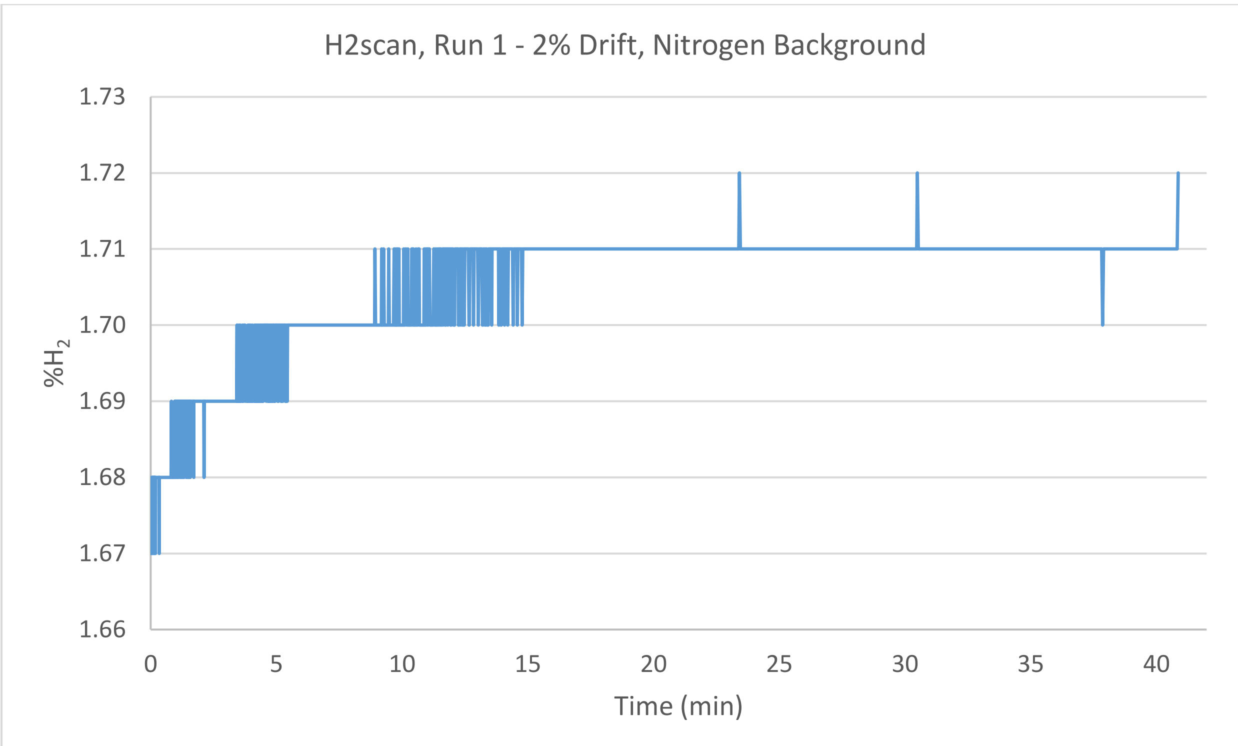

Figure 47. H2scan data for run 1 of the 2% drift test with a nitrogen background.

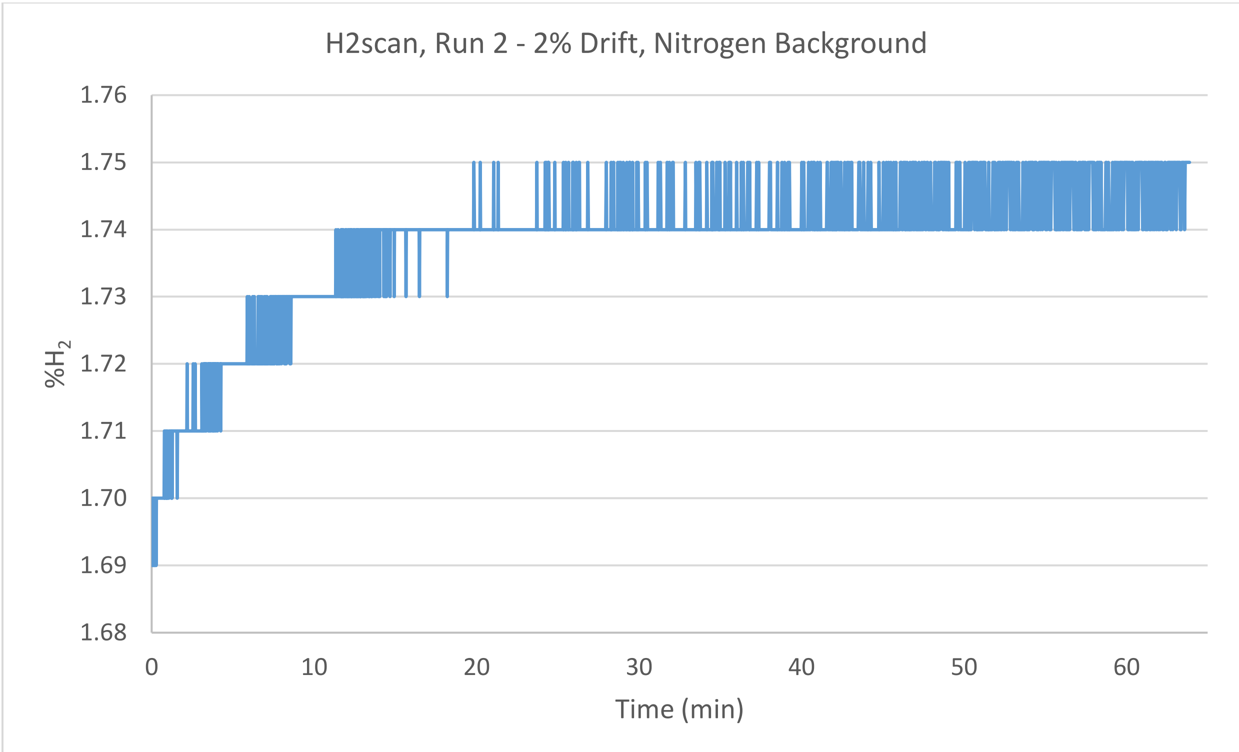

Figure 48. H2scan data for run 2 of the 2% drift test with a nitrogen background.

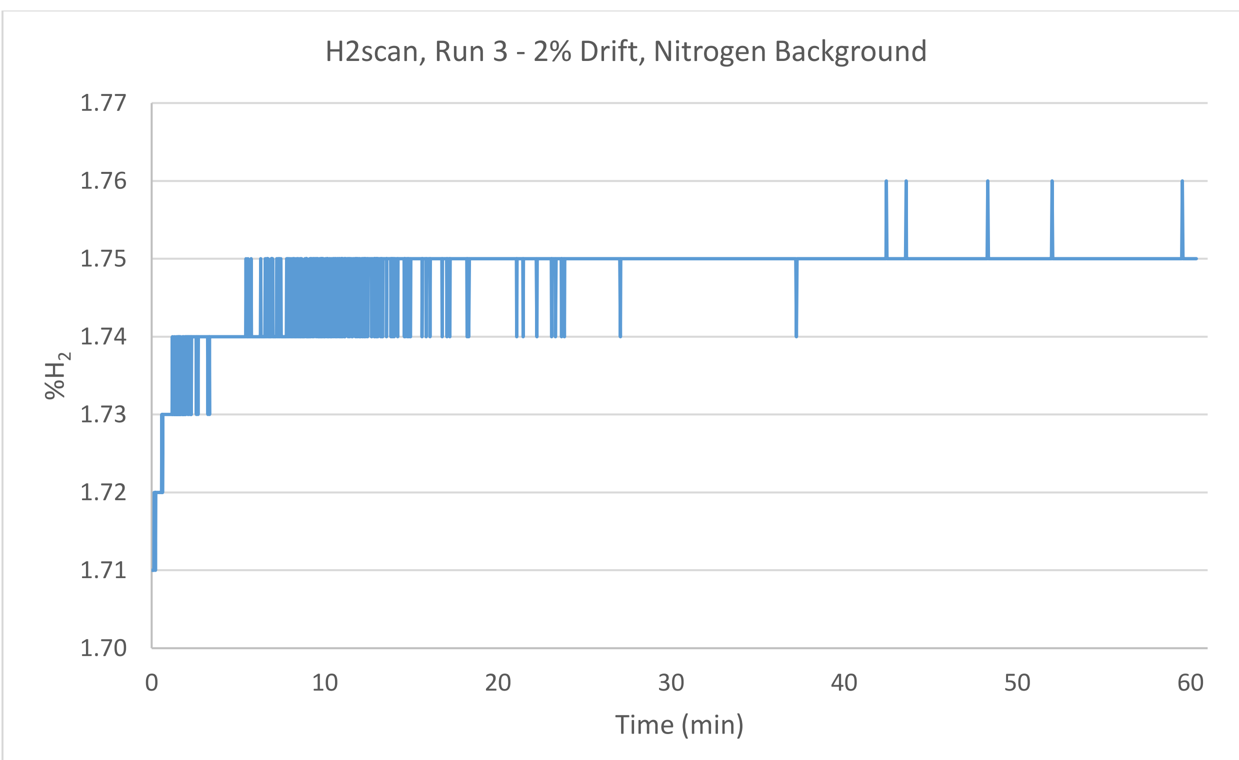

Figure 49. H2scan data for run 3 of the 2% drift test with a nitrogen background.

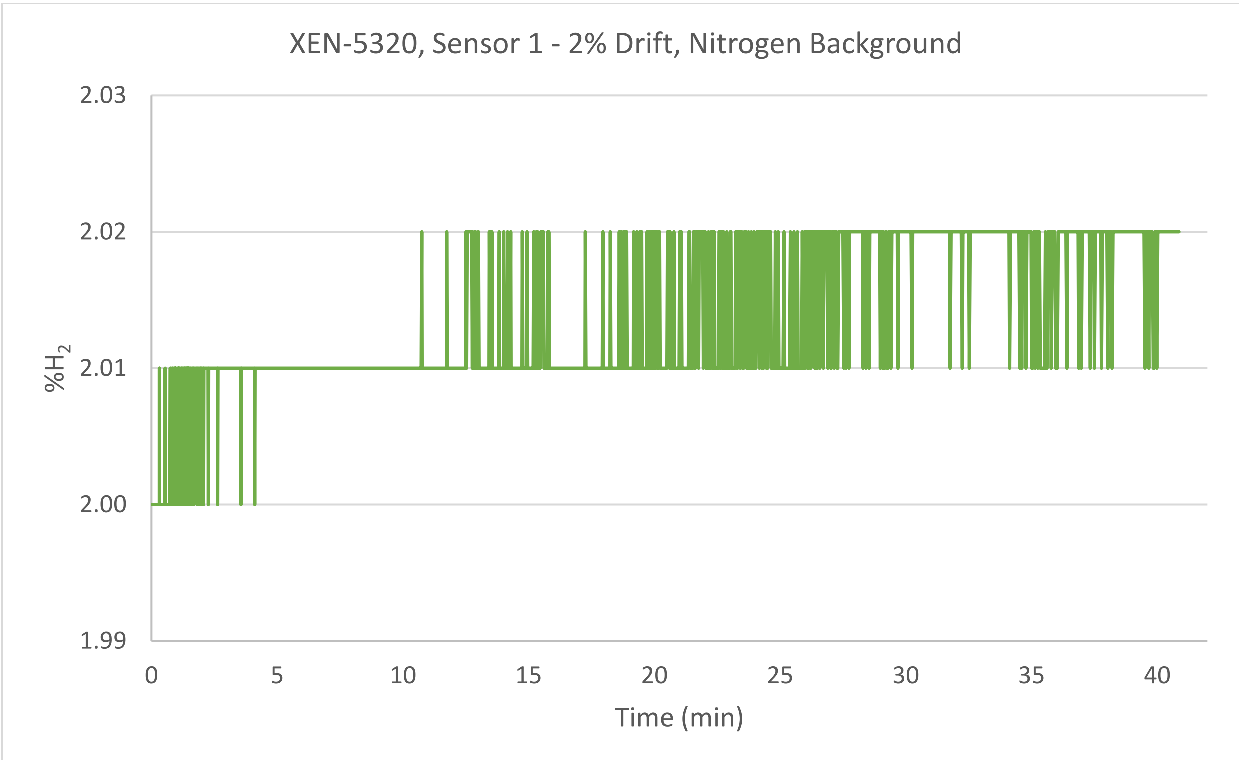

Figure 50. XEN-5320 data for sensor 1 in the 2% drift test with a nitrogen background.

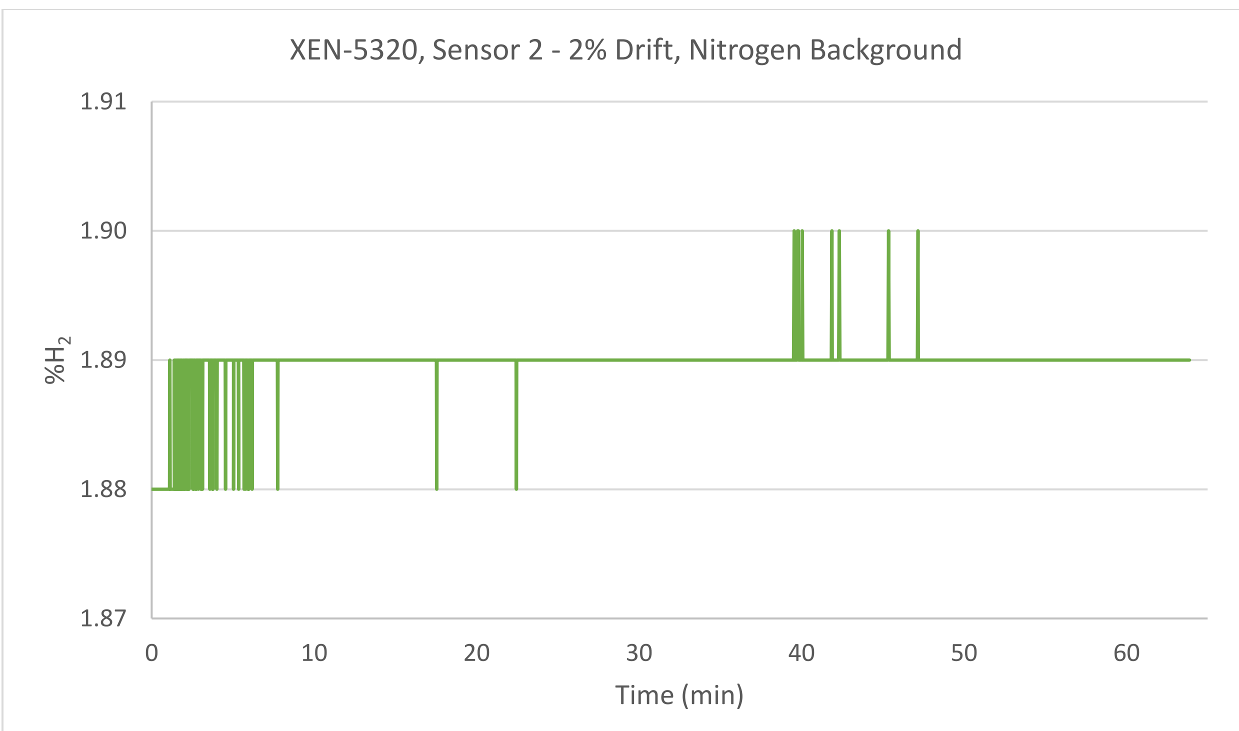

Figure 51. XEN-5320 data for sensor 2 in the 2% drift test with a nitrogen background.

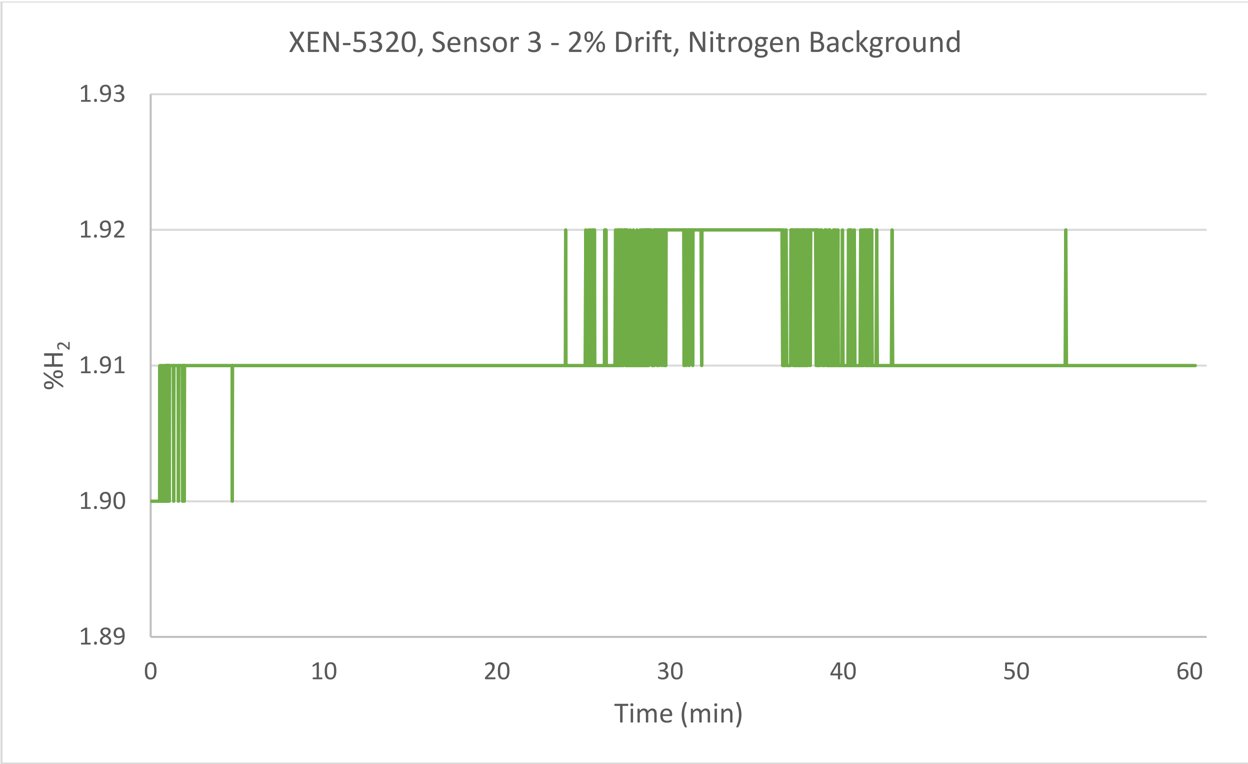

Figure 52. XEN-5320 data for sensor 3 in the 2% drift test with a nitrogen background.

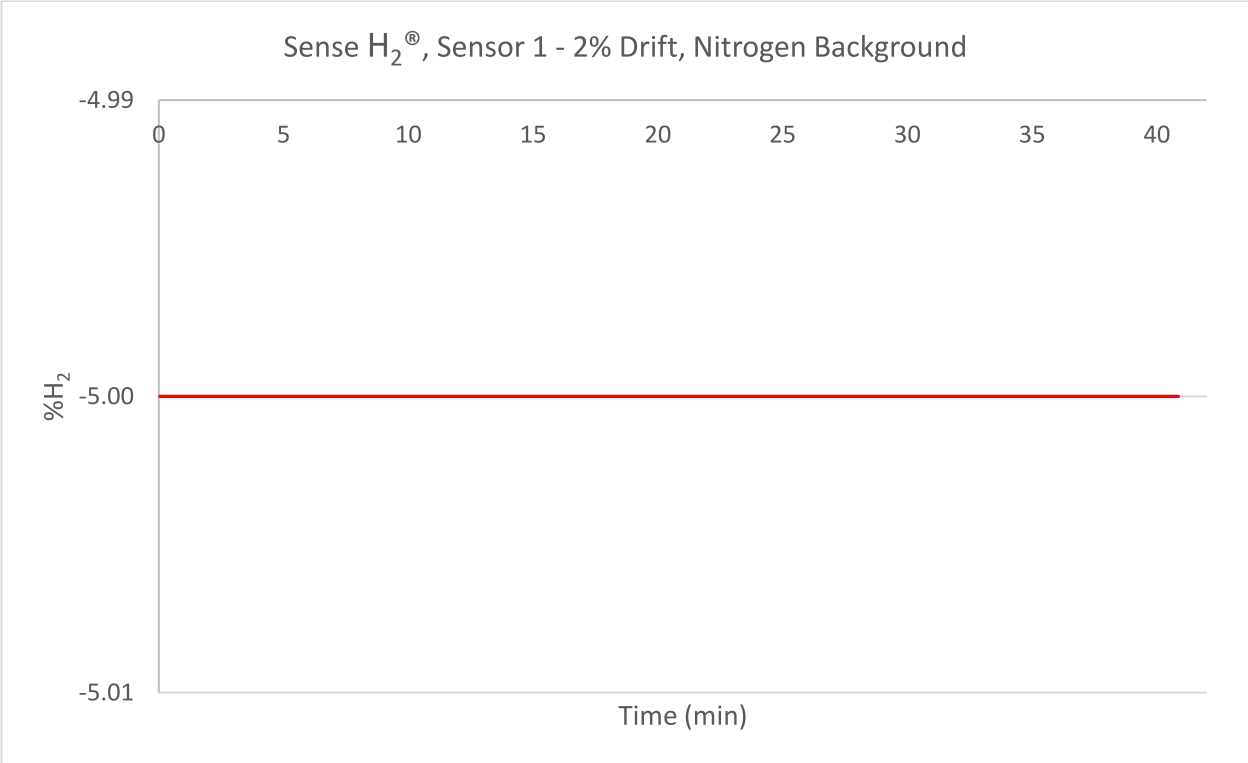

Figure 53. Sense H_2® data for sensor 1 in the 2% drift test with a nitrogen background.

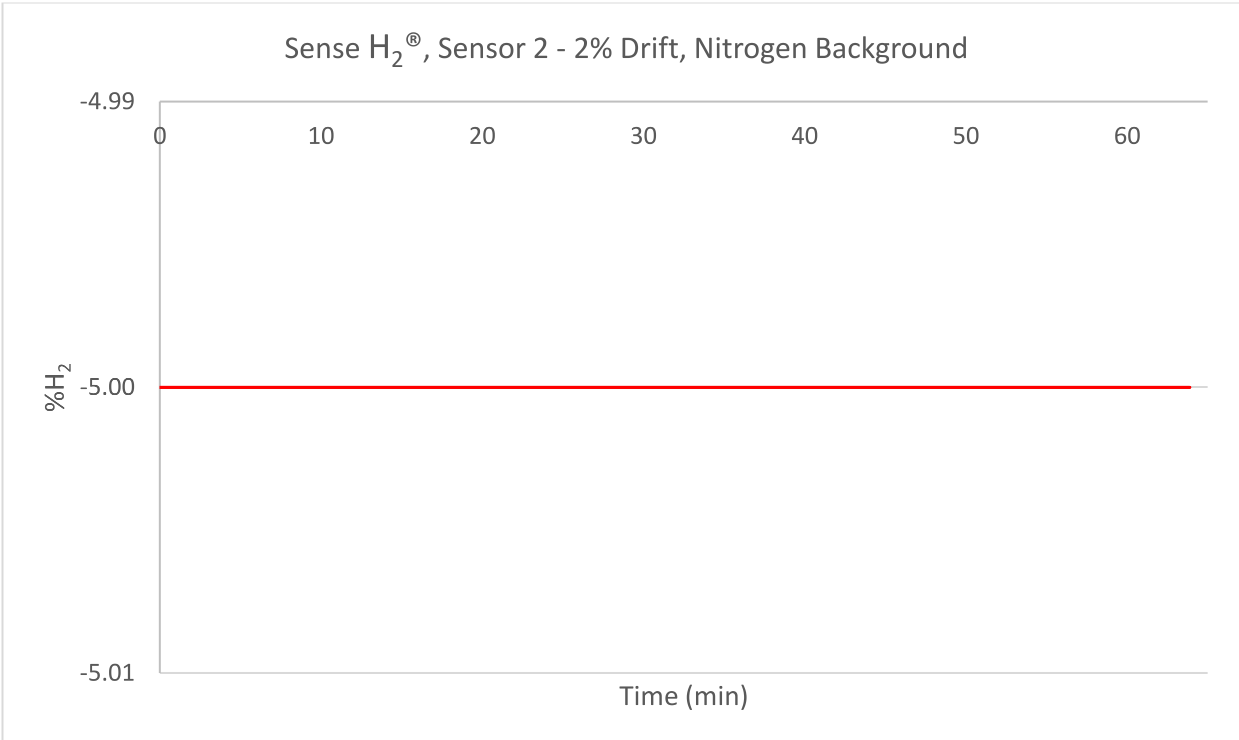

Figure 54. Sense H_2® data for sensor 2 in the 2% drift test with a nitrogen background.

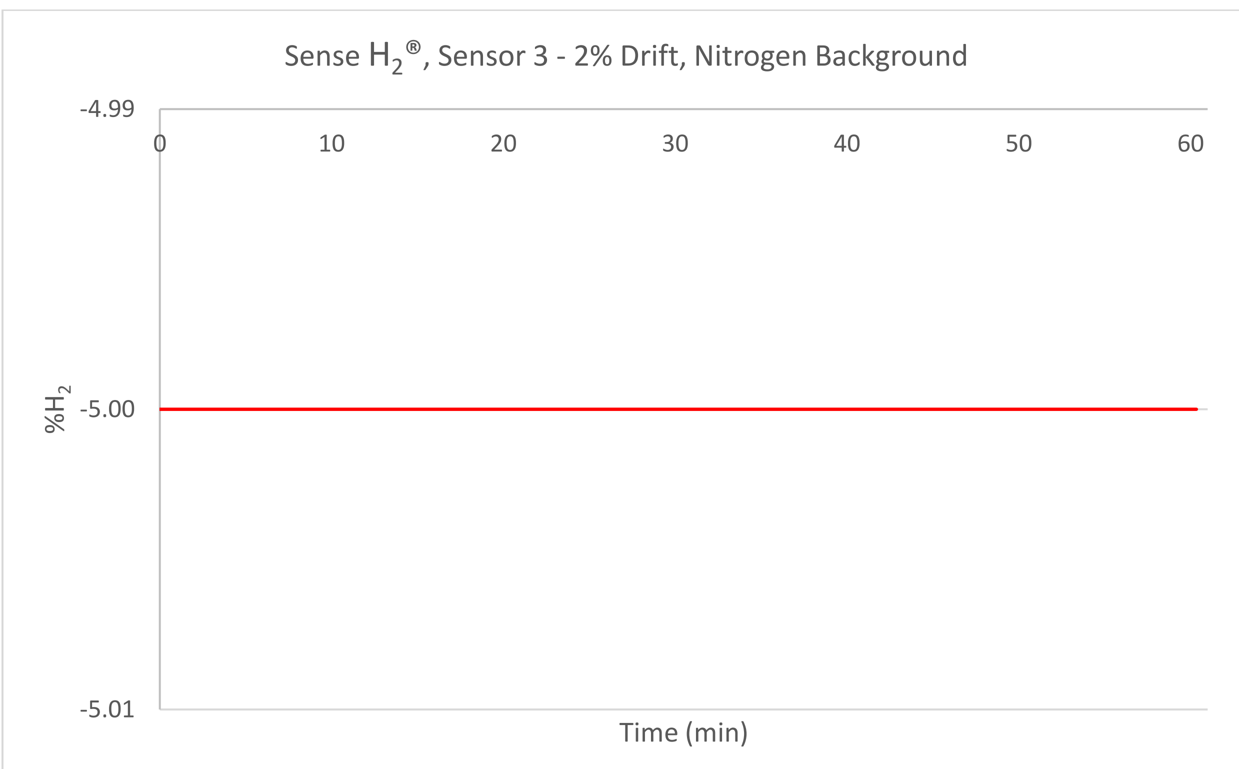

Figure 55. Sense H_2® data for sensor 3 in the 2% drift test with a nitrogen background.

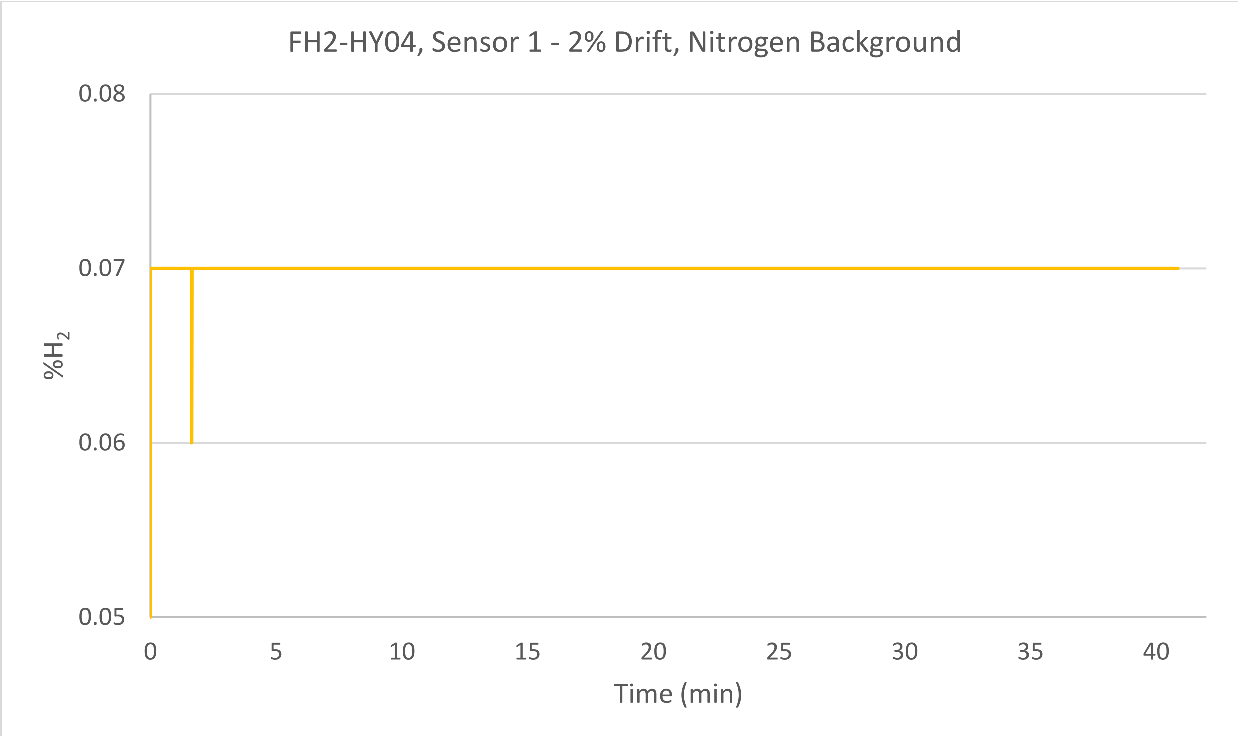

Figure 56. FH2-HY04 data for sensor 1 in the 2% drift test with a nitrogen background.

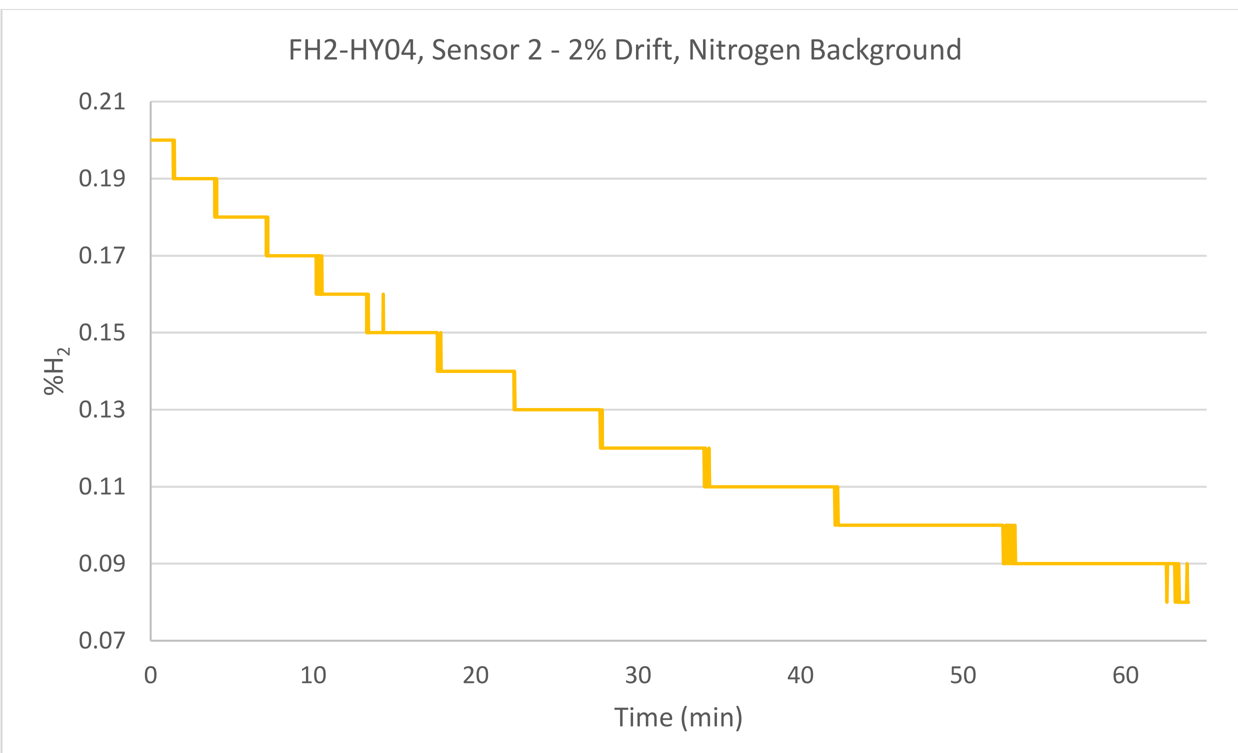

Figure 57. FH2-HY04 data for sensor 2 in the 2% drift test with a nitrogen background.

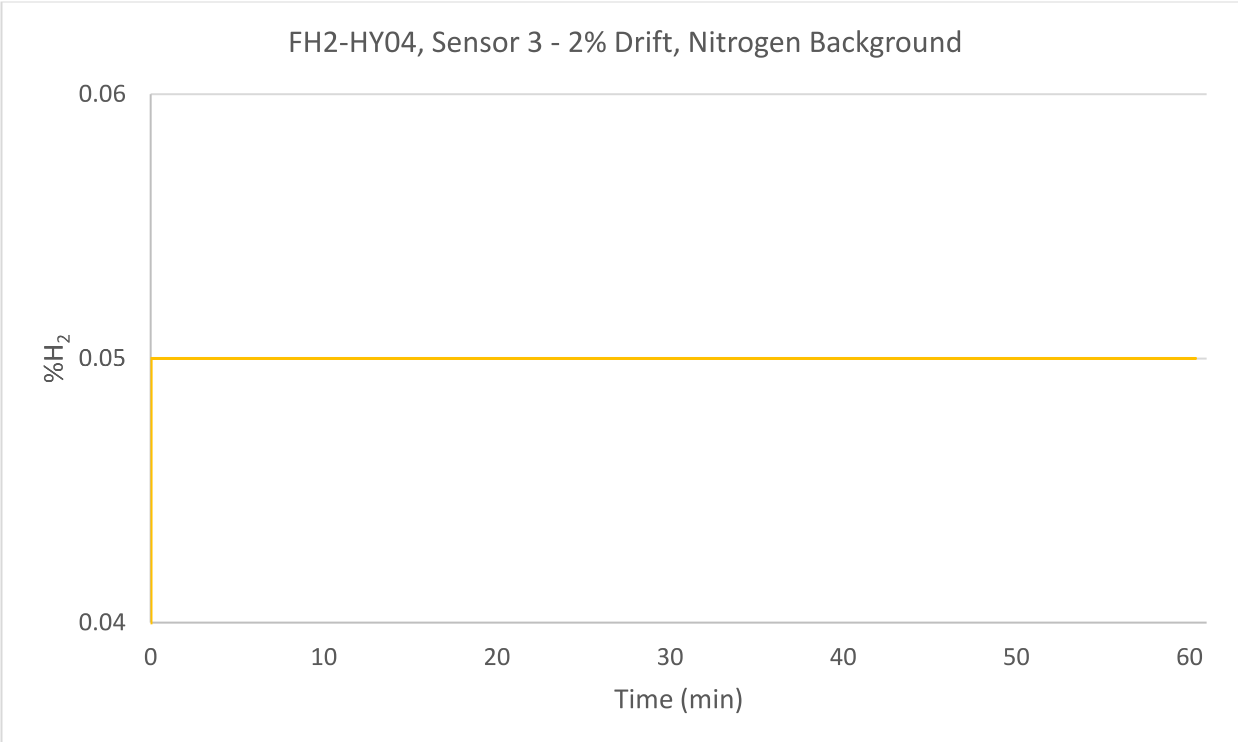

Figure 58. FH2-HY04 data for sensor 3 in the 2% drift test with a nitrogen background.

Table 6 gives the results of the 0% drift test with a background of nitrogen. The Sense H_2® and FH2-HY04 are omitted from the table because they were not functioning properly in a nitrogen background. The H2scan showed slightly more drift in a nitrogen background than in an air background, but was still fairly stable. The XEN-5320 showed almost no drift.

Table 6. 2% Drift Test Results – Nitrogen Background.

Sensor	Sensor/Run	Test Duration (min)	%H_2 Source Drift	Sensor Output Drift (%H_2)
H2scan 720B	1	40.9	0.00	0.02
	2	63.9	0.00	0.04
	3	60.3	0.00	0.02
XEN-5320	1	40.9	0.00	0.01
	2	63.9	0.00	0.01
	3	60.3	0.00	0.00

Results – 2% Drift, Helium Background

Figure 59 through Figure 62 show the data collected for each sensor during the 2% drift tests.

The H2scan continued to have similar performance with a background of helium to its performance in other gases.

As seen in previous test, the XEN-5320 could not detect hydrogen in a helium background, and the Sense H_2® and FH2-HY04 did not function anaerobically.

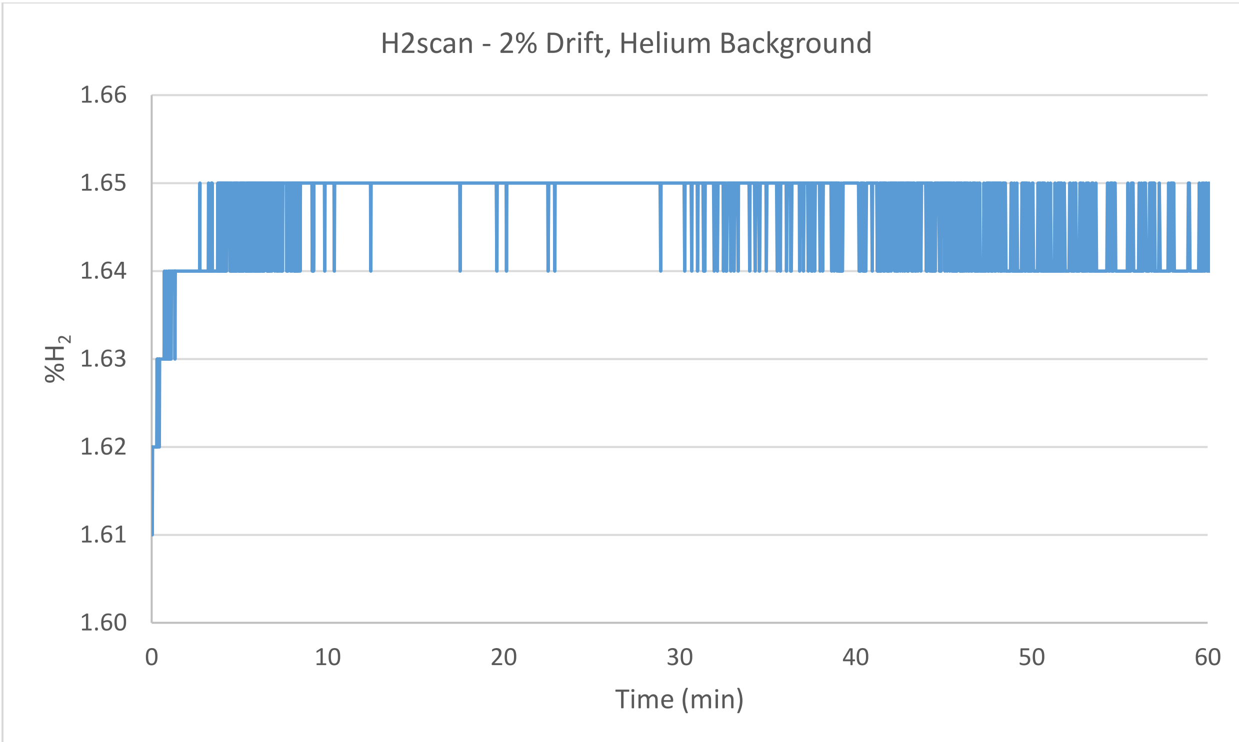

Figure 59. H2scan data for the 2% drift test with a helium background.

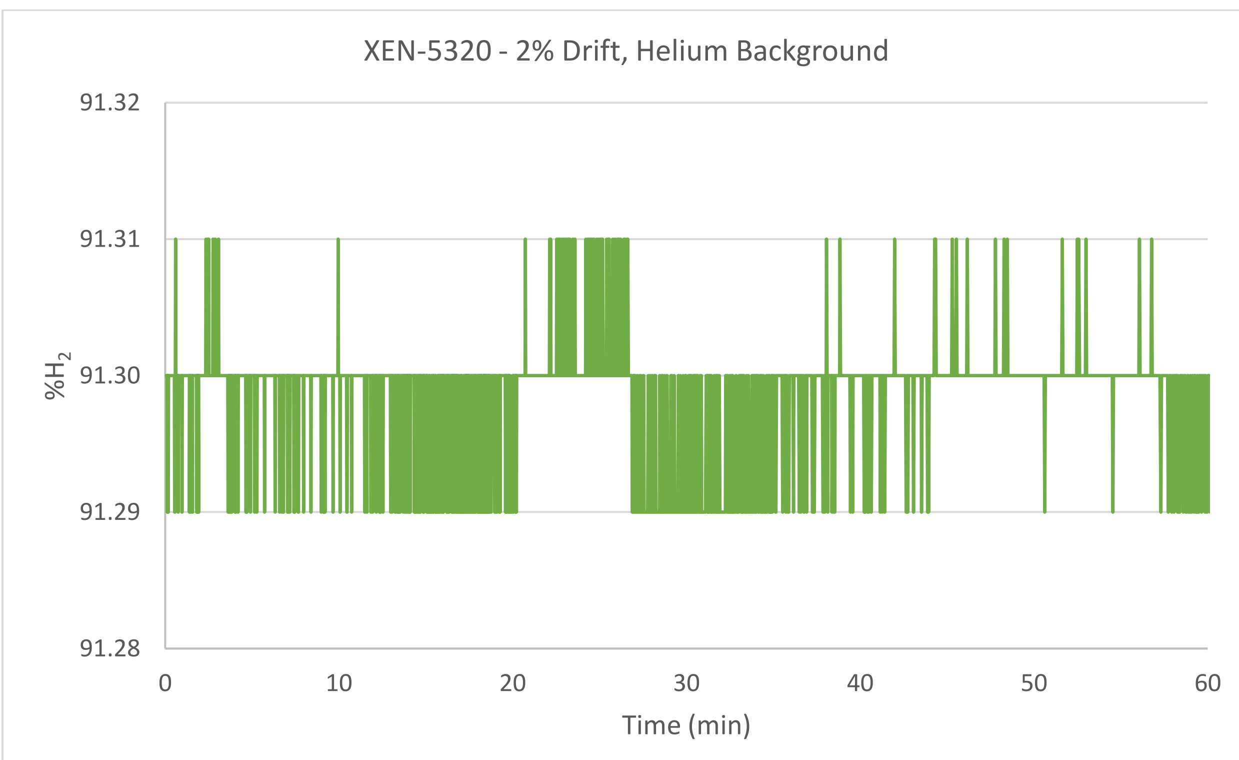

Figure 60. XEN-5320 data for the 2% drift test with a helium background.

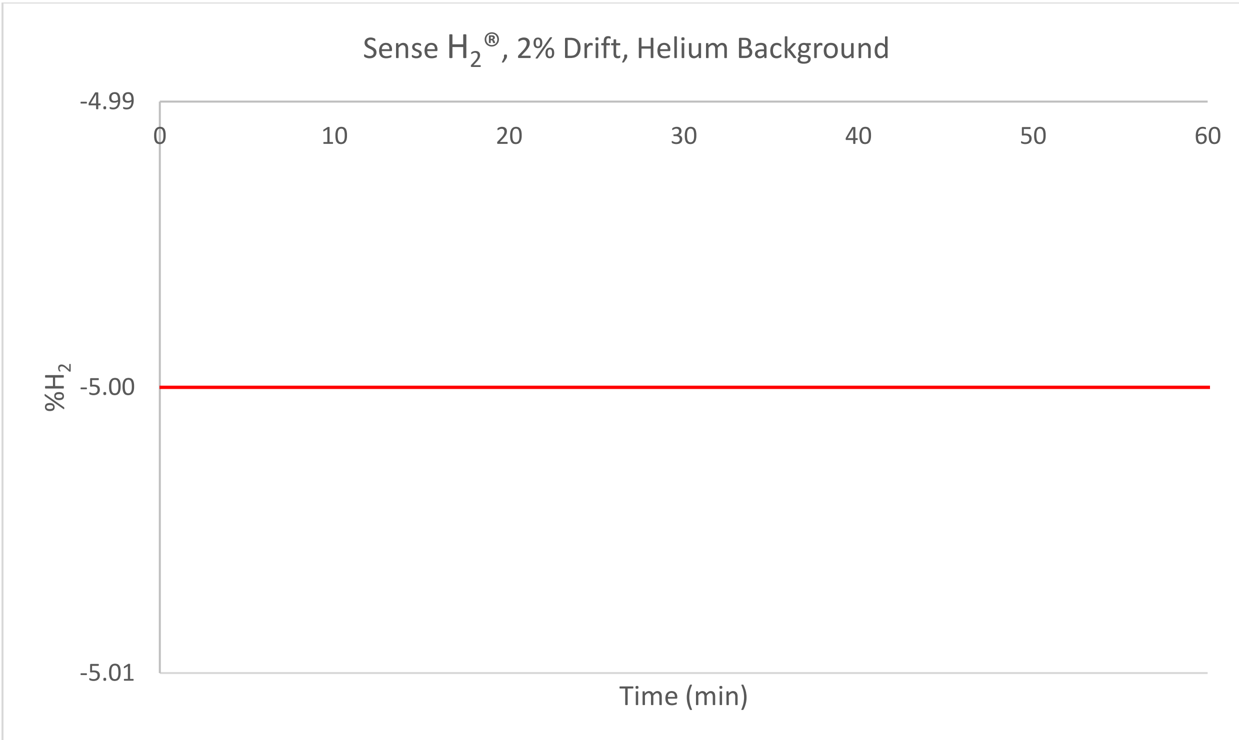

Figure 61. Sense H_2® data for the 2% drift test with a helium background.

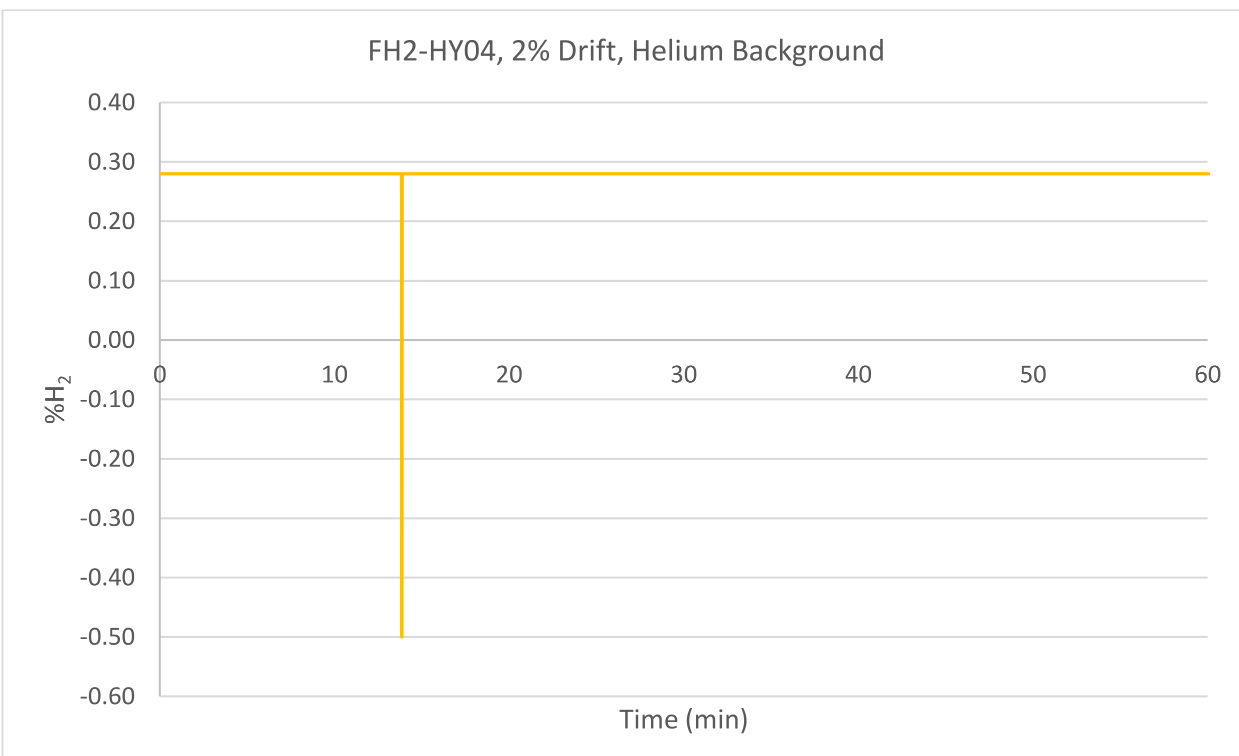

Figure 62. FH2-HY04 data for the 2% drift test with a helium background.

Table 7 gives the results of the 0% drift test with a background of helium. Because only the H2scan was functioning properly in a helium background, the other sensors are omitted from the table. In a helium background, the H2scan had no drift in this test.

Table 7. 2% Drift Test Results – Helium Background.

Sensor	Test Duration (min)	% H_2 Source Drift	Sensor Output Drift (% H_2)
H2scan 720B	60.2	0.00	0.00

Lower Detectable Limit

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

Procedure – LDL for Increasing Gas Concentrations

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

Procedure – LDL for Decreasing Gas Concentrations

1. Connect hydrogen gas mixture and appropriate (matching) background gas to the test system.
2. Power on hydrogen sensors.
3. Allow appropriate warm-up time, per manufacturer specification, prior to continuing.
4. Begin data collection.
5. Begin flow of hydrogen gas mixture and appropriate (matching) background gas, setting gas flows for a concentration of ~1% hydrogen (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 hydrogen concentration).
7. Adjust gas flows, decreasing the hydrogen concentration in the smallest interval available.
8. Allow outputs to stabilize.
9. Repeat the process of decreasing the hydrogen concentration until all sensors have stopped responding or the minimum hydrogen concentration possible has been reached.

Determining LDL

The LDL is determined by evaluating the data collected. For each sensor, the lowest concentration of hydrogen 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 hydrogen possible for each LDL test varied from 0.05% H_2 to 0.08% H_2, depending on the test. Increments of 0.01% hydrogen were used whenever possible. Due to MFC constraints, some steps were larger at the lowest concentrations.

Figure 63 through Figure 94 show the data collected during these tests, with all data for increasing hydrogen concentration tests first, followed by data for decreasing hydrogen concentration tests.

The H2scan was responsive to the small changes in gas concentrations above its LDL. In each test, its LDL was around 0.5% H_2, which is higher than the 0.4% H_2 specified by the manufacturer, but that could change following calibration.

Both the XEN-5320 and the FH2-HY04 responded to all hydrogen concentration changes, with the exception of one test in which the FH2-HY04 responded beginning at 0.08% H_2.

With increasing concentrations of hydrogen, the Sense H_2® began responding around 0.15% with one sensor, but did not respond until higher concentrations (above the manufacturer's claim of 0.25%) for the other two sensors. For decreasing hydrogen concentrations, this sensor had more consistent levels at which it stopped responding, all below the manufacturer's specified minimum level.

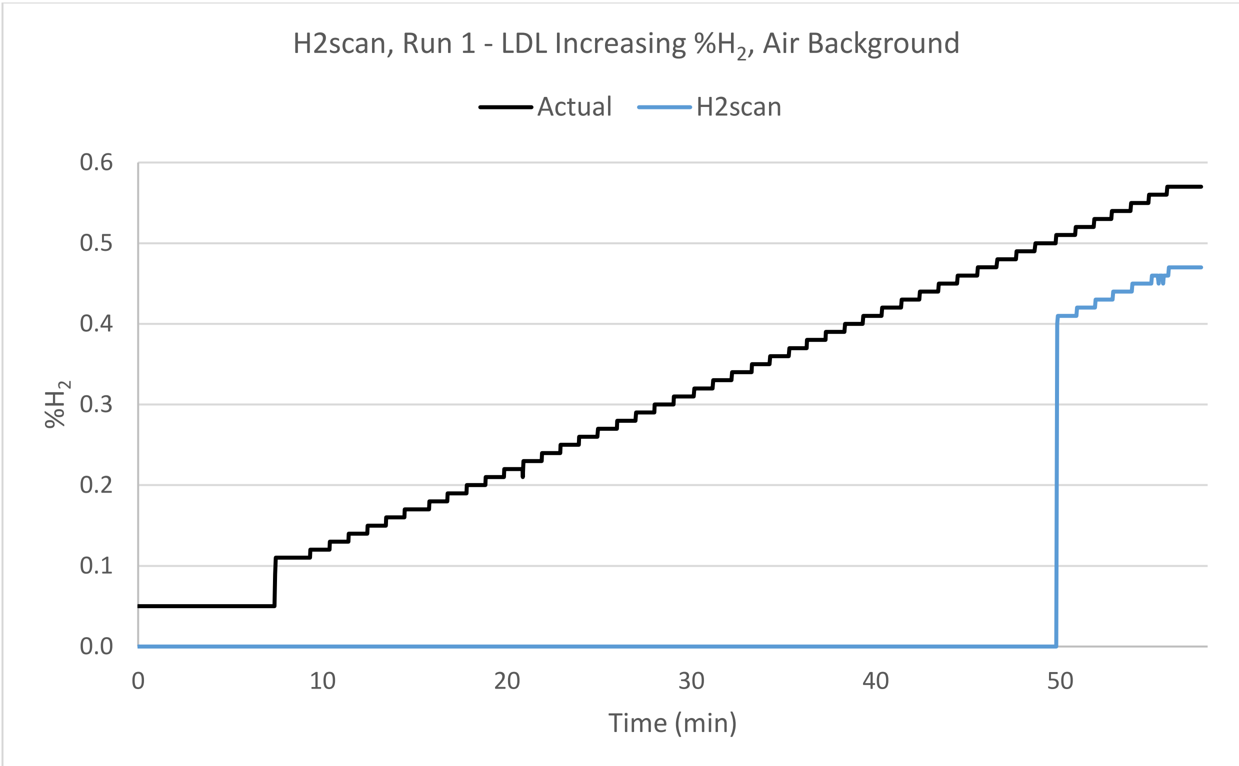

Figure 63. H2scan data for run 1 of the LDL test with increasing $\%H_2$ in an air background.

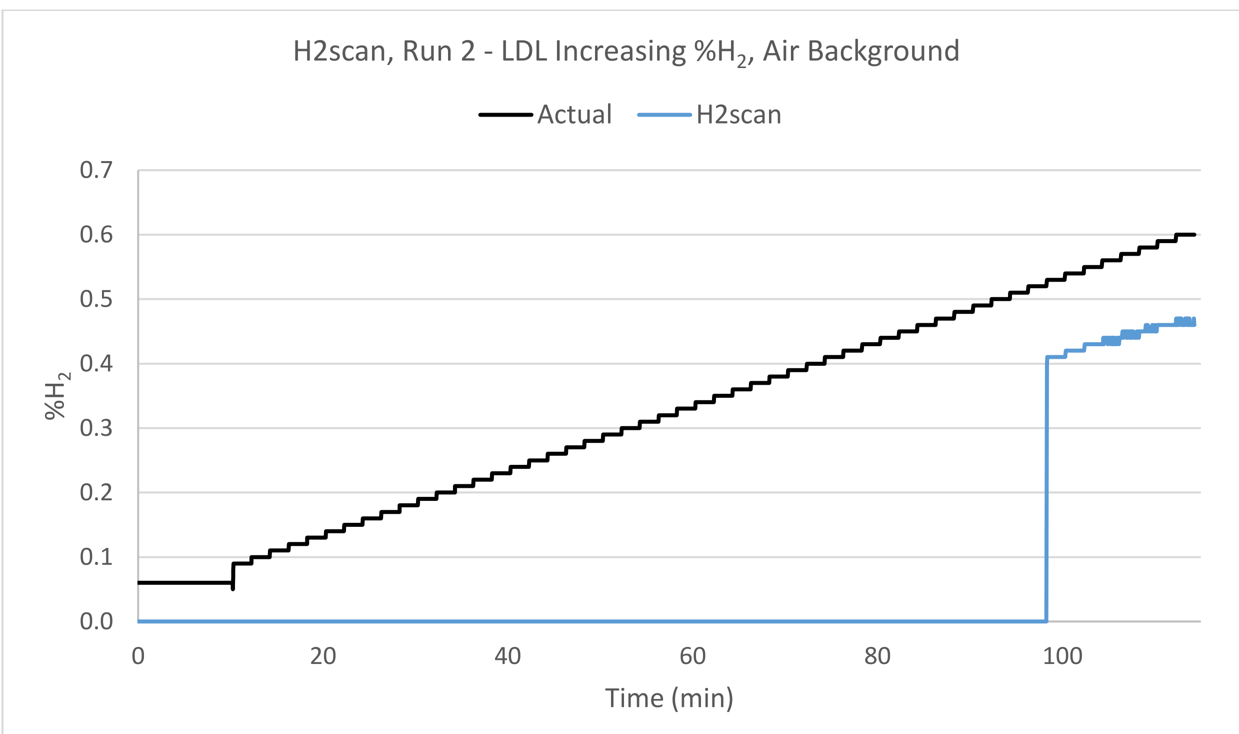

Figure 64. H2scan data for run 2 of the LDL test with increasing $\%H_2$ in an air background.

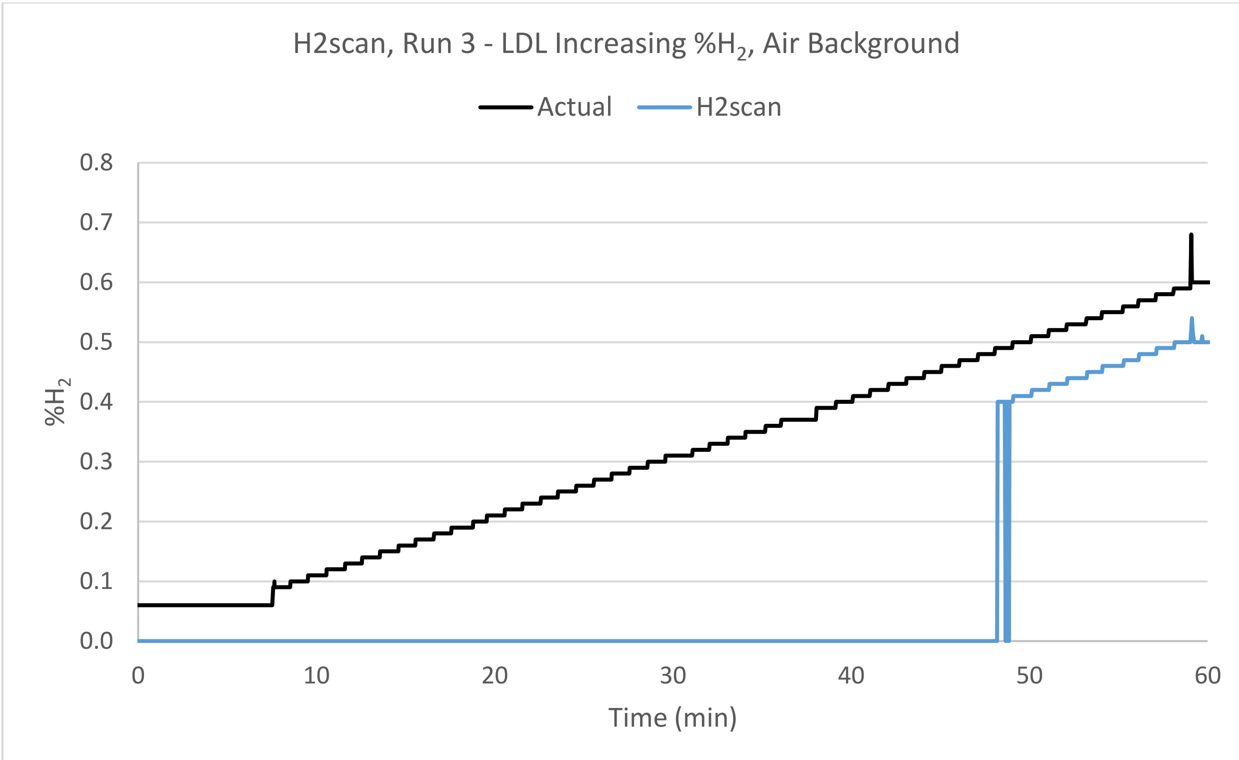

Figure 65. H2scan data for run 3 of the LDL test with increasing $\%H_2$ in an air background.

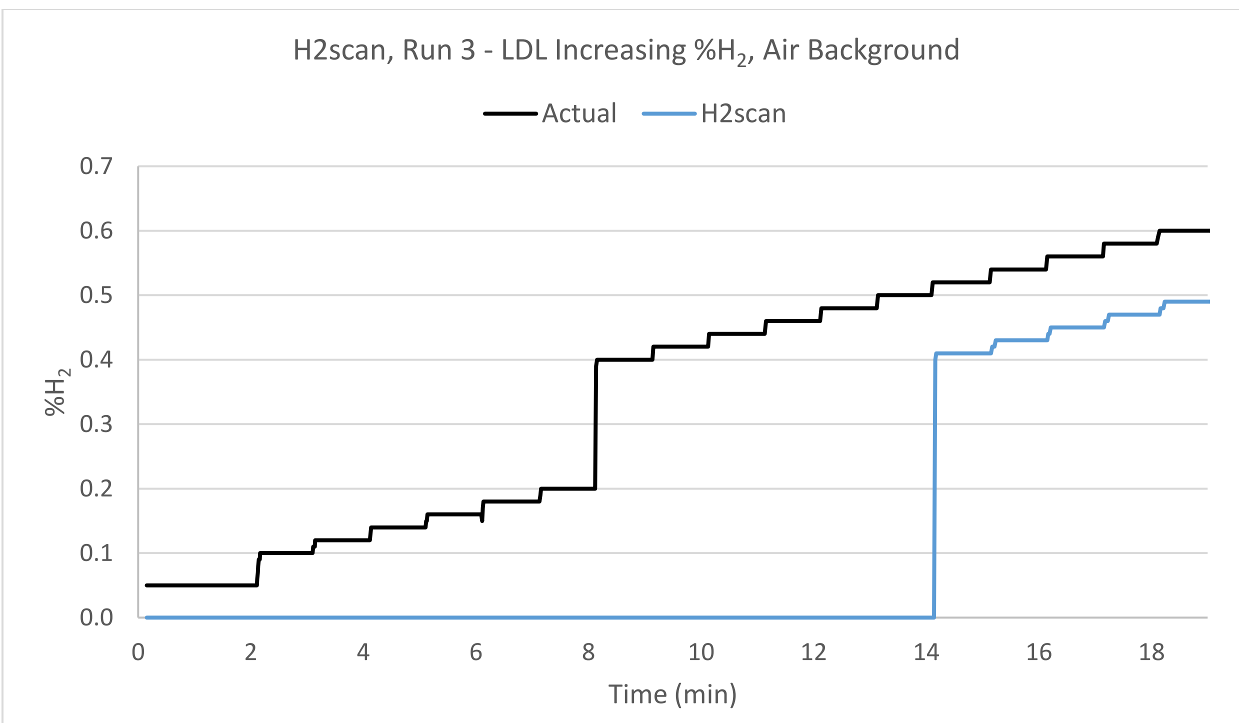

Figure 66. H2scan data for run 4 of the LDL test with increasing $\%H_2$ in an air background.

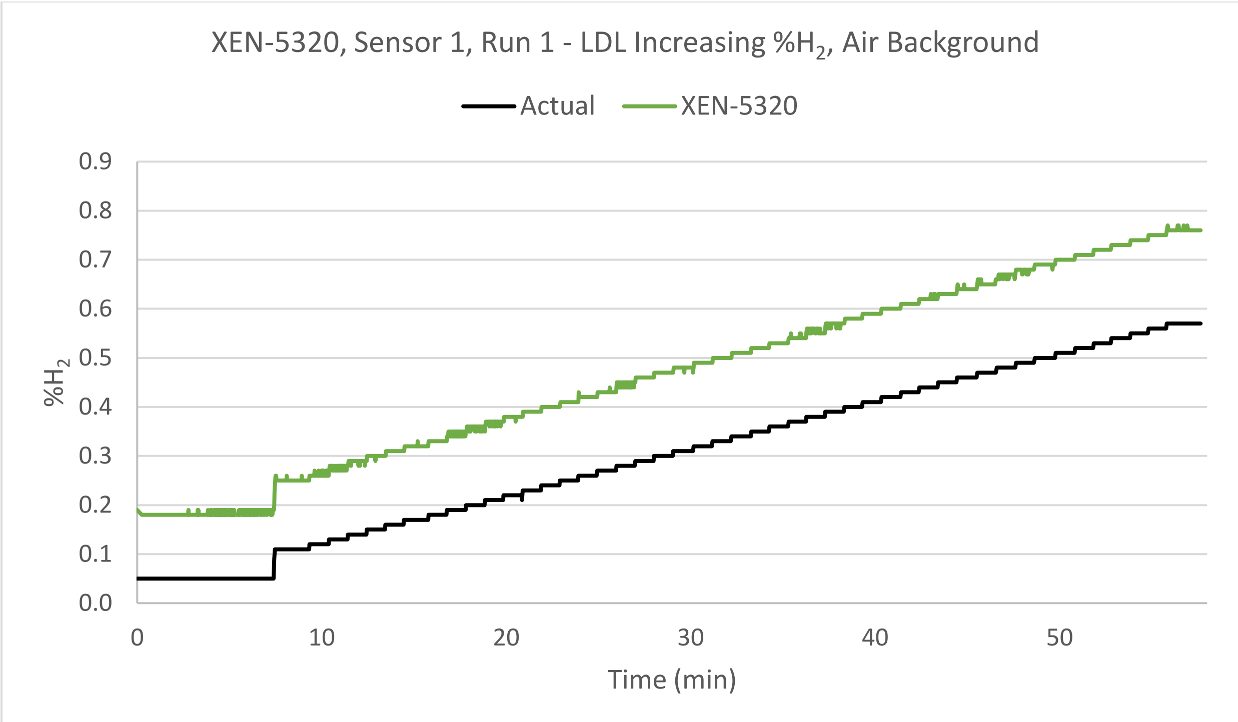

Figure 67. XEN-5320 data for sensor 1, run 1 of the LDL test with increasing $\%H_2$ in an air background.

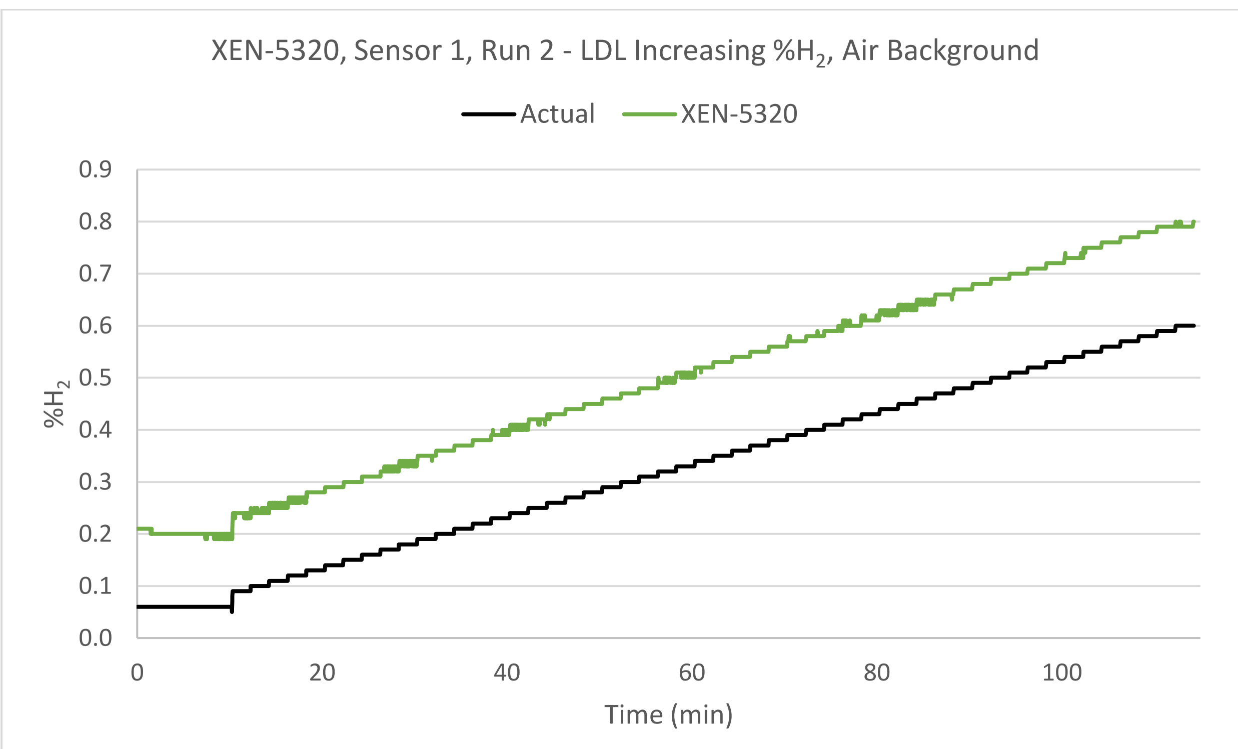

Figure 68. XEN-5320 data for sensor 1, run 2 of the LDL test with increasing $\%H_2$ in an air background.

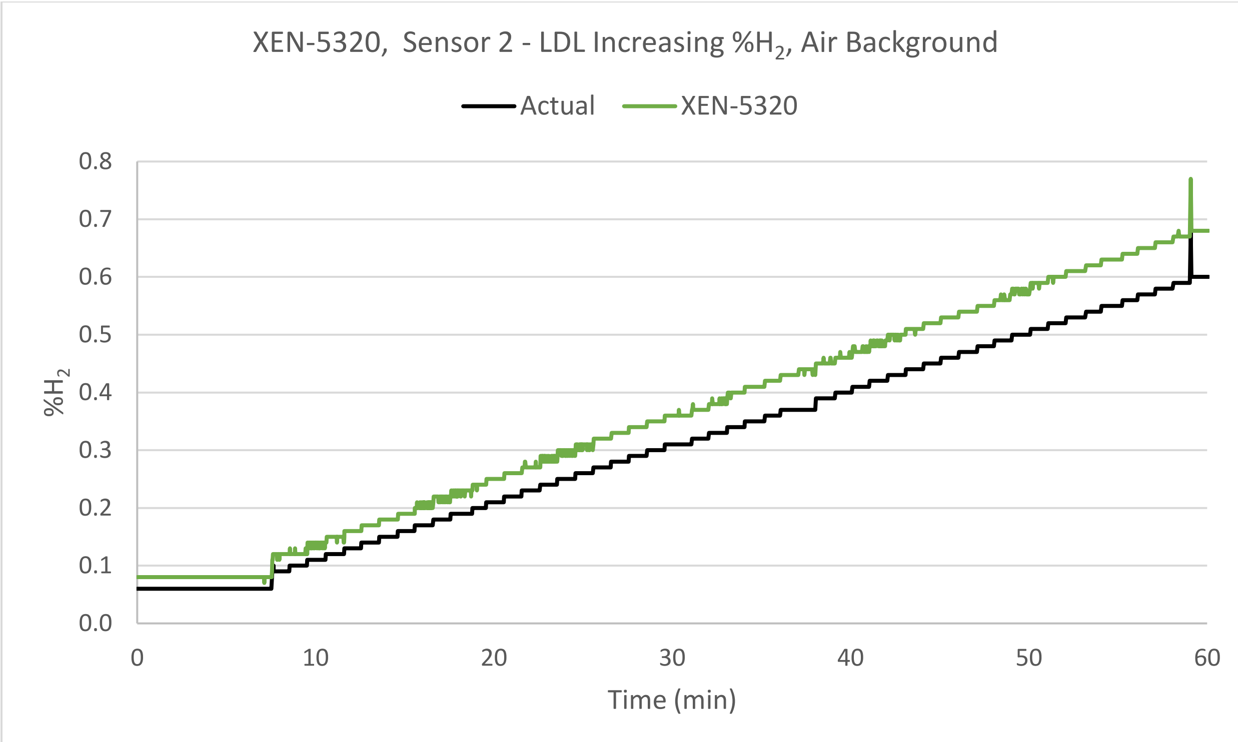

Figure 69. XEN-5320 data for sensor 2 of the LDL test with increasing $\%H_2$ in an air background.

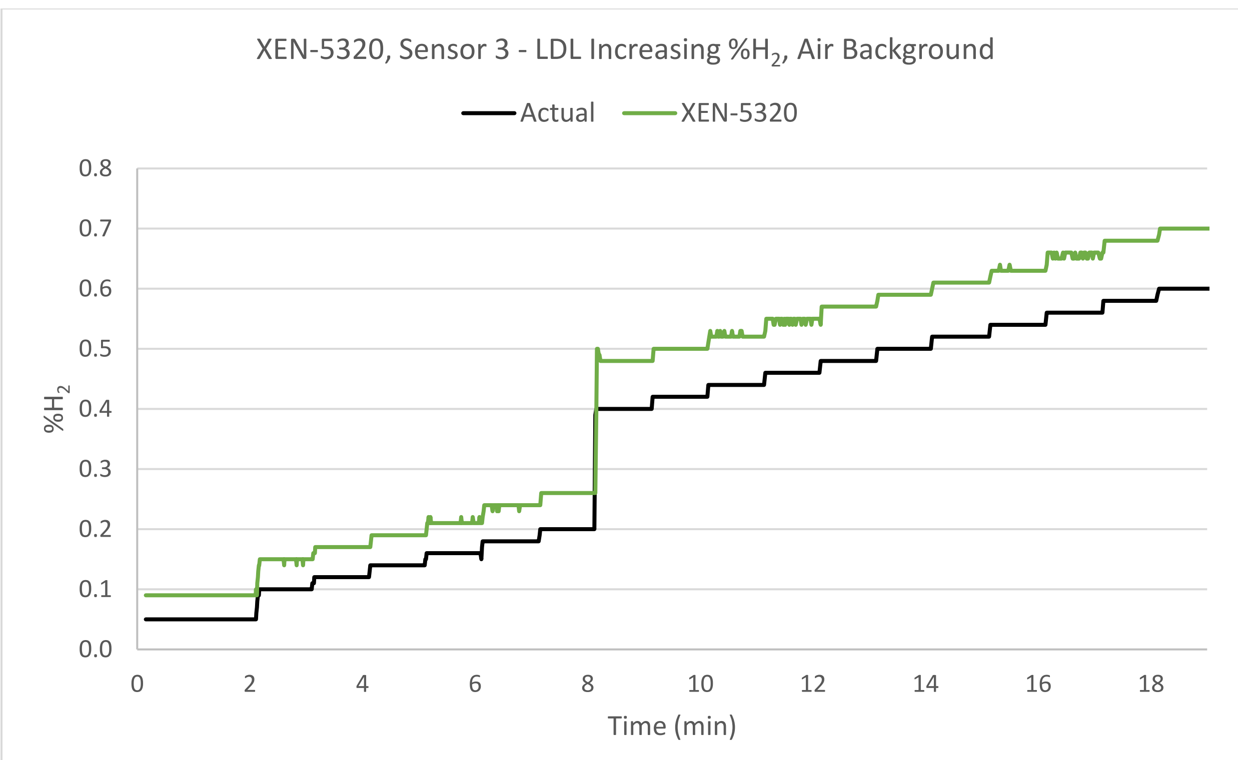

Figure 70. XEN-5320 data for sensor 3 of the LDL test with increasing $\%H_2$ in an air background.

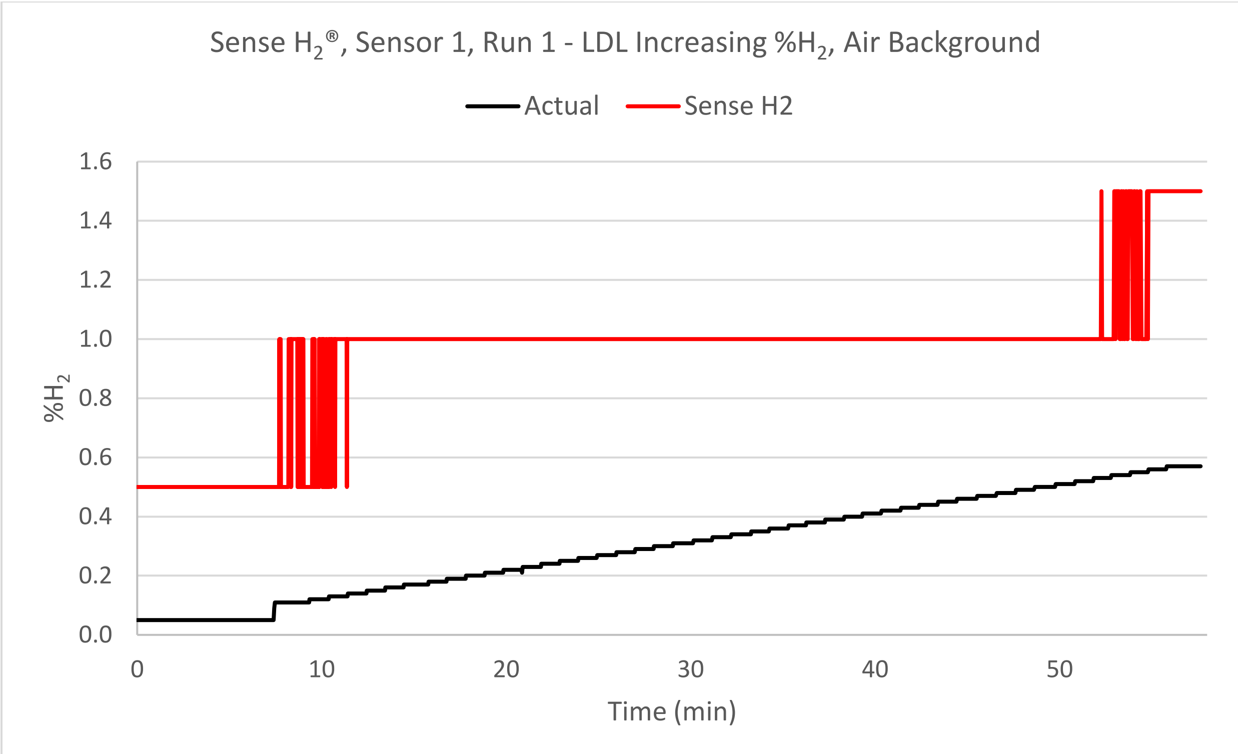

Figure 71. Sense H_2® data for sensor 1, run 1 of the LDL test with increasing $\%H_2$ in an air background.

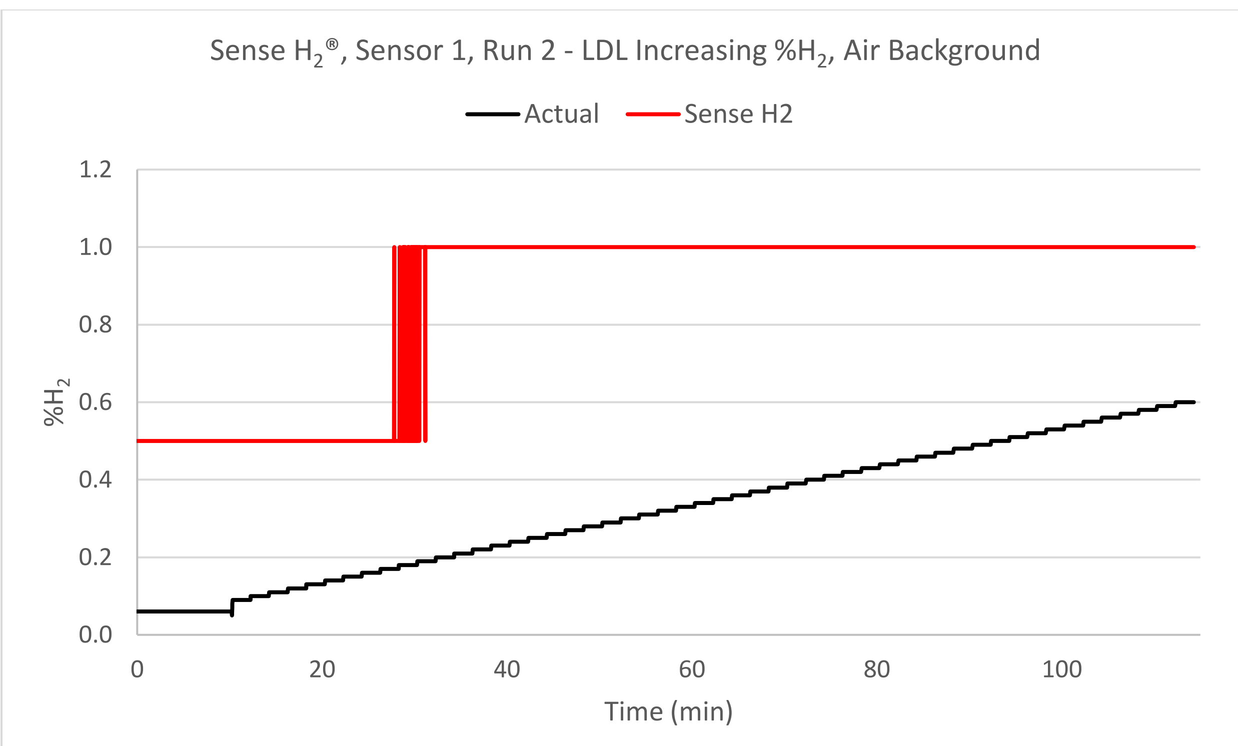

Figure 72. Sense H_2® data for sensor 1, run 2 of the LDL test with increasing $\%H_2$ in an air background.

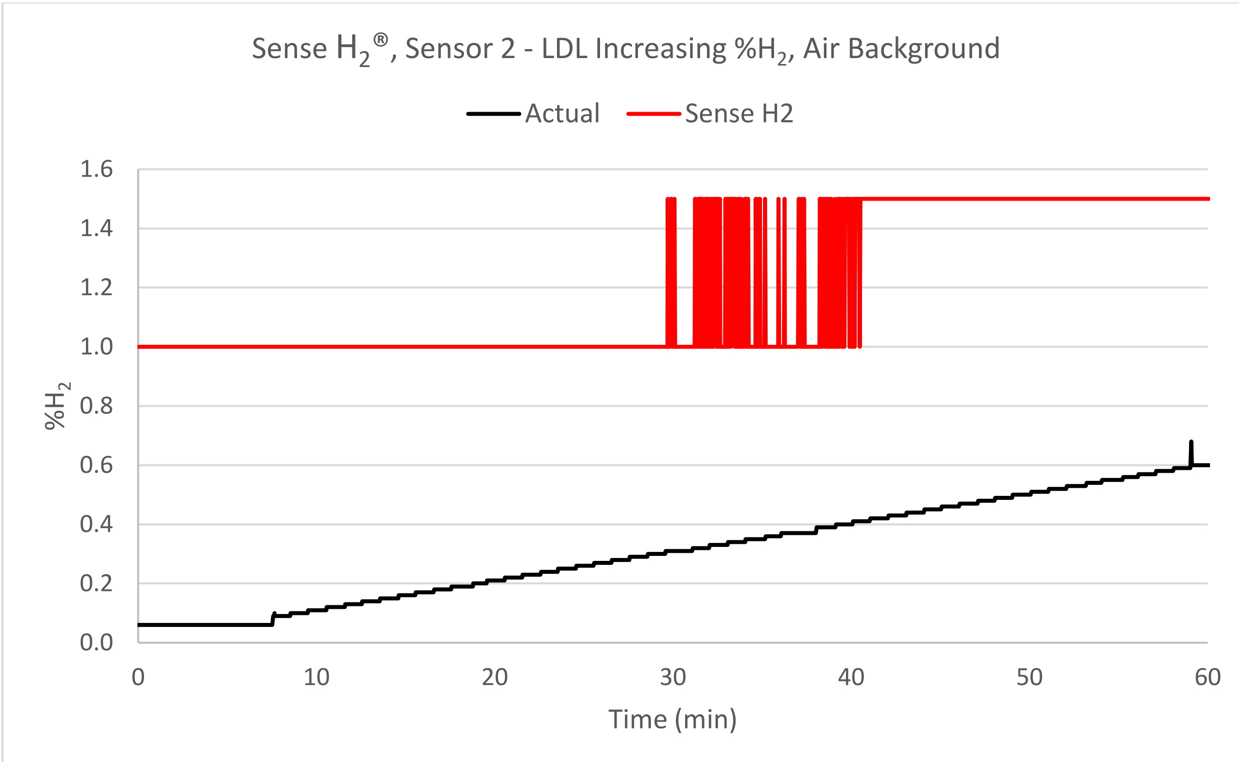

Figure 73. Sense H_2® data for sensor 2 of the LDL test with increasing $\%H_2$ in an air background.

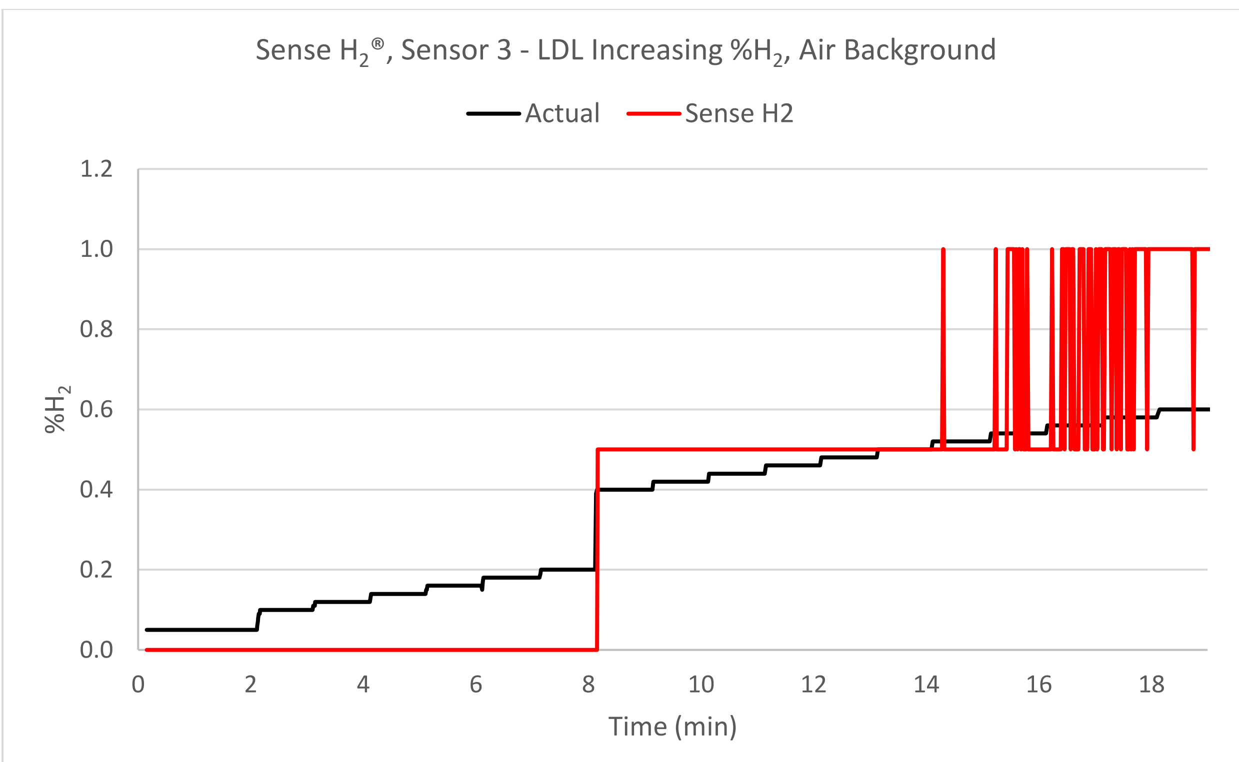

Figure 74. Sense H_2® data for sensor 3 of the LDL test with increasing $\%H_2$ in an air background.

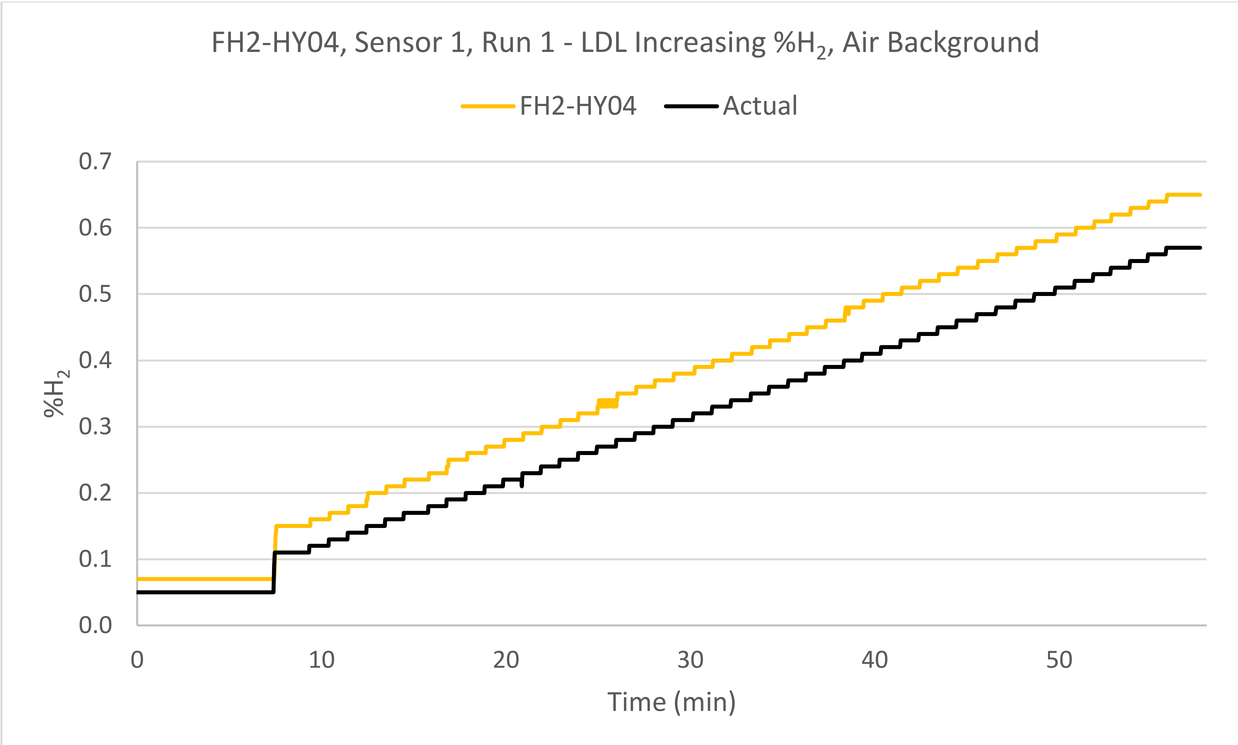

Figure 75. FH2-HY04 data for sensor 1, run 1 of the LDL test with increasing $\%H_2$ in an air background.

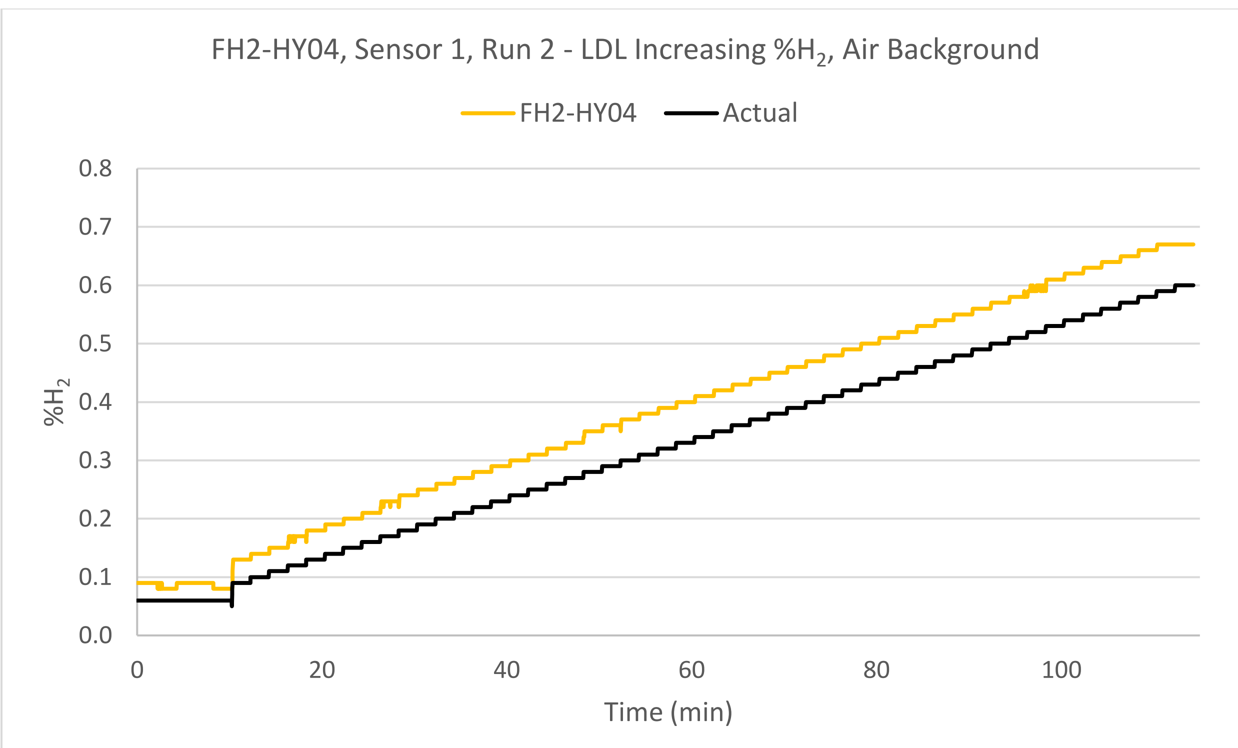

Figure 76. FH2-HY04 data for sensor 1, run 2 of the LDL test with increasing $\%H_2$ in an air background.

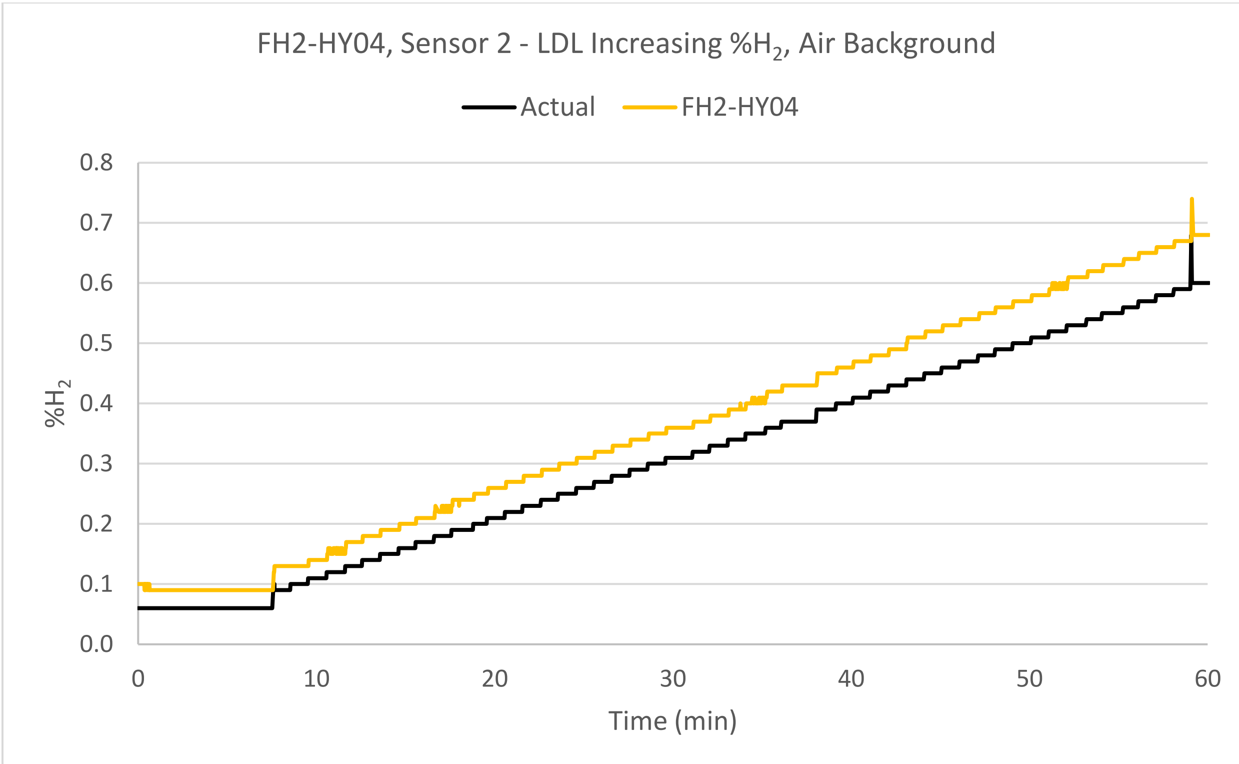

Figure 77. FH2-HY04 data for sensor 2 of the LDL test with increasing $\%H_2$ in an air background.

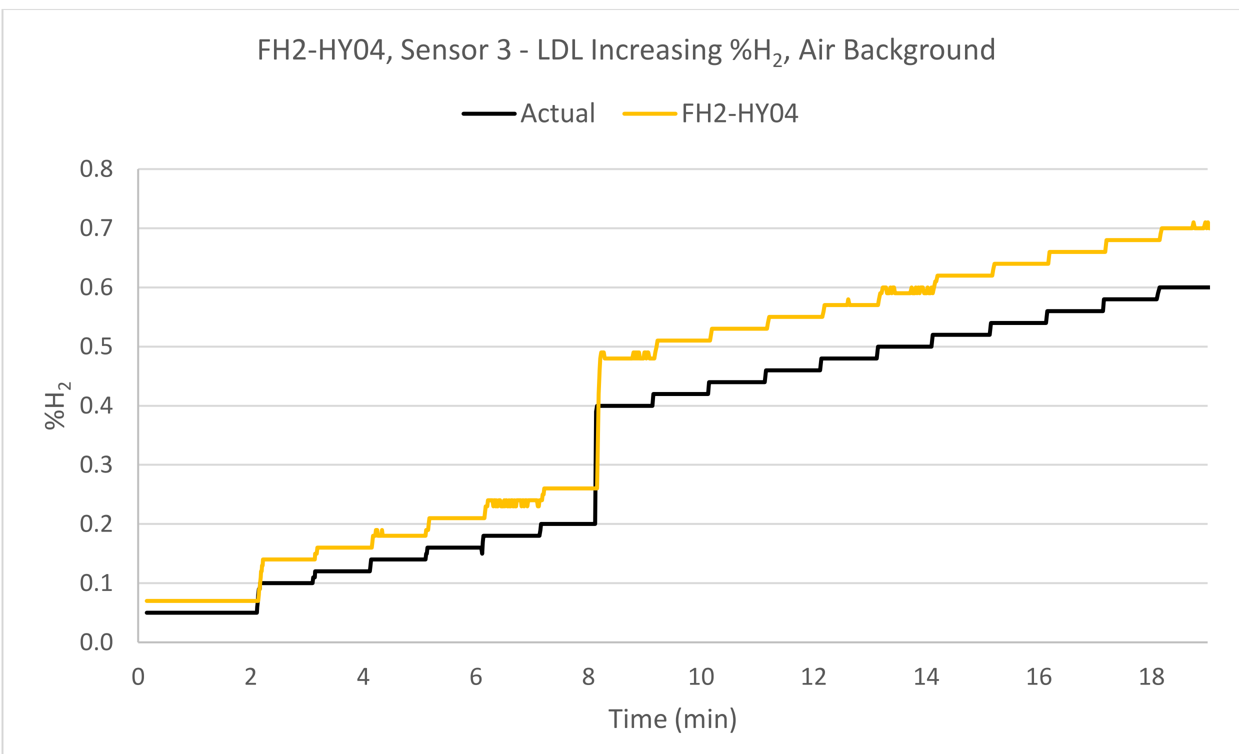

Figure 78. FH2-HY04 data for sensor 3 of the LDL test with increasing $\%H_2$ in an air background.

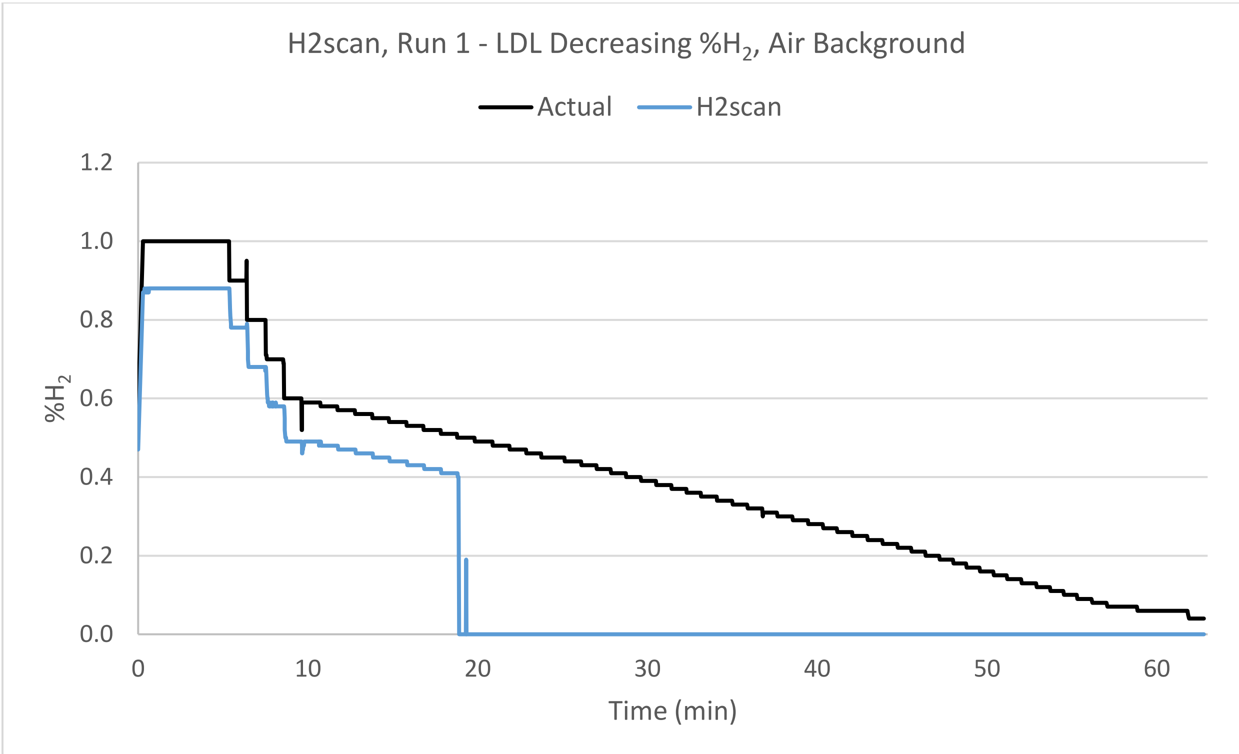

Figure 79. H2scan data for run 1 of the LDL test with decreasing $\%H_2$ in an air background.

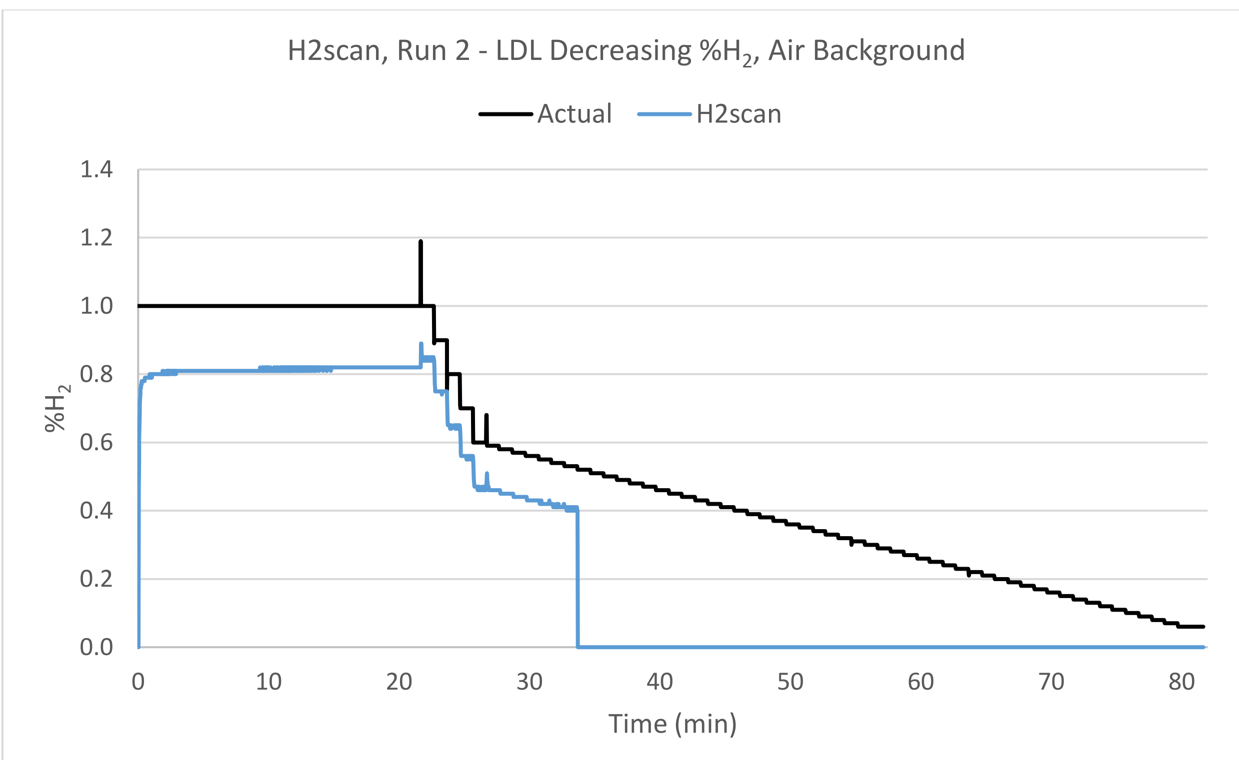

Figure 80. H2scan data for run 2 of the LDL test with decreasing $\%H_2$ in an air background.

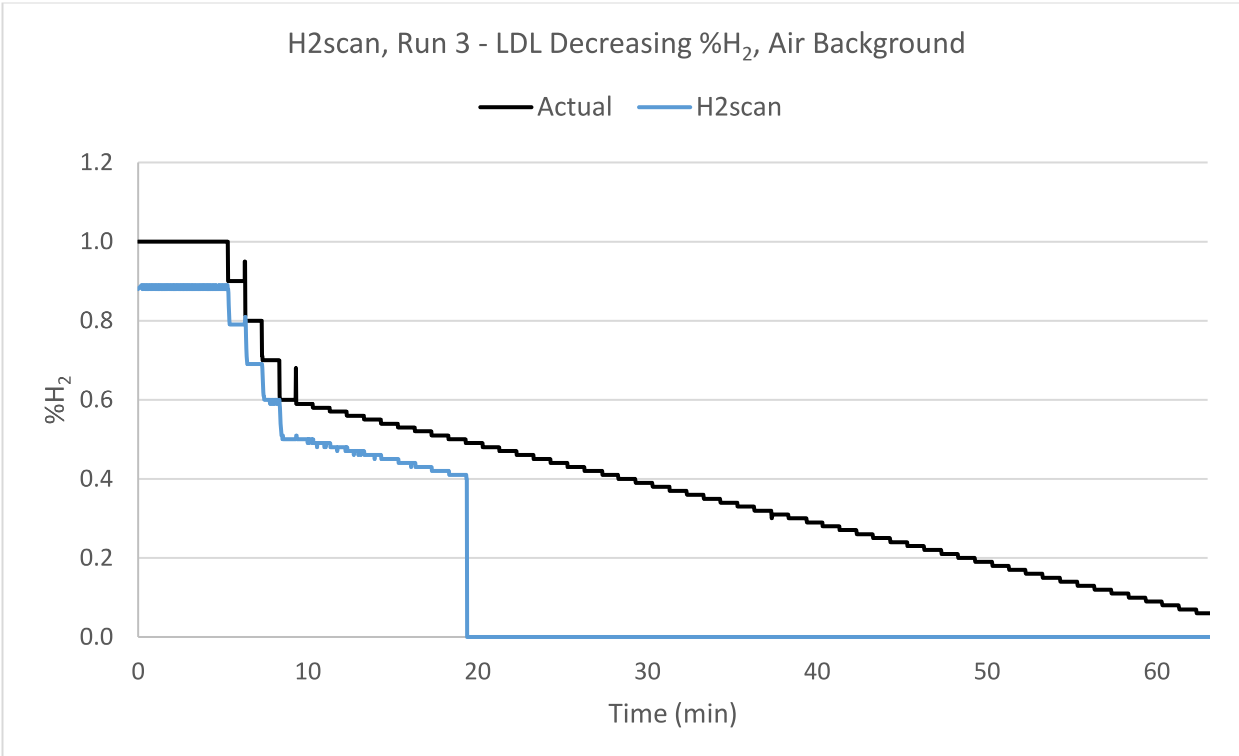

Figure 81. H2scan data for run 3 of the LDL test with decreasing $\%H_2$ in an air background.

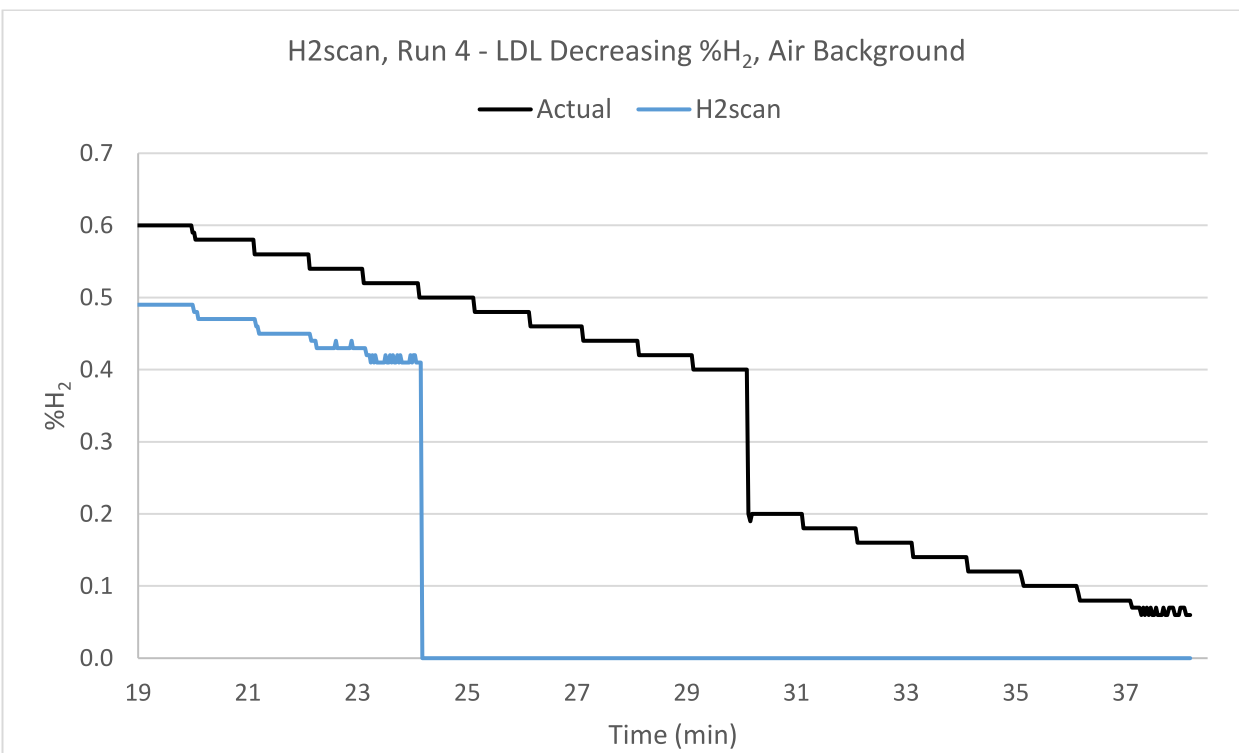

Figure 82. H2scan data for run 4 of the LDL test with decreasing $\%H_2$ in an air background.

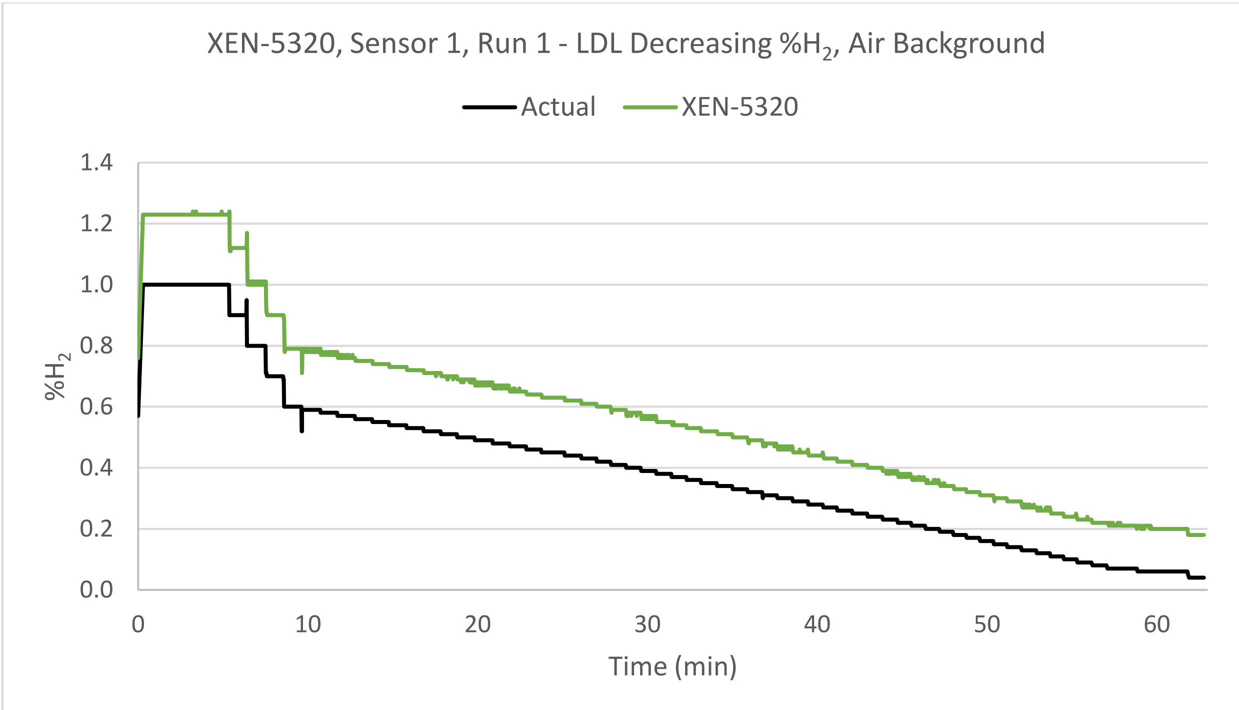

Figure 83. XEN-5320 data for sensor 1, run 1 of the LDL test with decreasing $\%H_2$ in an air background.

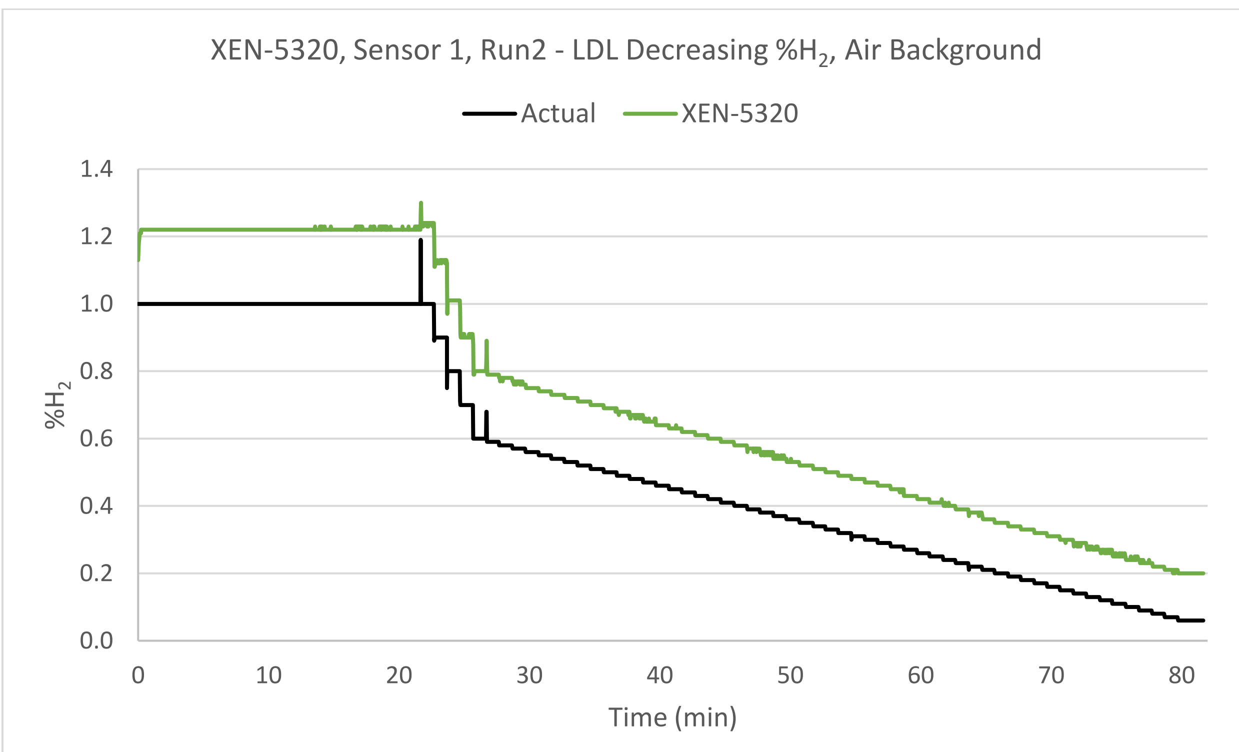

Figure 84. XEN-5320 data for sensor 1, run 2 of the LDL test with decreasing $\%H_2$ in an air background.

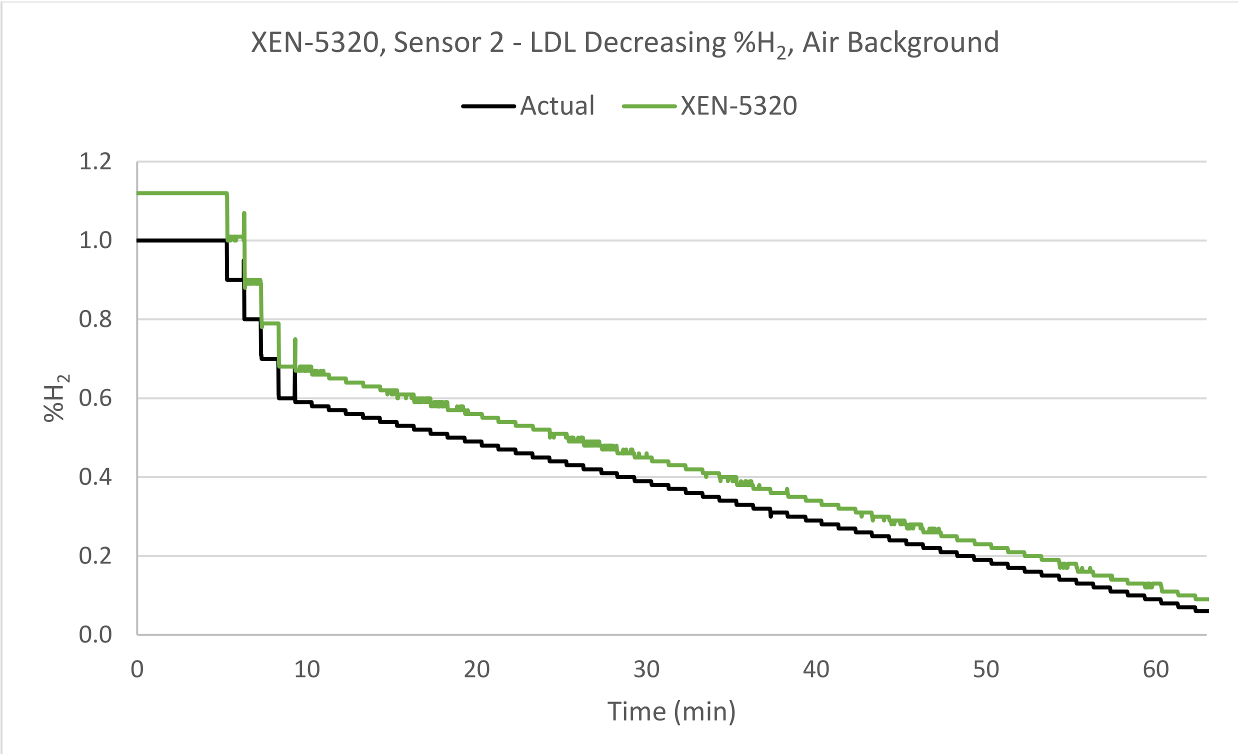

Figure 85. XEN-5320 data for sensor 2 of the LDL test with decreasing $\%H_2$ in an air background.

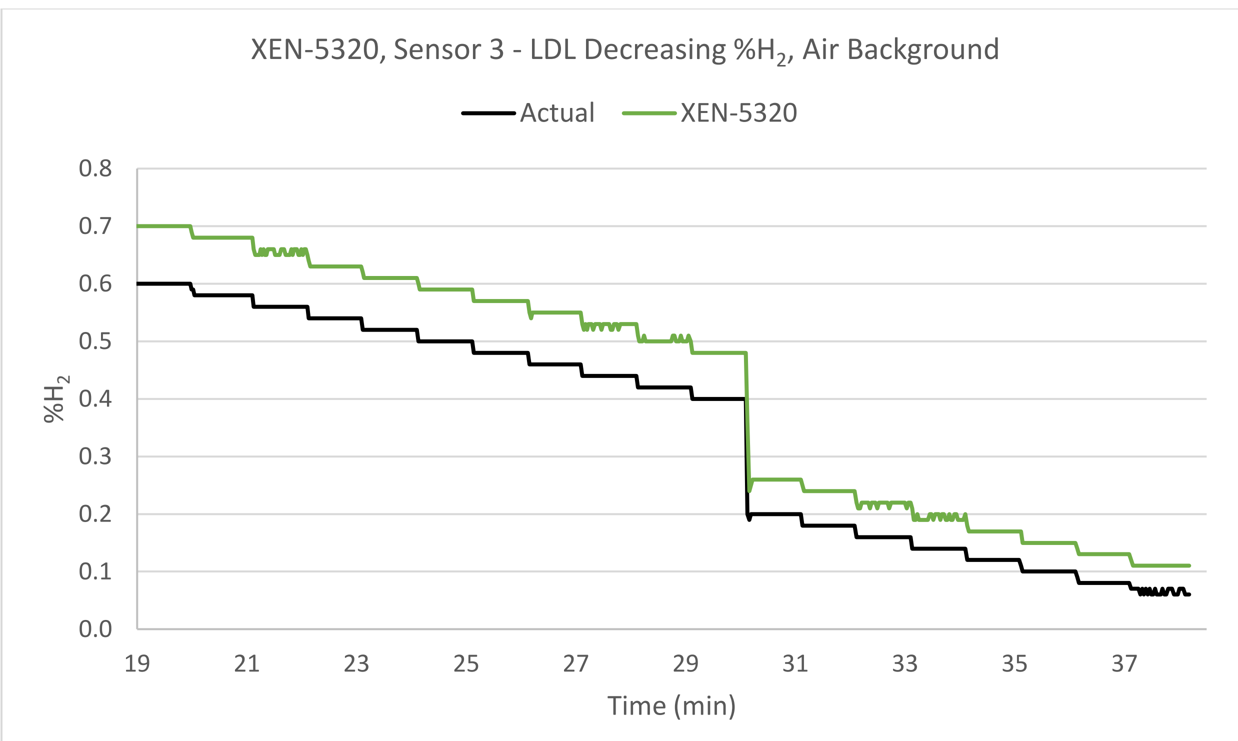

Figure 86. XEN-5320 data for sensor 3 of the LDL test with decreasing $\%H_2$ in an air background.

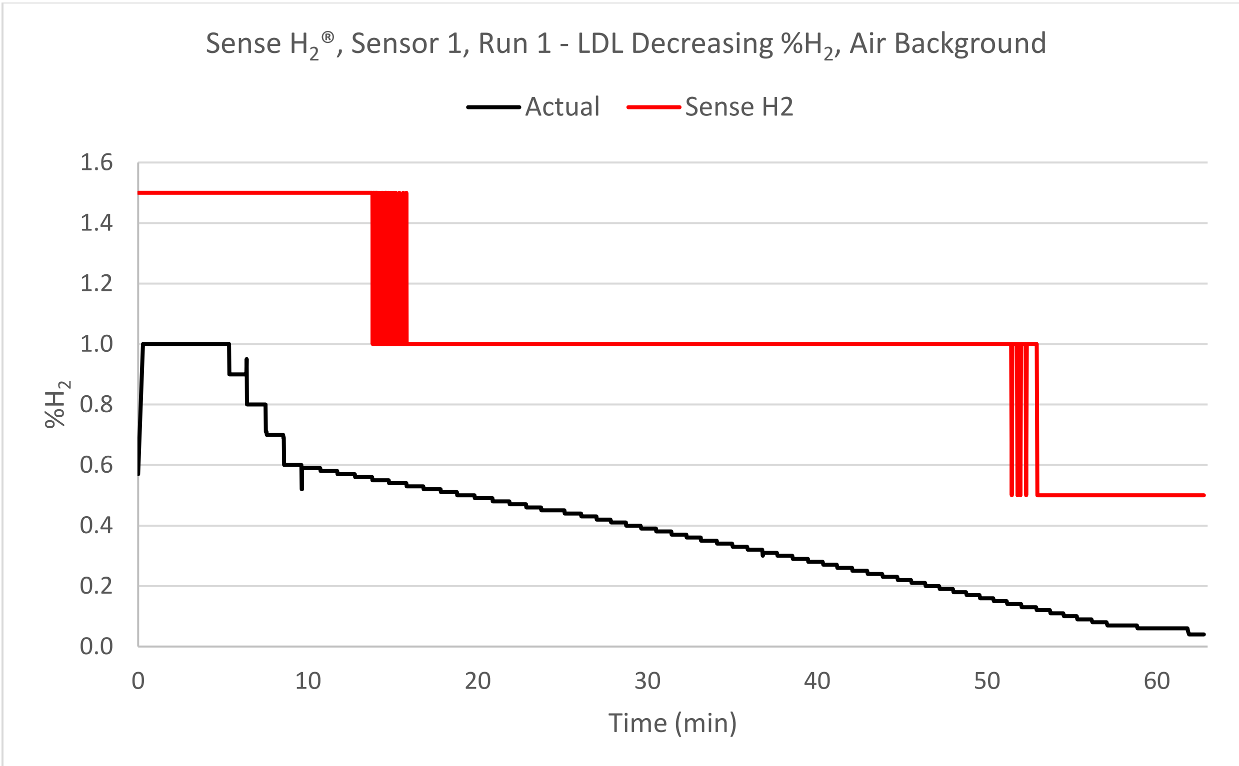

Figure 87. Sense H_2® data for sensor 1, run 1 of the LDL test with decreasing % H_2 in an air background.

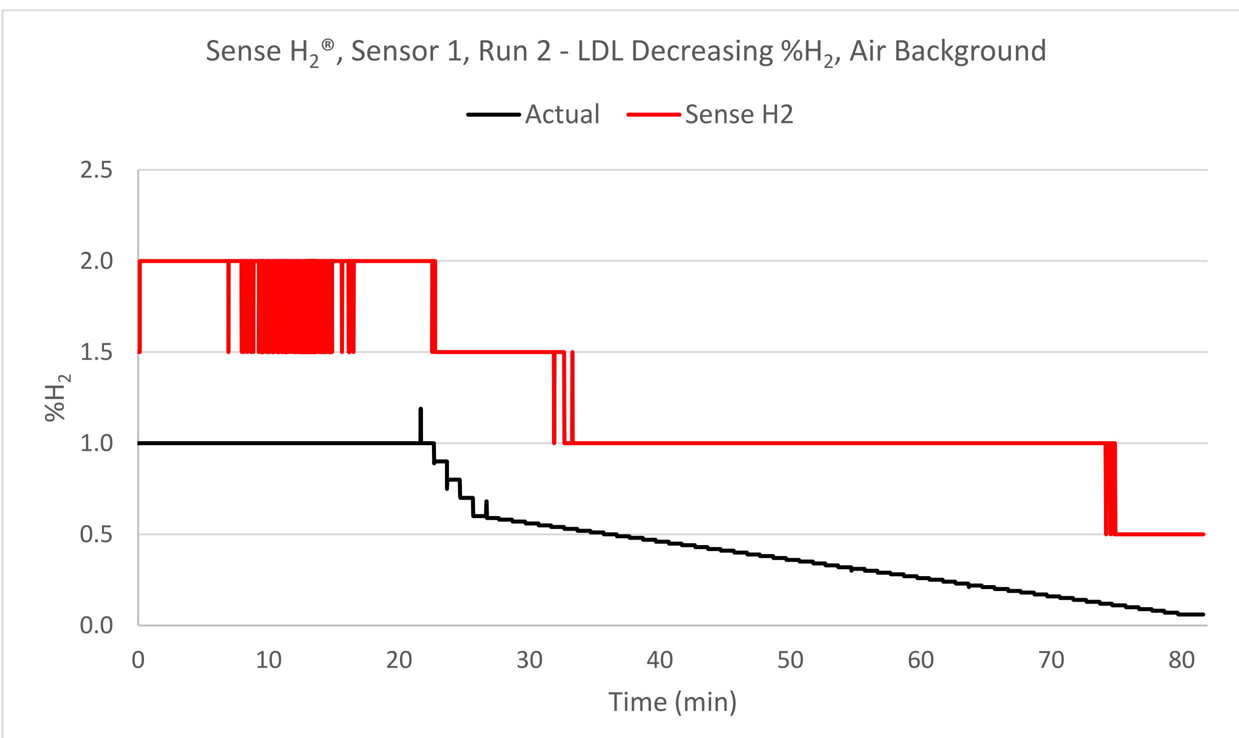

Figure 88. Sense H_2® data for sensor 1, run 2 of the LDL test with decreasing % H_2 in an air background.

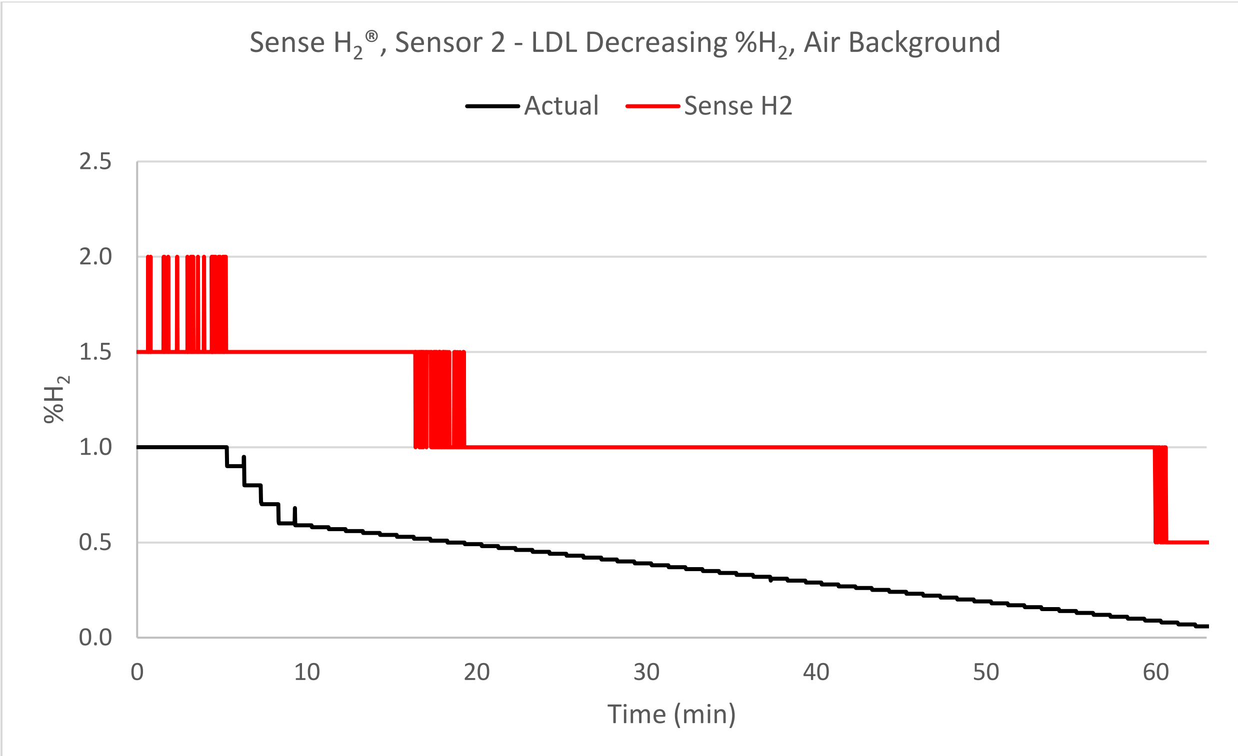

Figure 89. Sense H_2® data for sensor 2 of the LDL test with decreasing %H_2 in an air background.

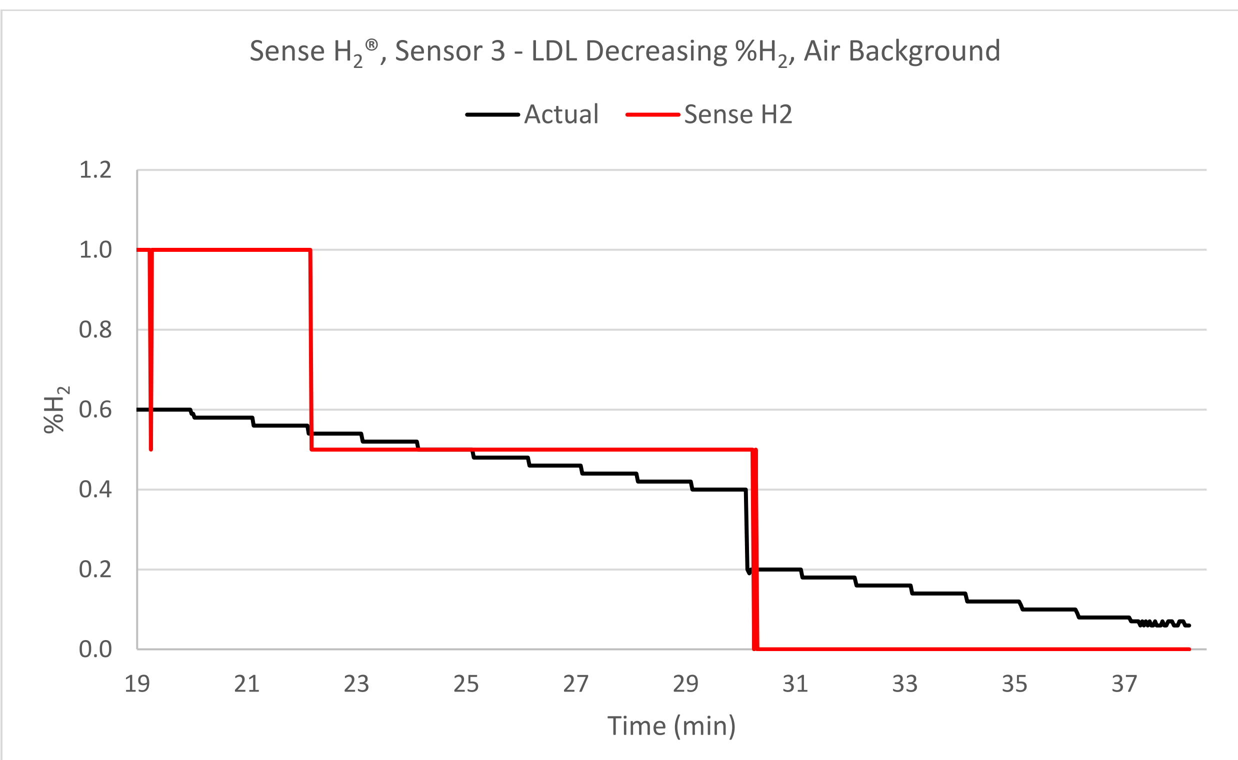

Figure 90. Sense H_2® data for sensor 3 of the LDL test with decreasing %H_2 in an air background.

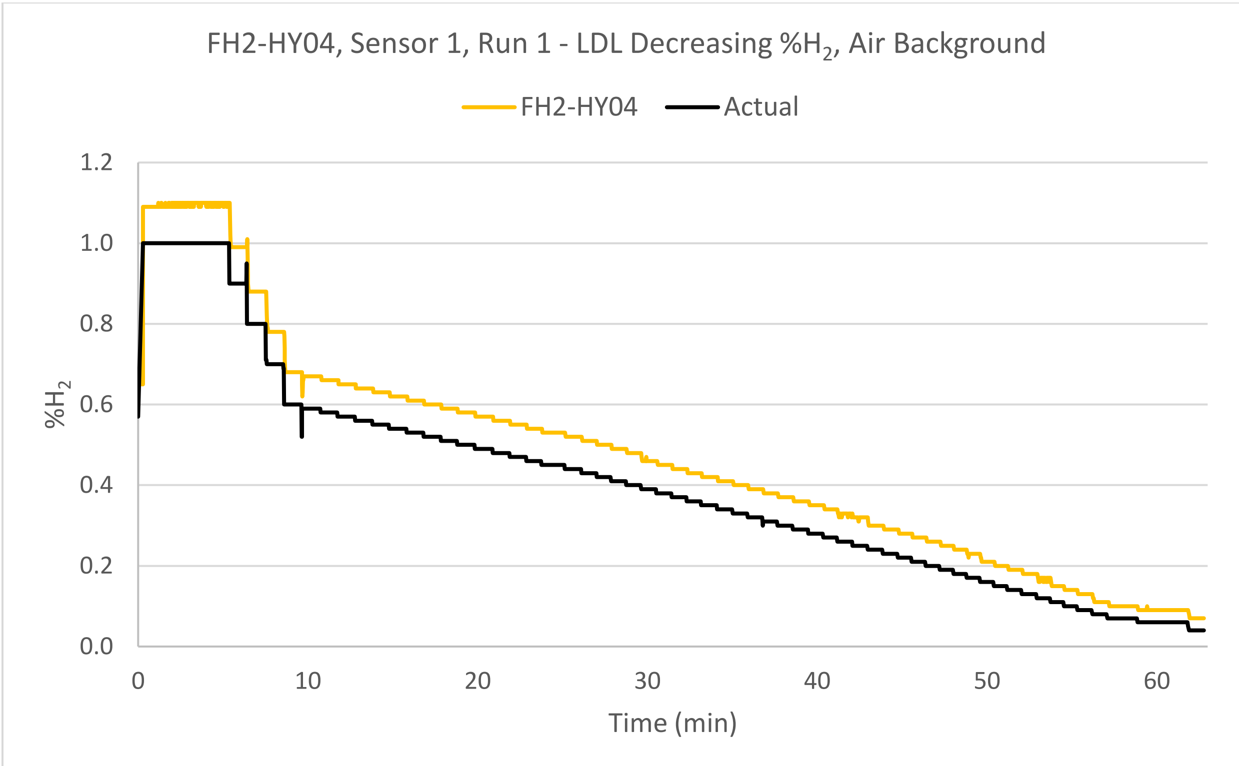

Figure 91. FH2-HY04 data for sensor 1, run 1 of the LDL test with decreasing $\%H_2$ in an air background.

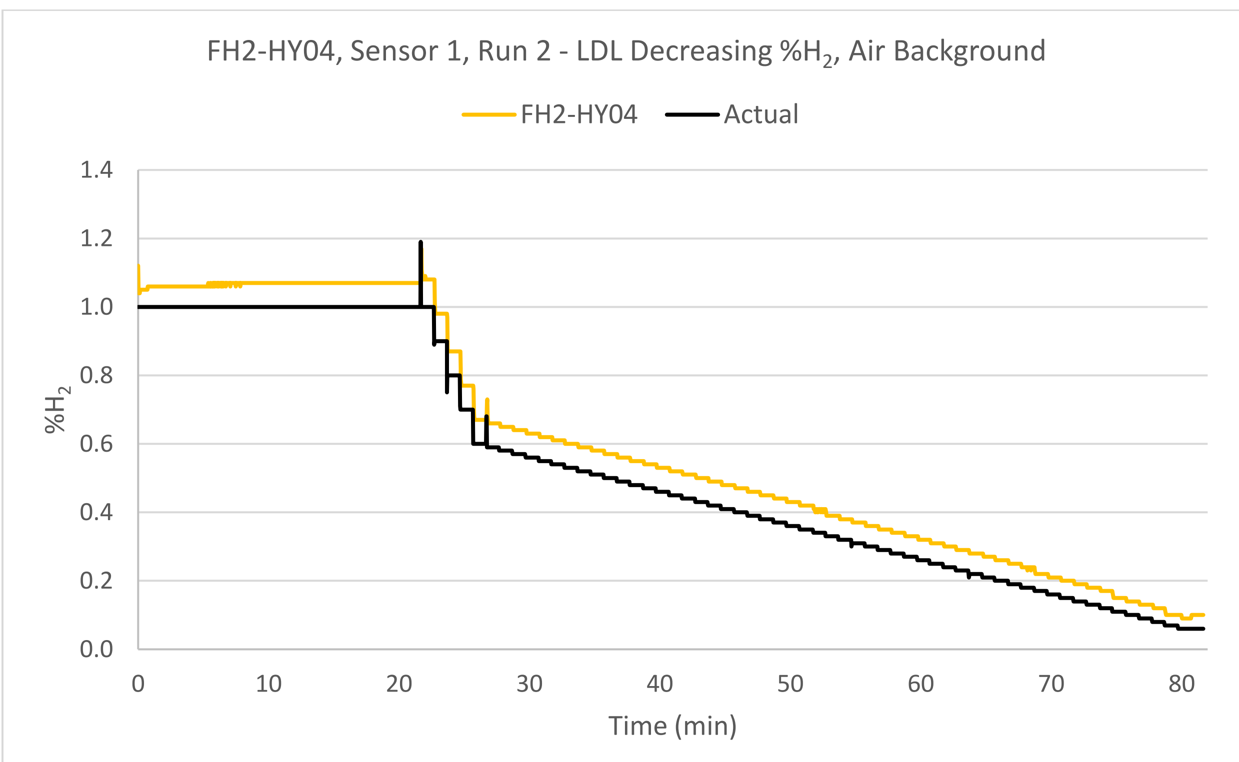

Figure 92. FH2-HY04 data for sensor 1, run 2 of the LDL test with decreasing $\%H_2$ in an air background.

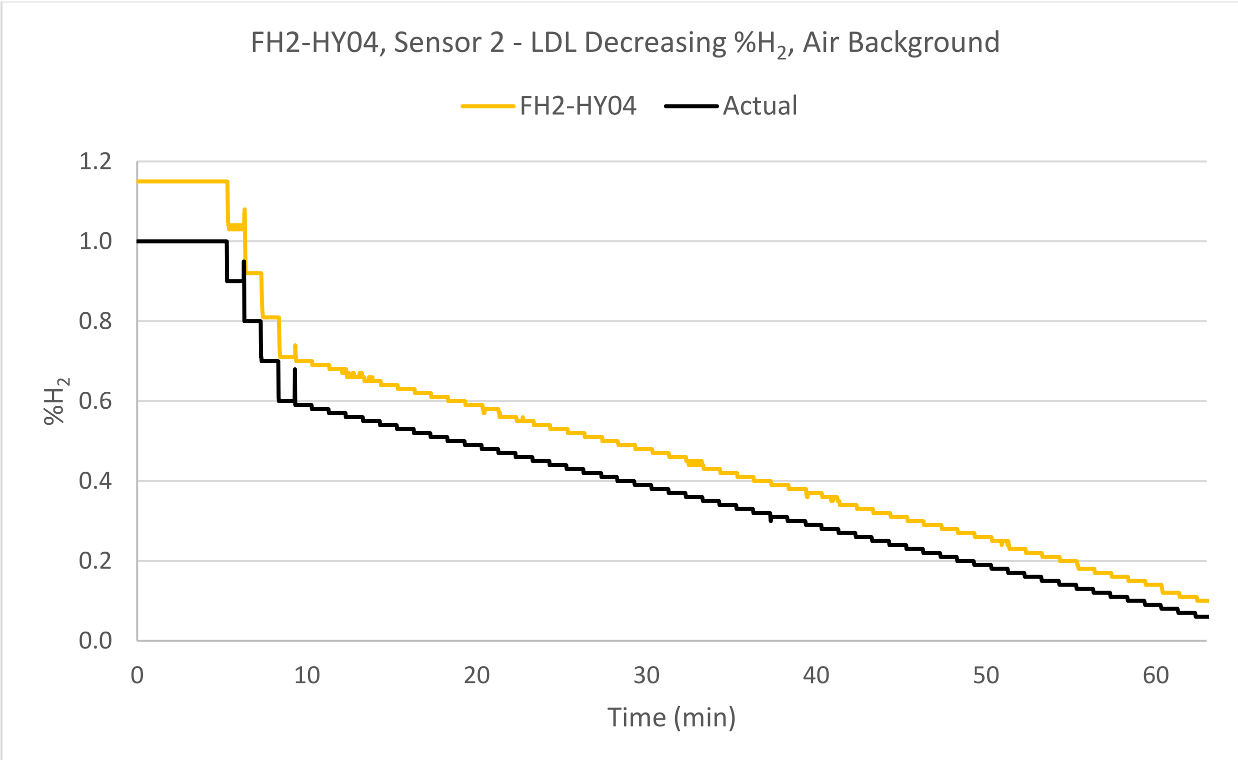

Figure 93. FH2-HY04 data for sensor 2 of the LDL test with decreasing $\%H_2$ in an air background.

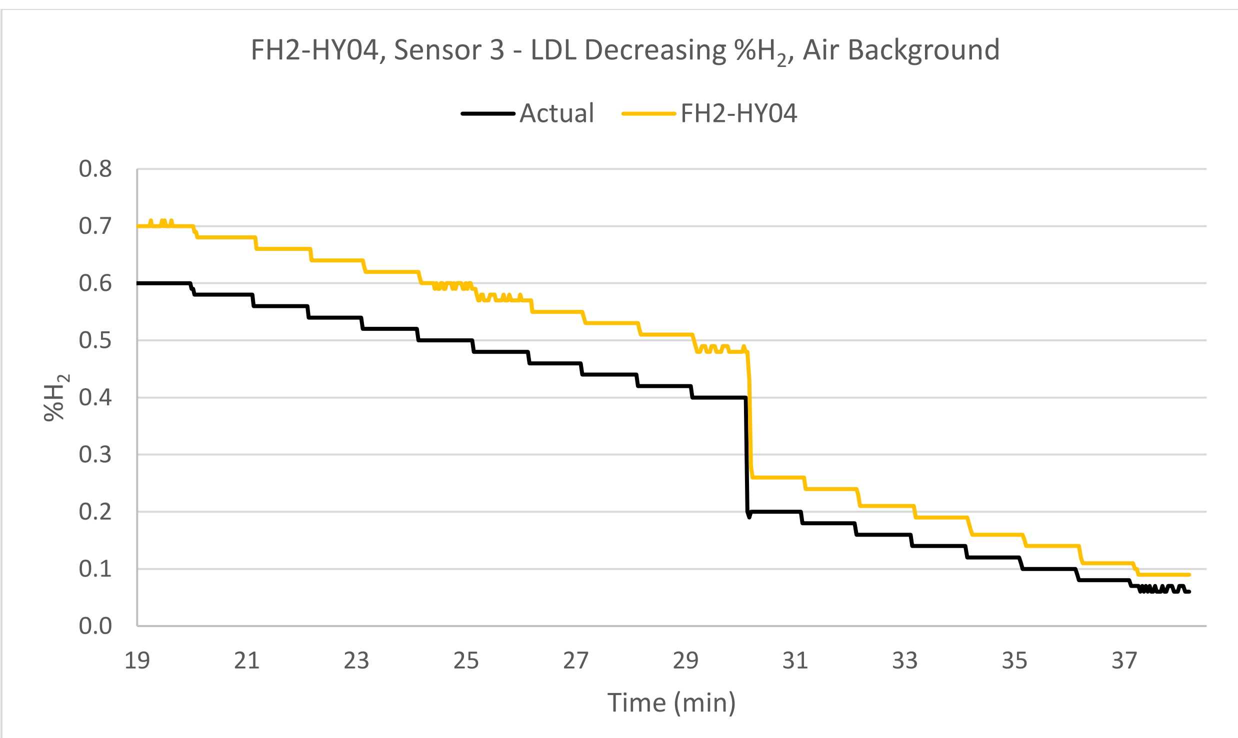

Figure 94. FH2-HY04 data for sensor 3 of the LDL test with decreasing $\%H_2$ in an air background.

It should be noted that the concentrations specified, or shown as “actual” hydrogen 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 8 lists the lower detectible limits measured for each sensor.

Table 8. Lower Detectible Limit Test Results – Air Background.

Sensor	**Sensor/Run**	**LDL for Increasing %H_2 (%H_2)**	**LDL for Decreasing %H_2 (%H_2)**	**Average LDL (%H_2)**
H2scan 720B	Run 1	0.51	0.51	Increasing %H_2 = 0.51 Decreasing %H_2 = 0.52
	Run 2	0.53	0.53	
	Run 3	0.49	0.50	
	Run 4	0.52	0.52	
XEN-5320	Sensor 1, Run 1	0.11*	0.06*	< 0.10
	Sensor 1, Run 2	0.09*	0.07*	
	Sensor 2	0.09*	0.07*	
	Sensor 3	0.10*	0.08*	
Sense H_2®	Sensor 1, Run 1	0.12	0.13	Increasing %H_2 = 0.25 Decreasing %H_2 = 0.13
	Sensor 1, Run 2	0.17	0.12	
	Sensor 2	0.31	0.08	
	Sensor 3	0.40	0.20	
FH2-HY04	Sensor 1, Run 1	0.11*	0.06*	< 0.10
	Sensor 1, Run 2	0.09*	0.08	
	Sensor 2	0.09*	0.07*	
	Sensor 3	0.10*	0.08*	

* minimum concentration above baseline provided during the test

Results – Nitrogen Background

With the test setup and equipment used, the minimum concentration of hydrogen possible for each LDL test varied from 0.05% H_2 to 0.08% H_2, depending on the test. Increments of 0.01% hydrogen were used whenever possible. Due to MFC constraints, some steps were larger at the lowest values.

Figure 95 through Figure 118 show the data collected during these tests, with all data for increasing hydrogen concentration tests first, followed by data for decreasing hydrogen concentration tests.

The H2scan results for the LDL were more consistent with a nitrogen background than they were with an air background, but were at essentially the same average concentration.

The XEN-5320 continued to respond to all concentrations of hydrogen above the baseline provided.

As with previous tests, the Sense H_2® and FH2-HY04 did not function anaerobically.

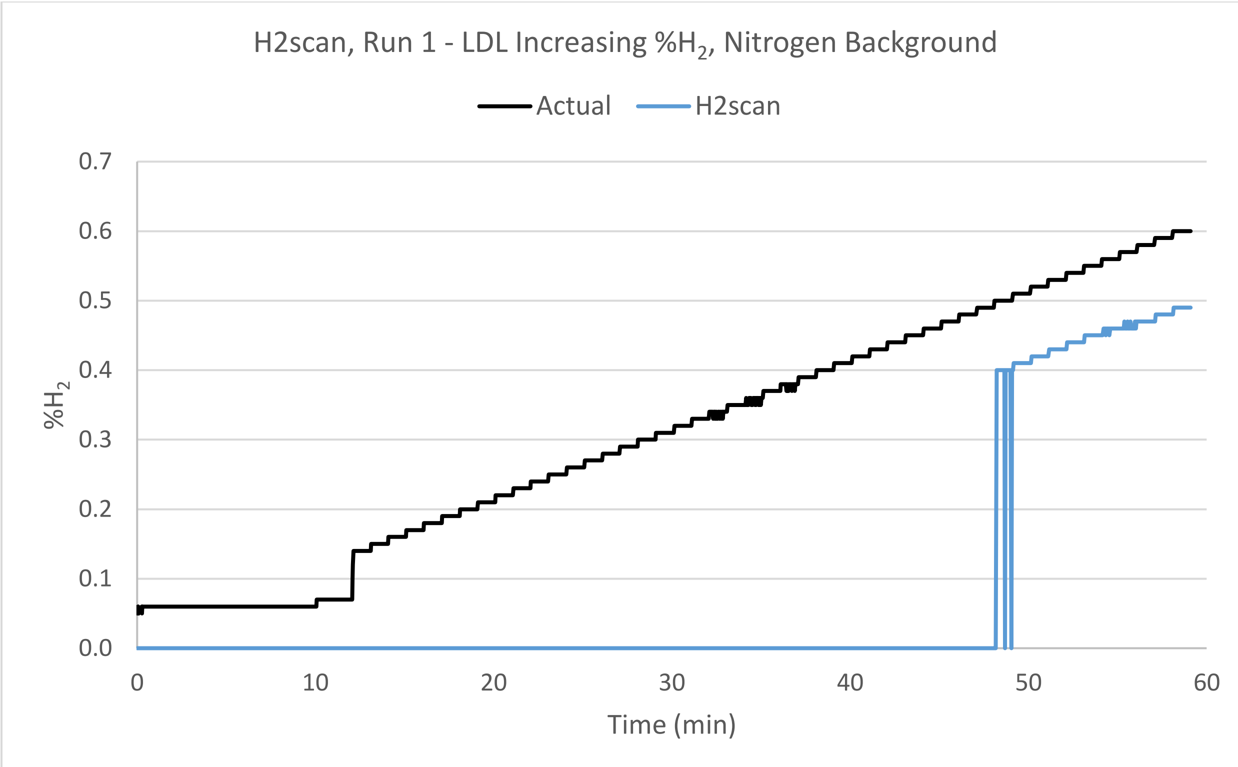

Figure 95. H2scan data for run 1 of the LDL test with increasing $\%H_2$ in a nitrogen background.

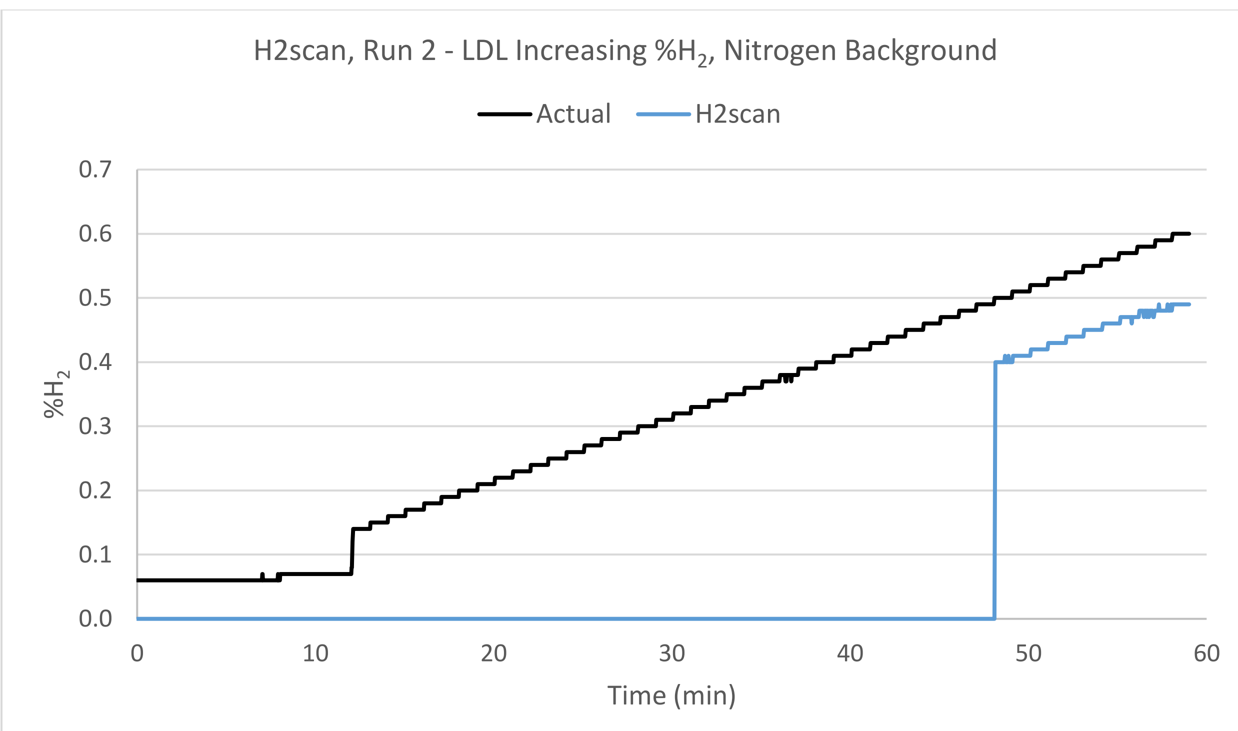

Figure 96. H2scan data for run 2 of the LDL test with increasing $\%H_2$ in a nitrogen background.

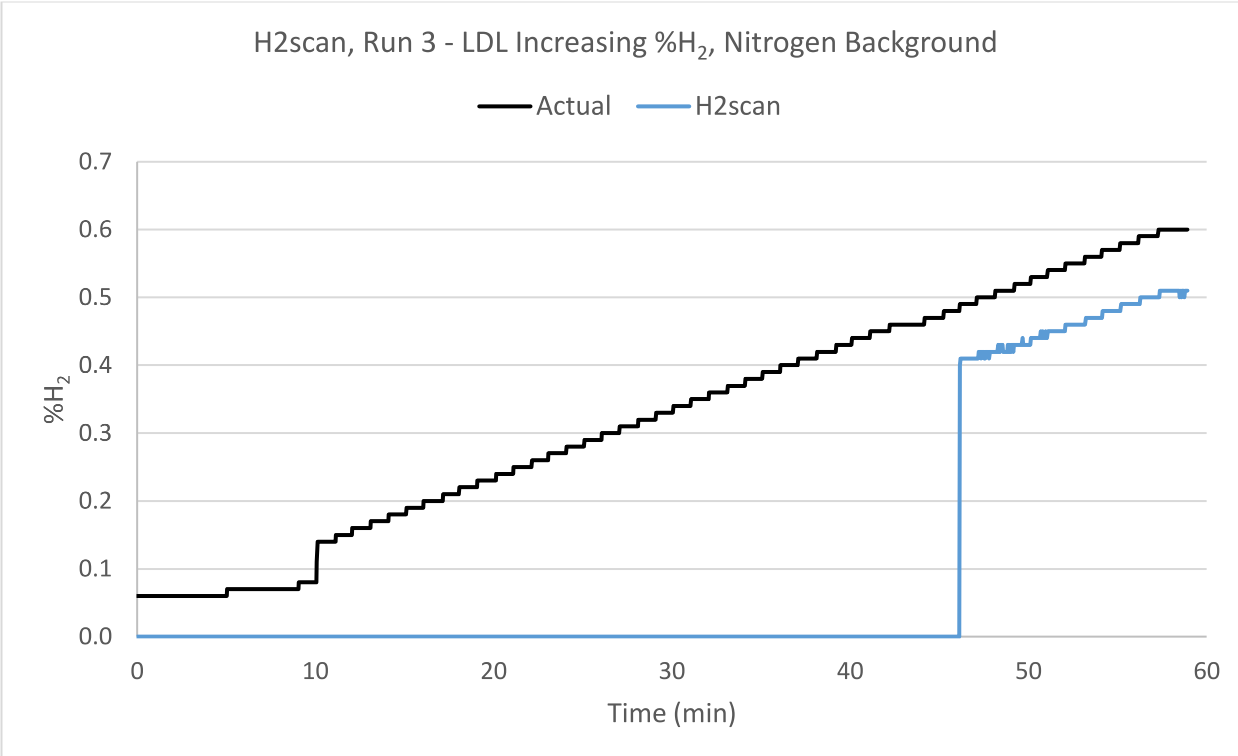

Figure 97. H2scan data for run 3 of the LDL test with increasing %H_2 in a nitrogen background.

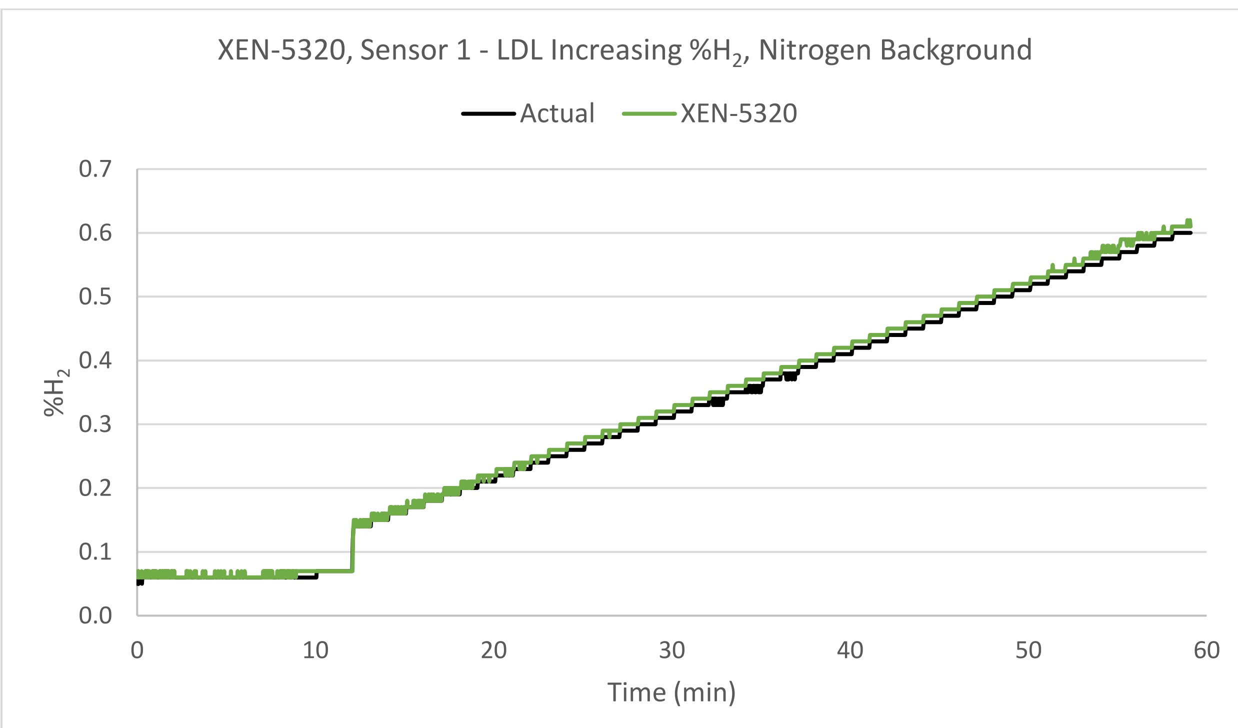

Figure 98. XEN-5320 data for sensor 1 of the LDL test with increasing %H_2 in a nitrogen background.

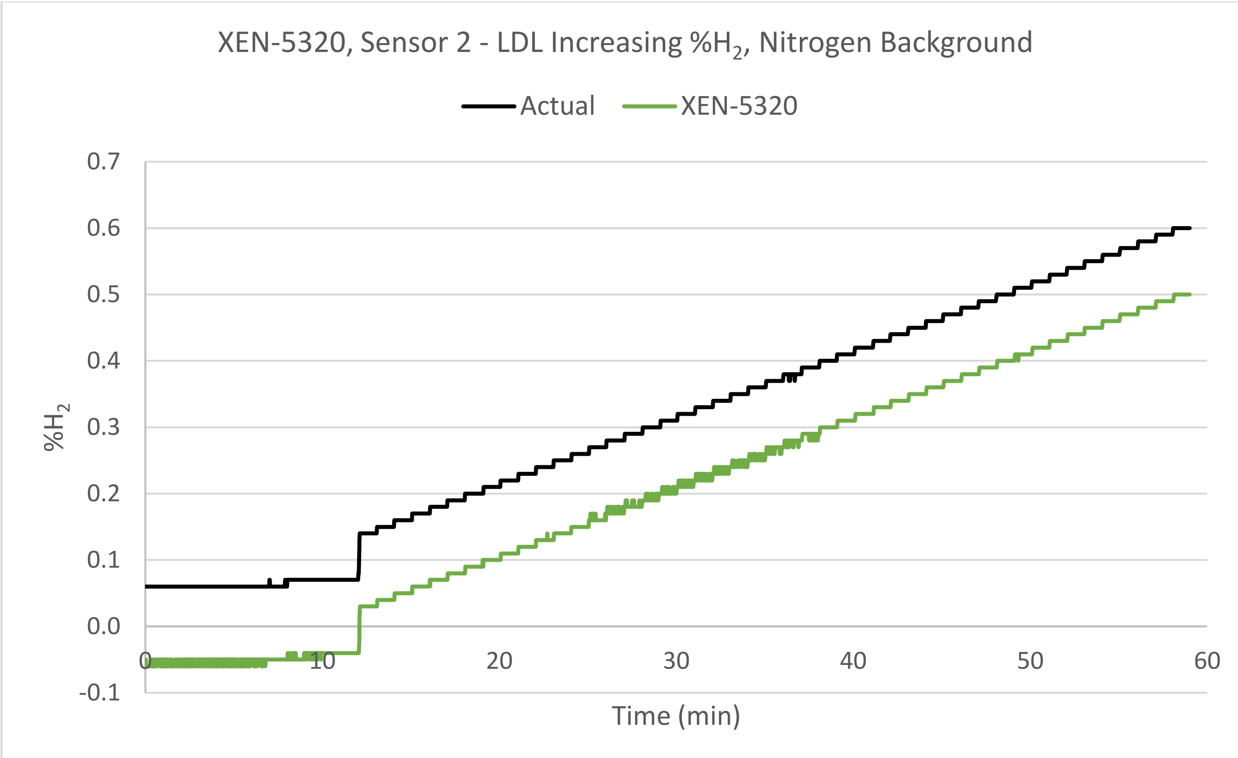

Figure 99. XEN-5320 data for sensor 2 of the LDL test with increasing $\%H_2$ in a nitrogen background.

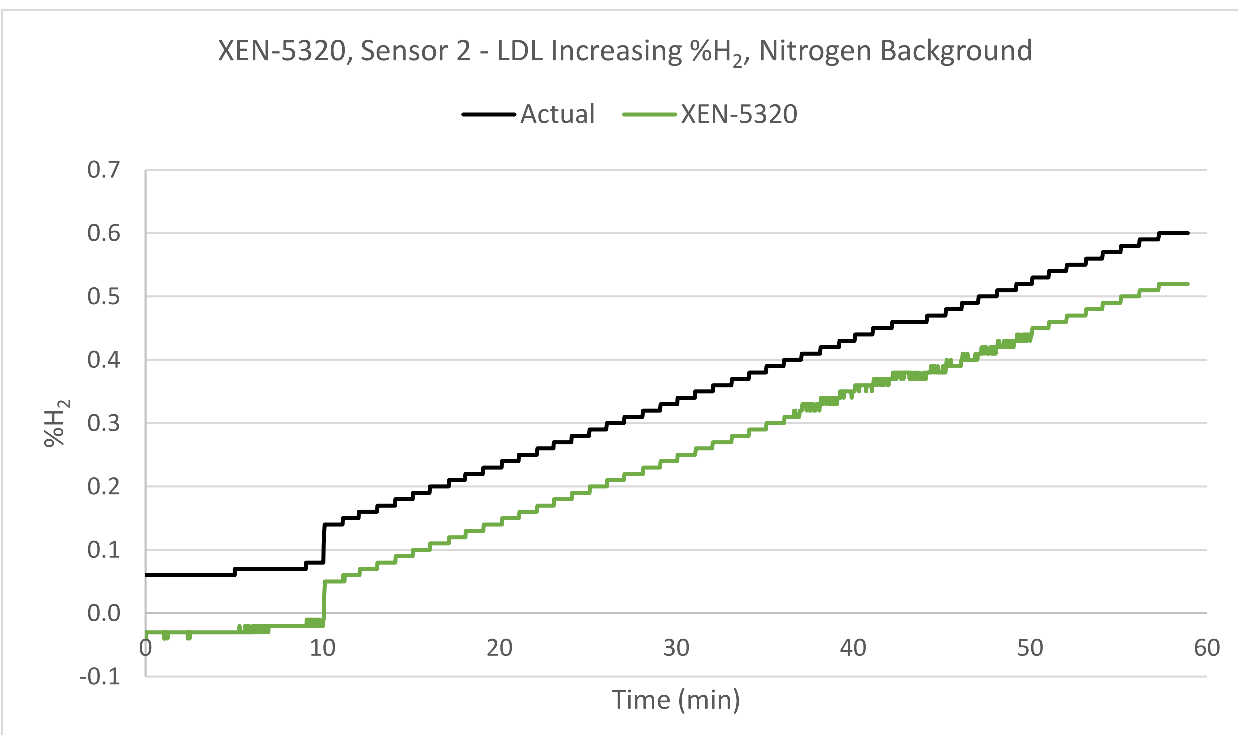

Figure 100. XEN-5320 data for sensor 3 of the LDL test with increasing $\%H_2$ in a nitrogen background.

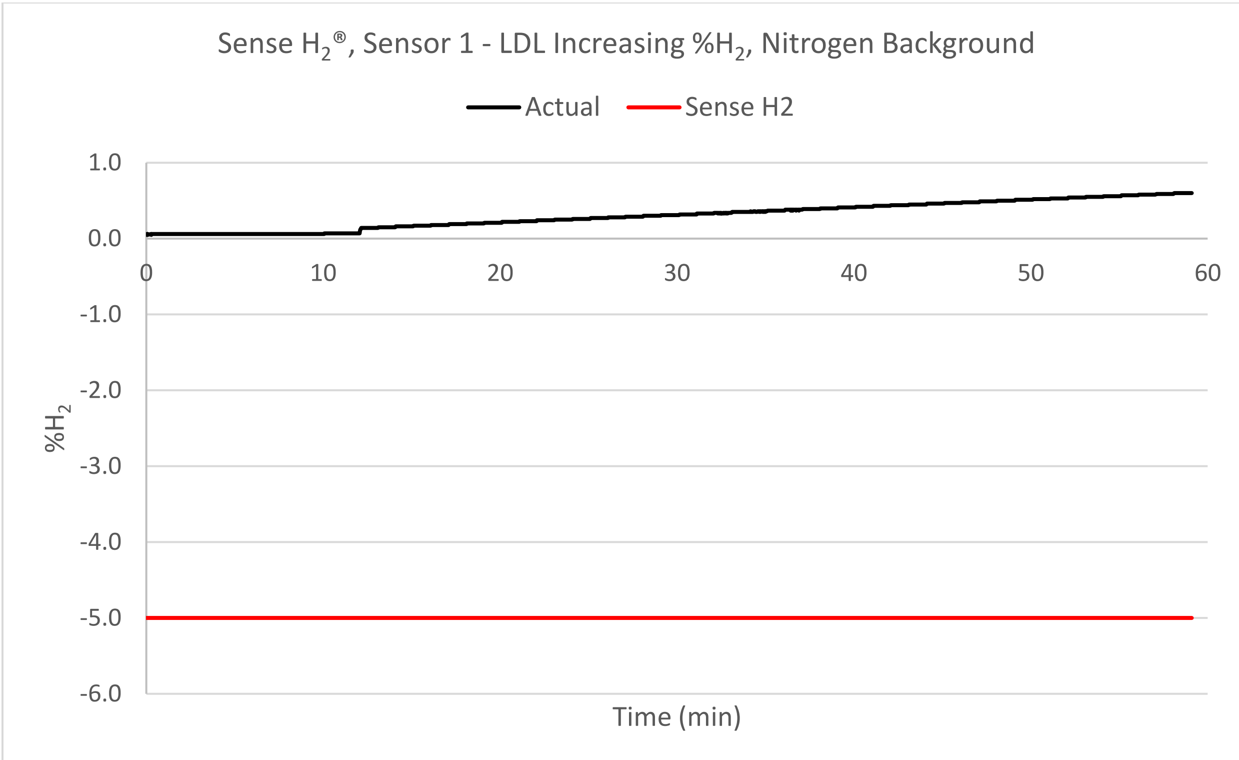

Figure 101. Sense H_2® data for sensor 1 of the LDL test with increasing $\%H_2$ in a nitrogen background.

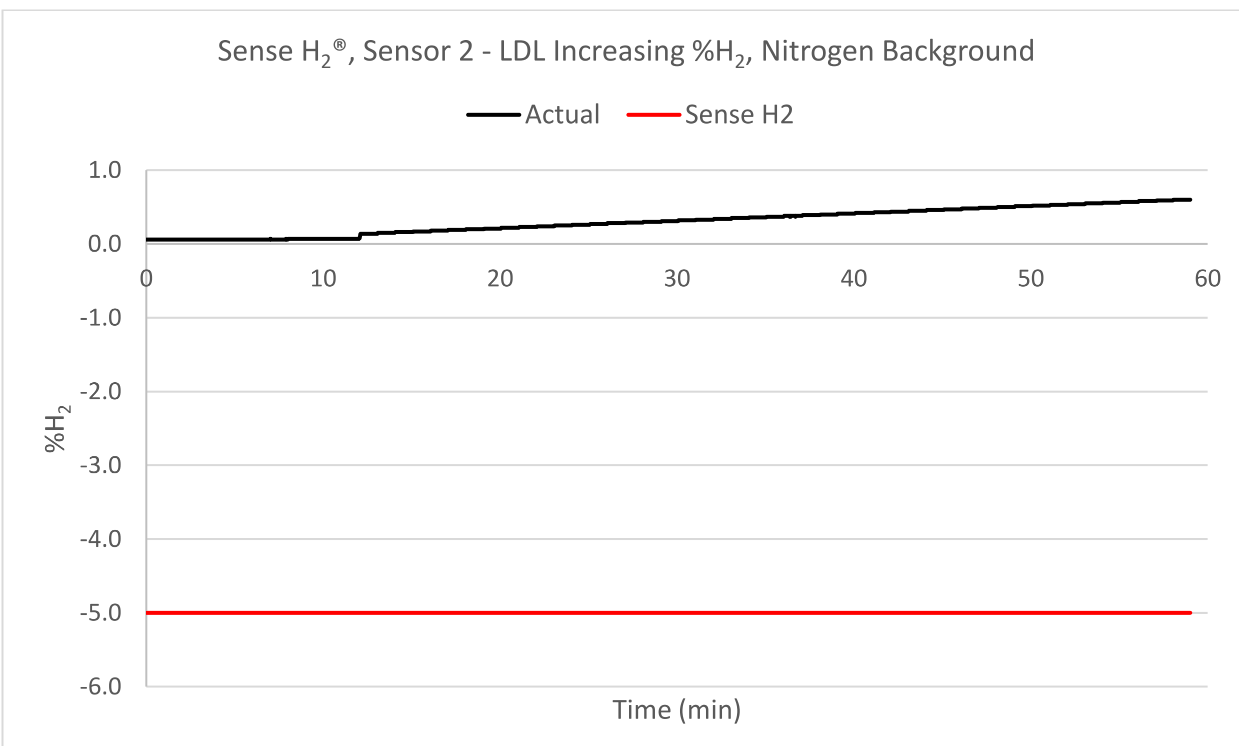

Figure 102. Sense H_2® data for sensor 2 of the LDL test with increasing $\%H_2$ in a nitrogen background.

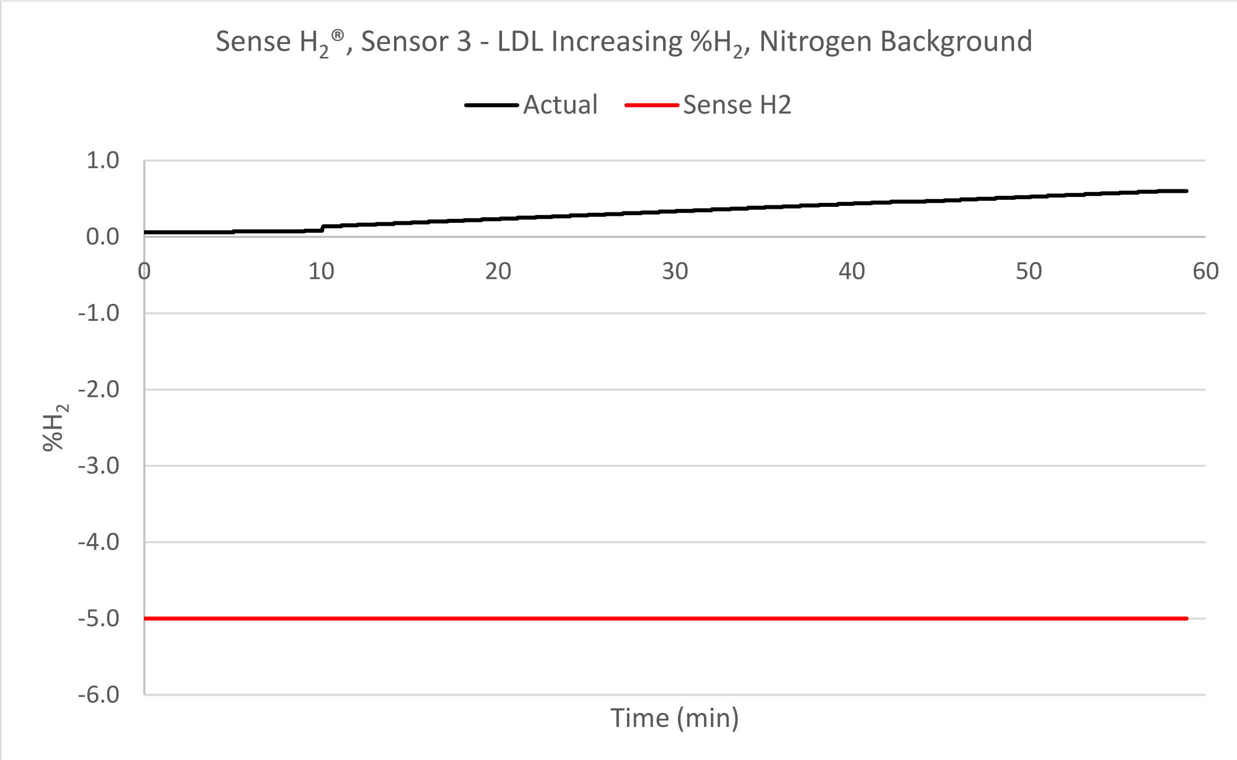

Figure 103. Sense H_2® data for sensor 3 of the LDL test with increasing %H_2 in a nitrogen background.

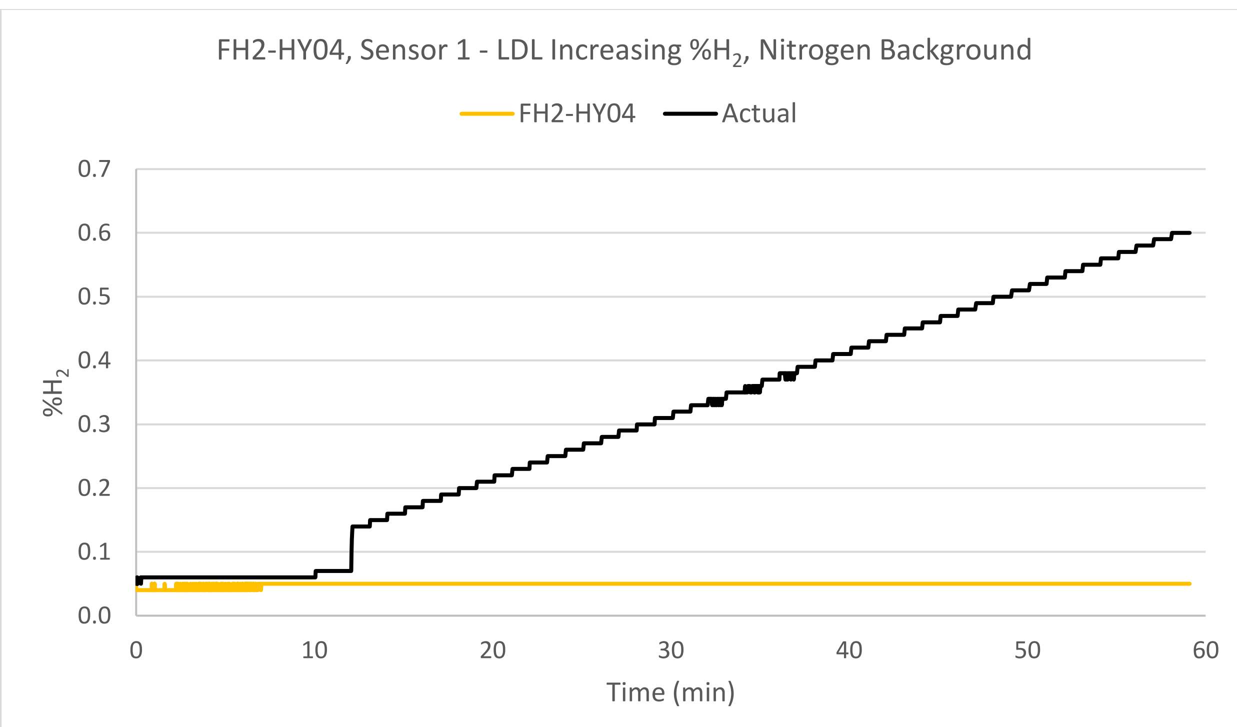

Figure 104. FH2-HY04 data for sensor 1 of the LDL test with increasing %H_2 in a nitrogen background.

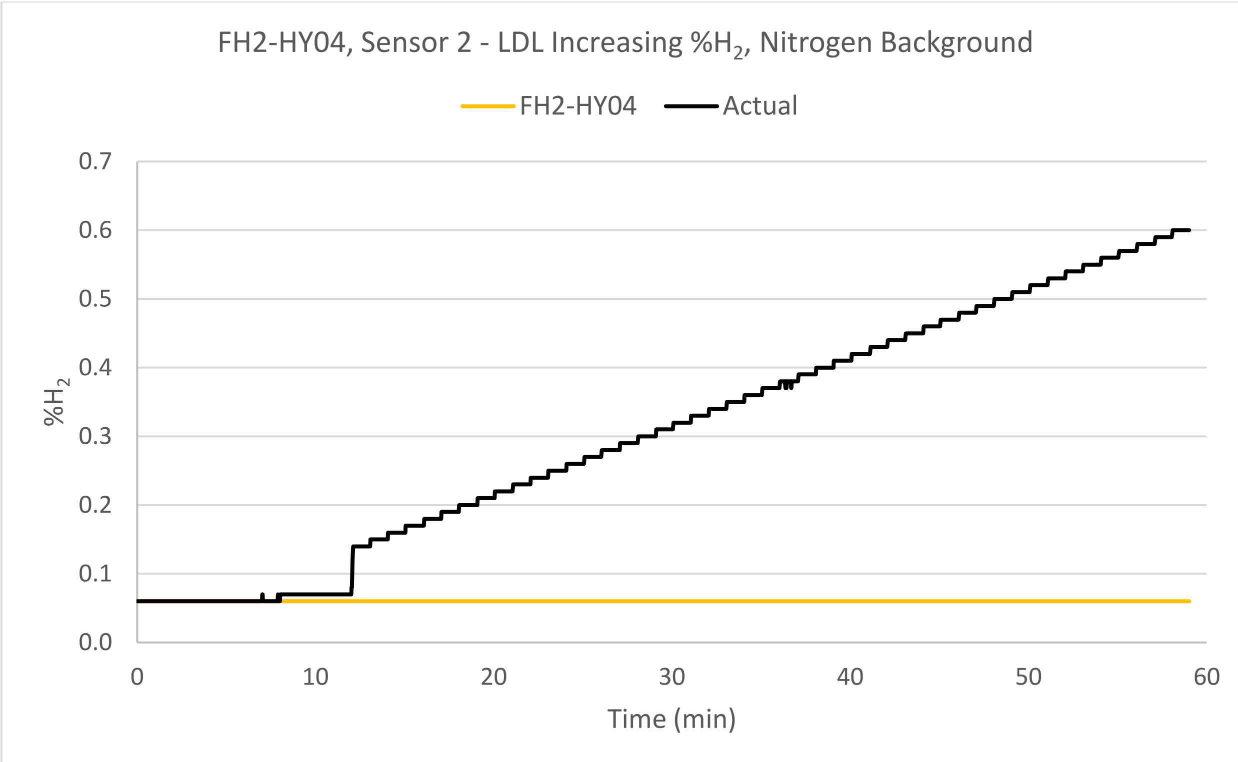

Figure 105. FH2-HY04 data for sensor 2 of the LDL test with increasing $\%H_2$ in a nitrogen background.

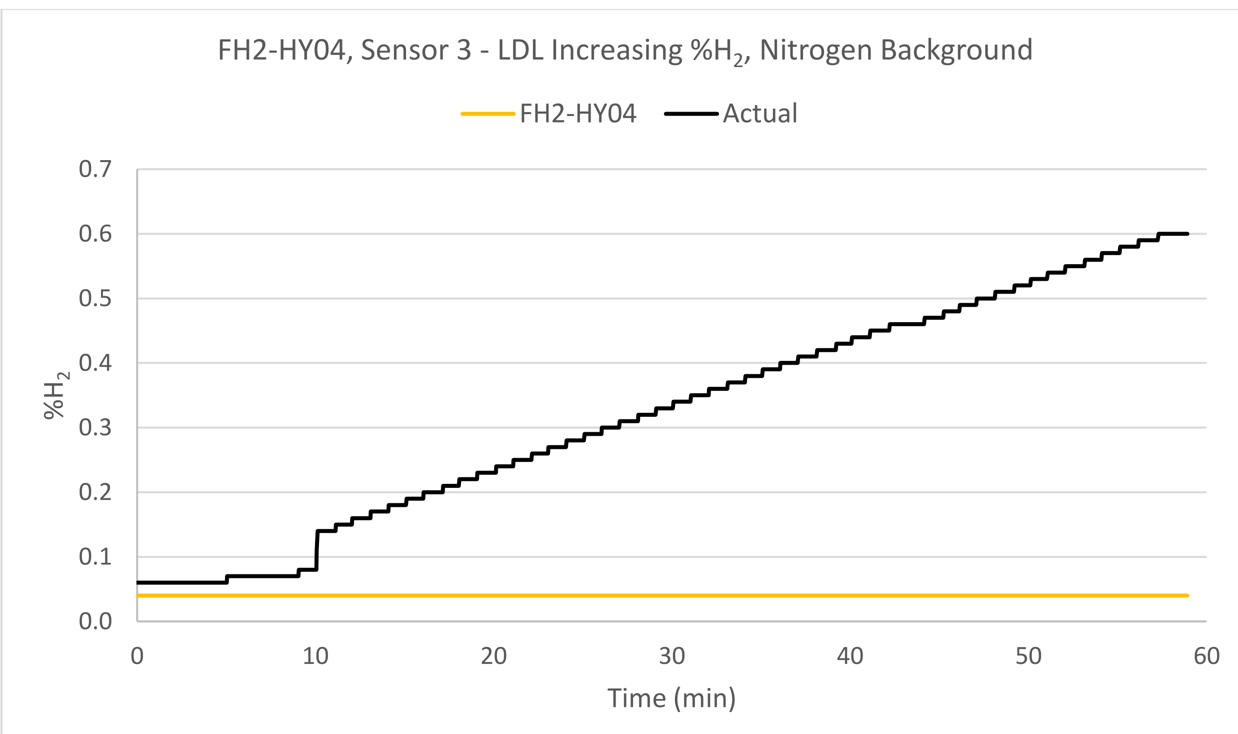

Figure 106. FH2-HY04 data for sensor 3 of the LDL test with increasing $\%H_2$ in a nitrogen background.

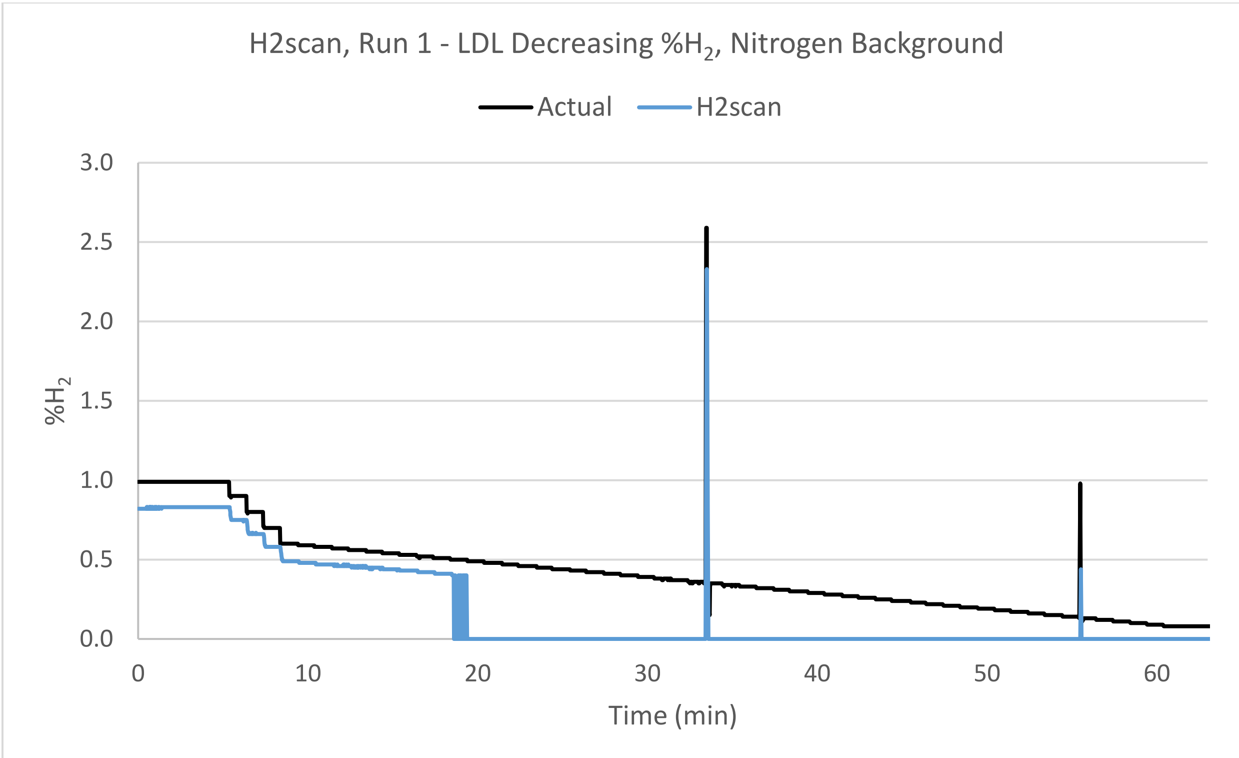

Figure 107. H2scan data for run 1 of the LDL test with decreasing $\%H_2$ in a nitrogen background.

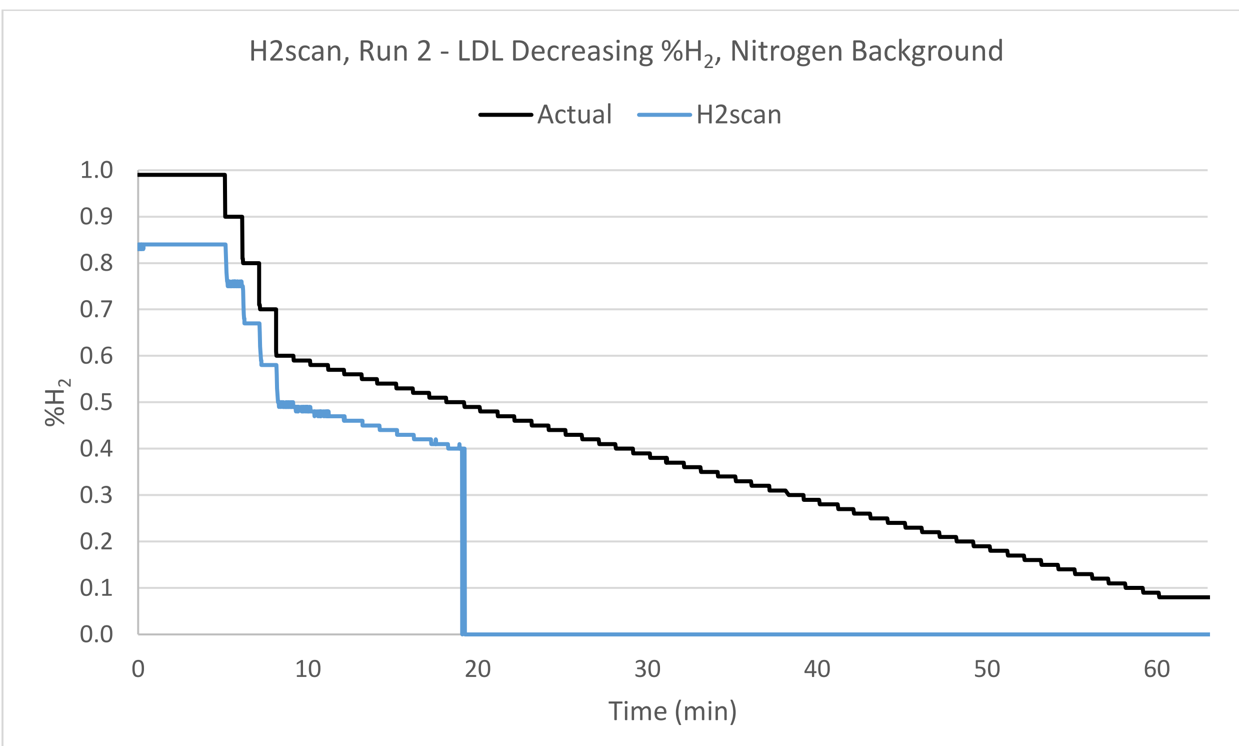

Figure 108. H2scan data for run 2 of the LDL test with decreasing $\%H_2$ in a nitrogen background.

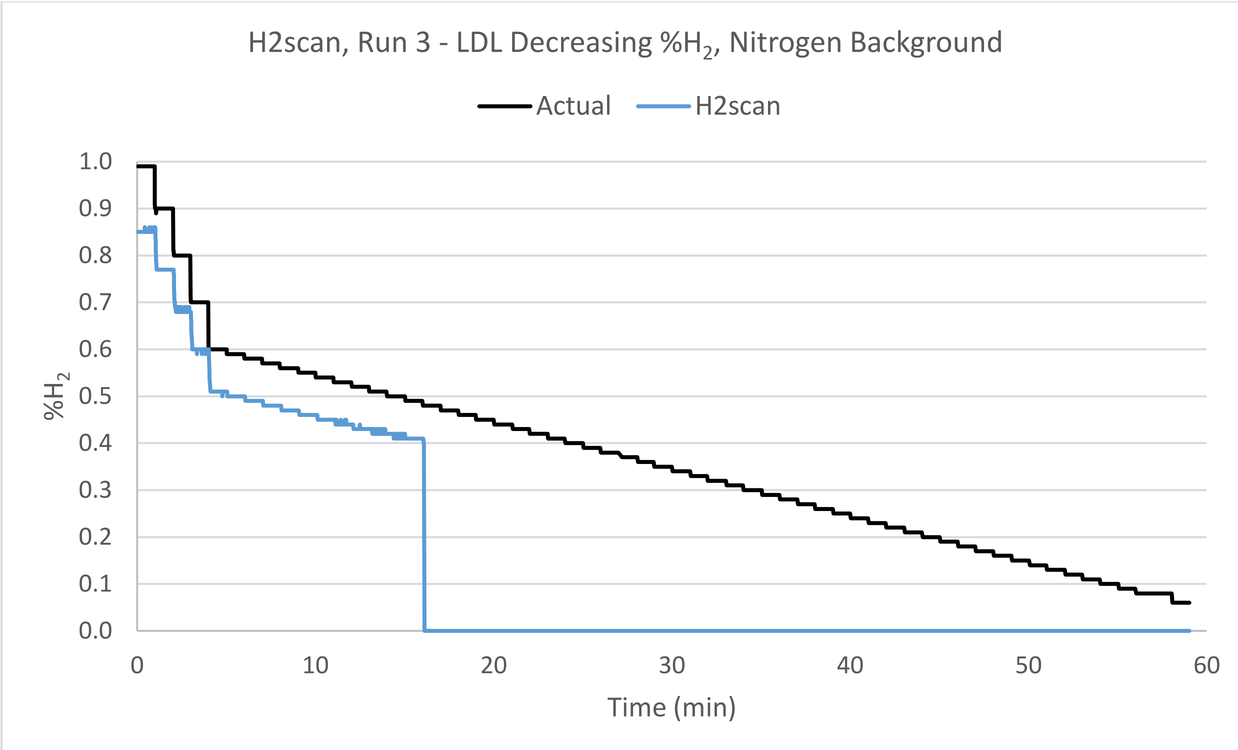

Figure 109. H2scan data for run 3 of the LDL test with decreasing $\%H_2$ in a nitrogen background.

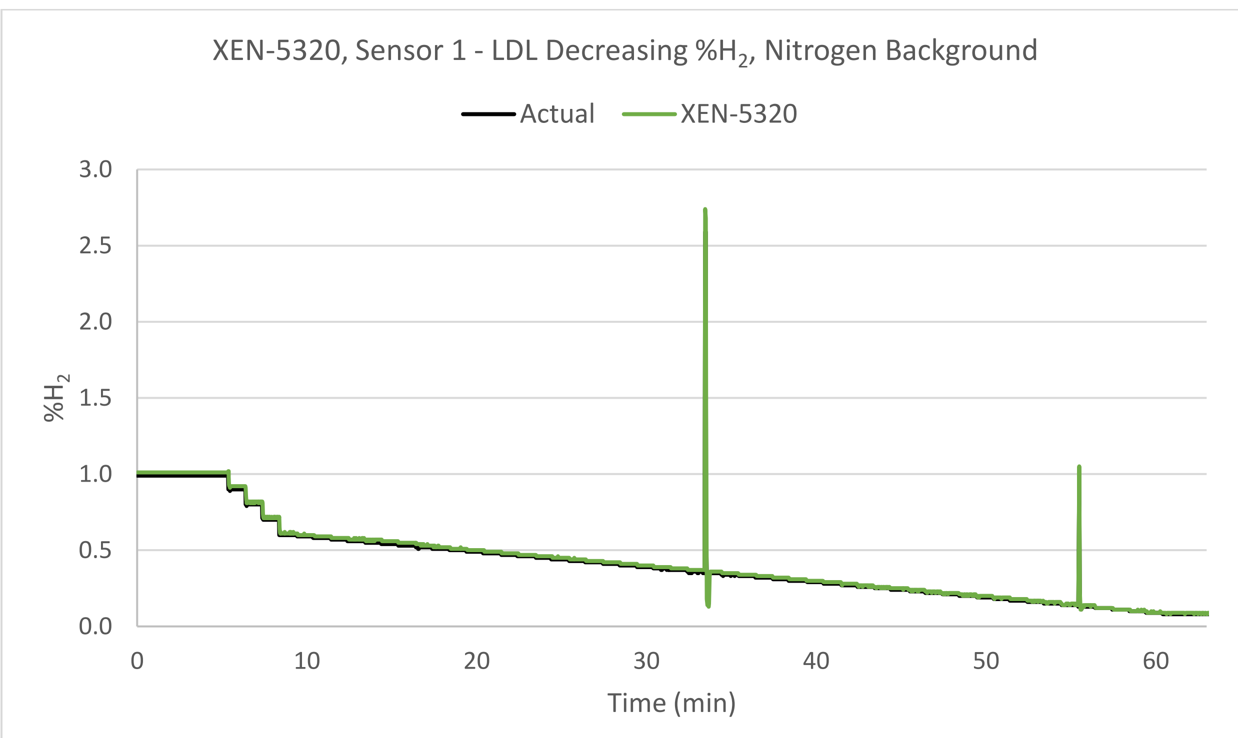

Figure 110. XEN-5320 data for sensor 1 of the LDL test with decreasing $\%H_2$ in a nitrogen background.

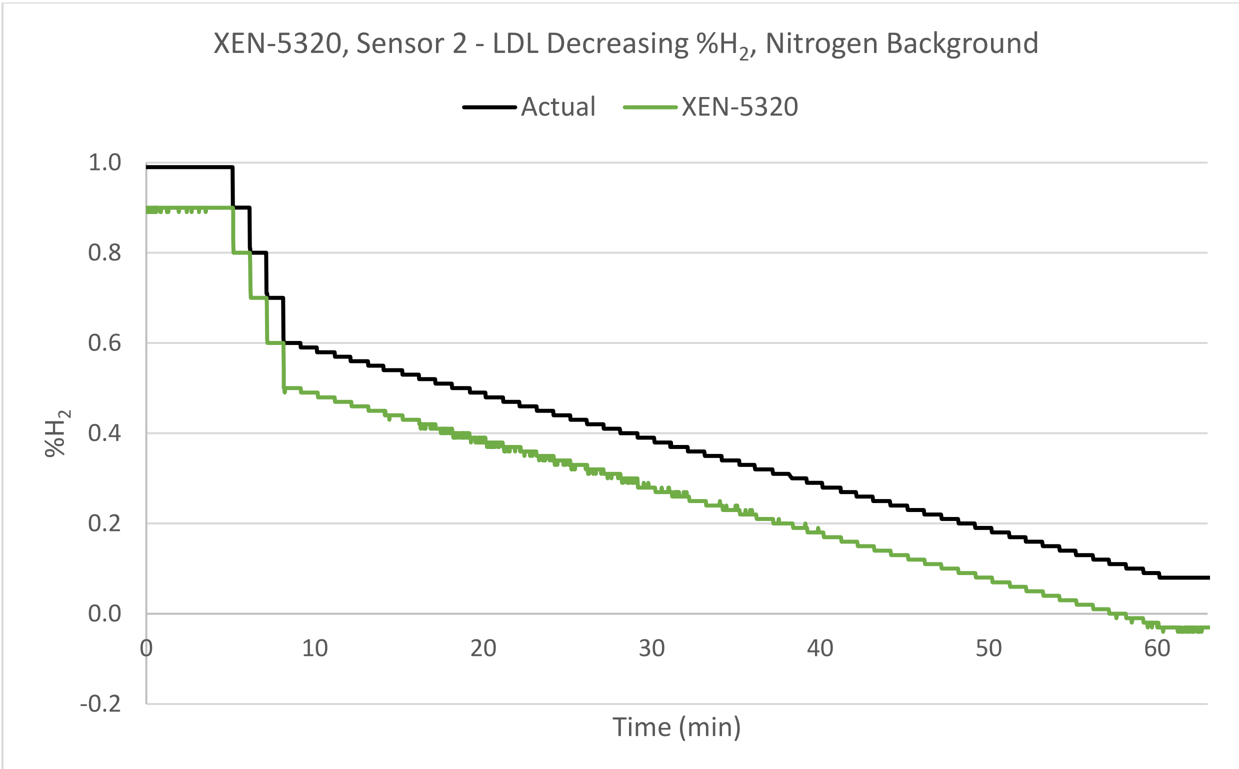

Figure 111. XEN-5320 data for sensor 2 of the LDL test with decreasing $\%H_2$ in a nitrogen background.

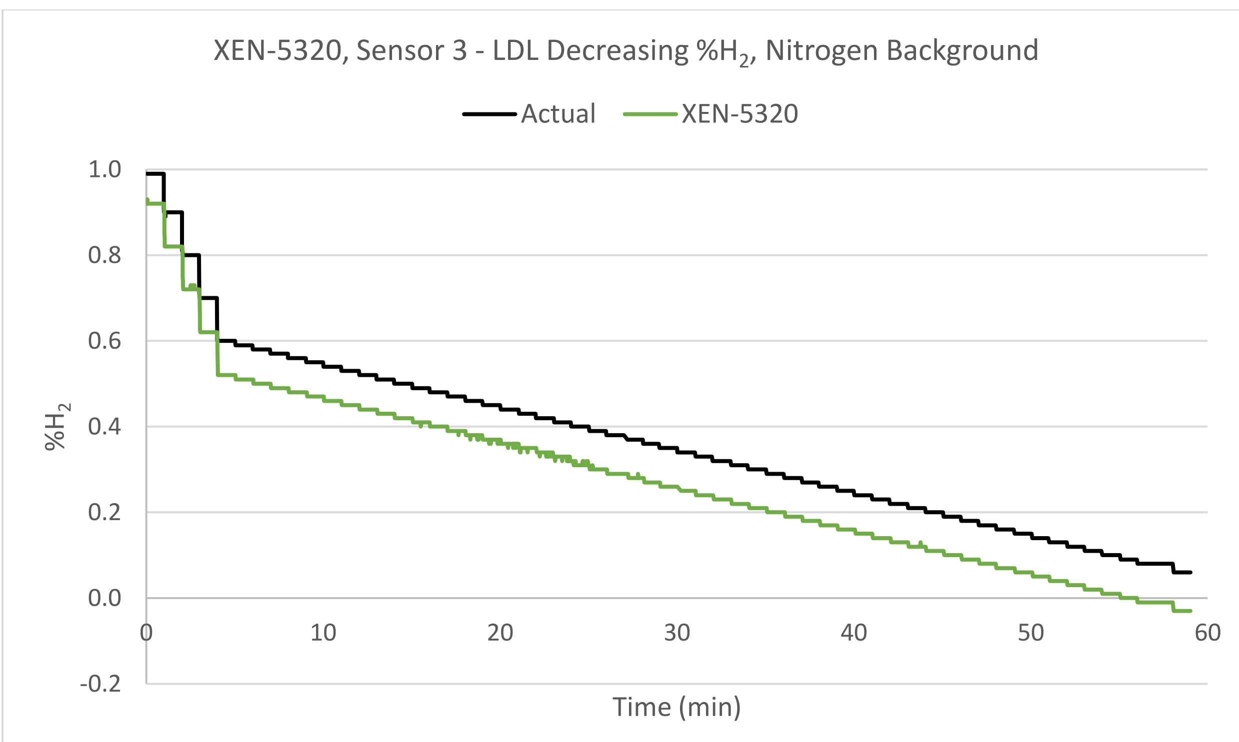

Figure 112. XEN-5320 data for sensor 3 of the LDL test with decreasing $\%H_2$ in a nitrogen background.

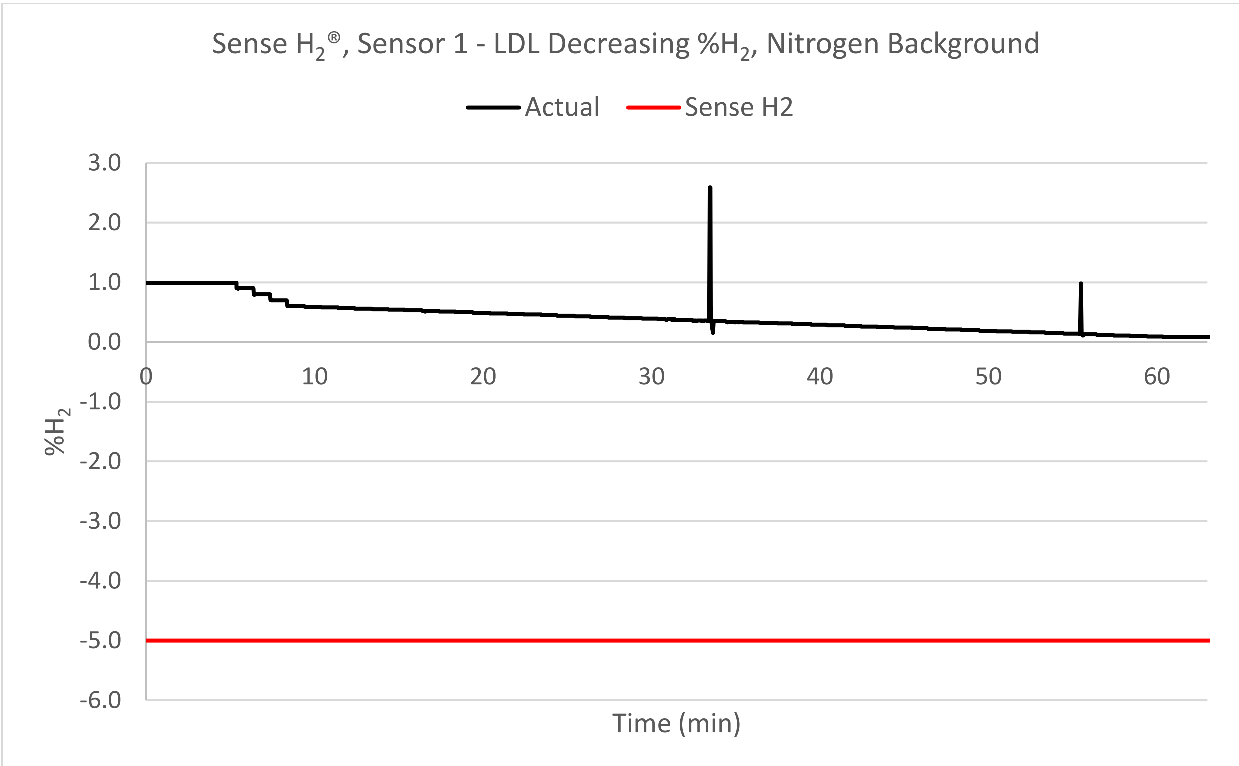

Figure 113. Sense H_2® data for sensor 1 of the LDL test with decreasing %H_2 in a nitrogen background.

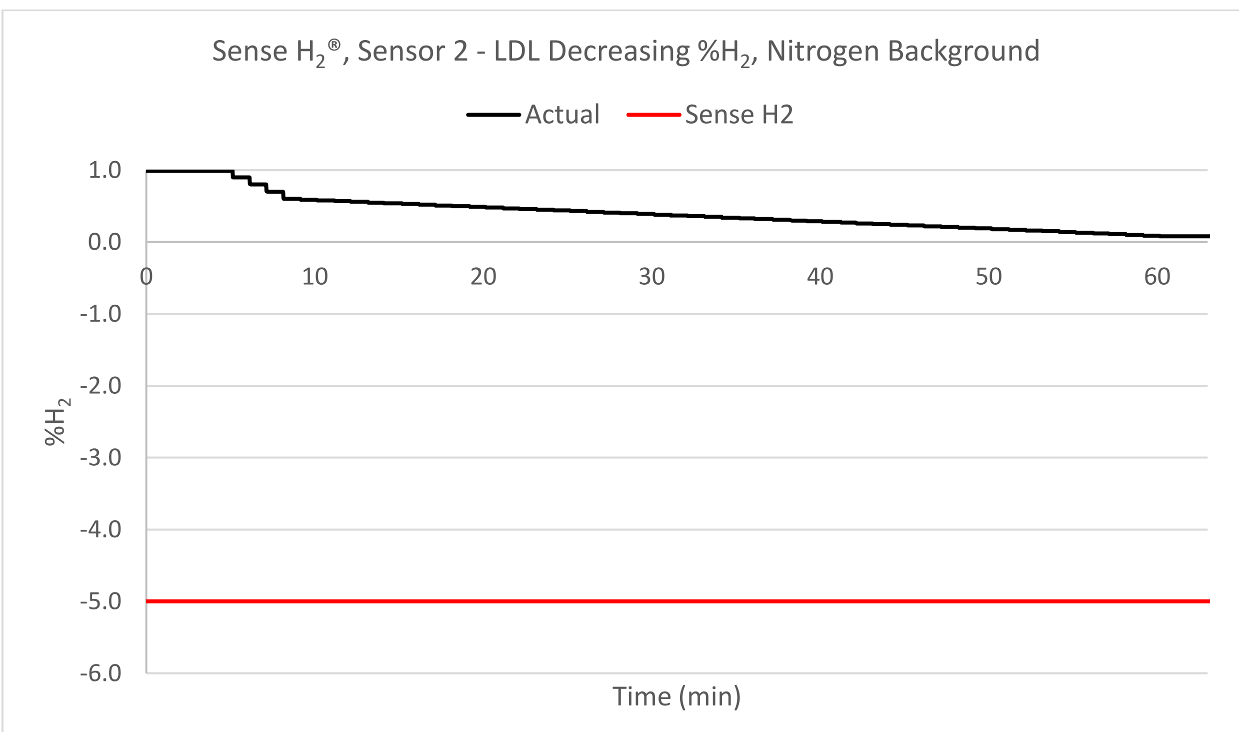

Figure 114. Sense H_2® data for sensor 2 of the LDL test with decreasing %H_2 in a nitrogen background.

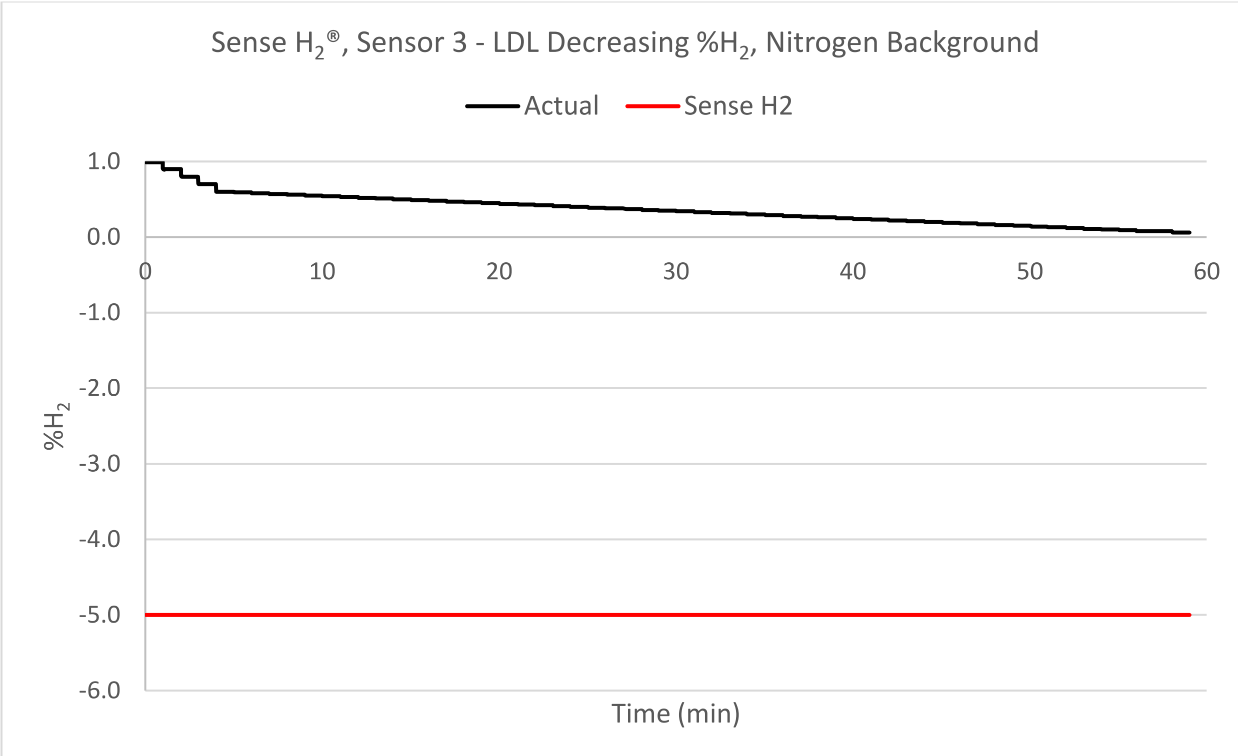

Figure 115. Sense H_2® data for sensor 3 of the LDL test with decreasing $\%H_2$ in a nitrogen background.

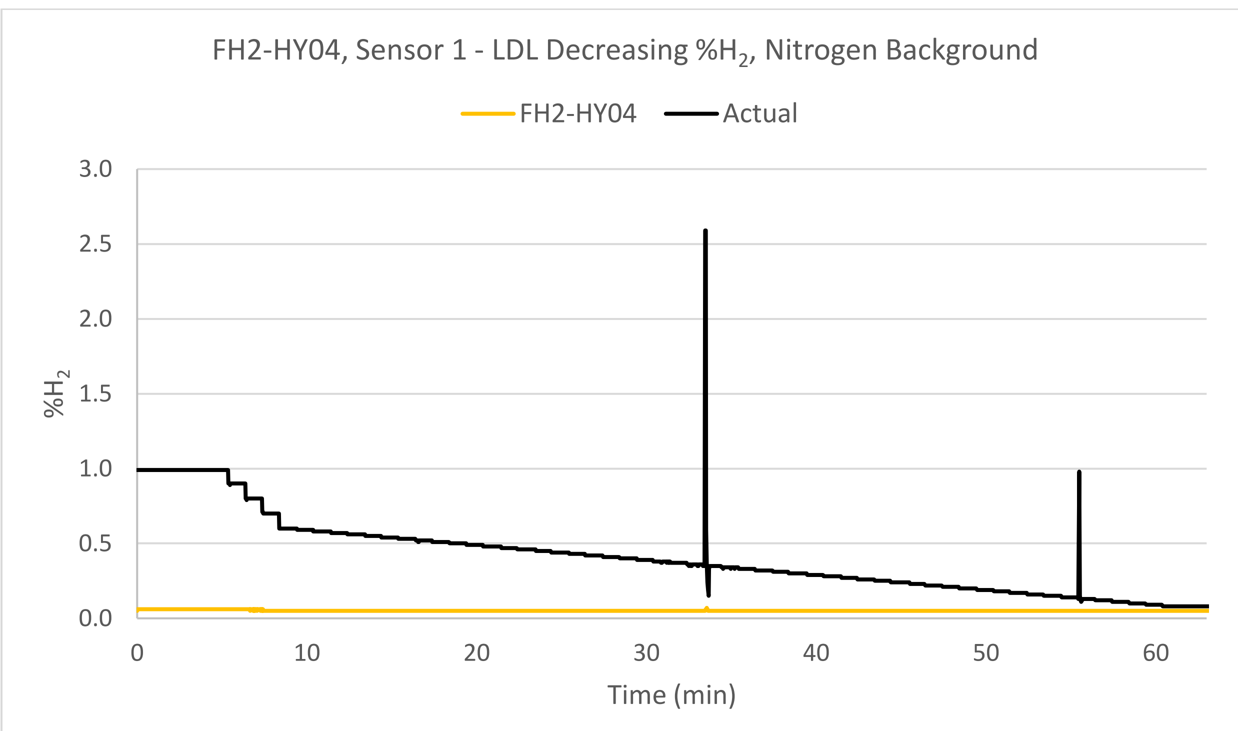

Figure 116. FH2-HY04 data for sensor 1 of the LDL test with decreasing $\%H_2$ in a nitrogen background.

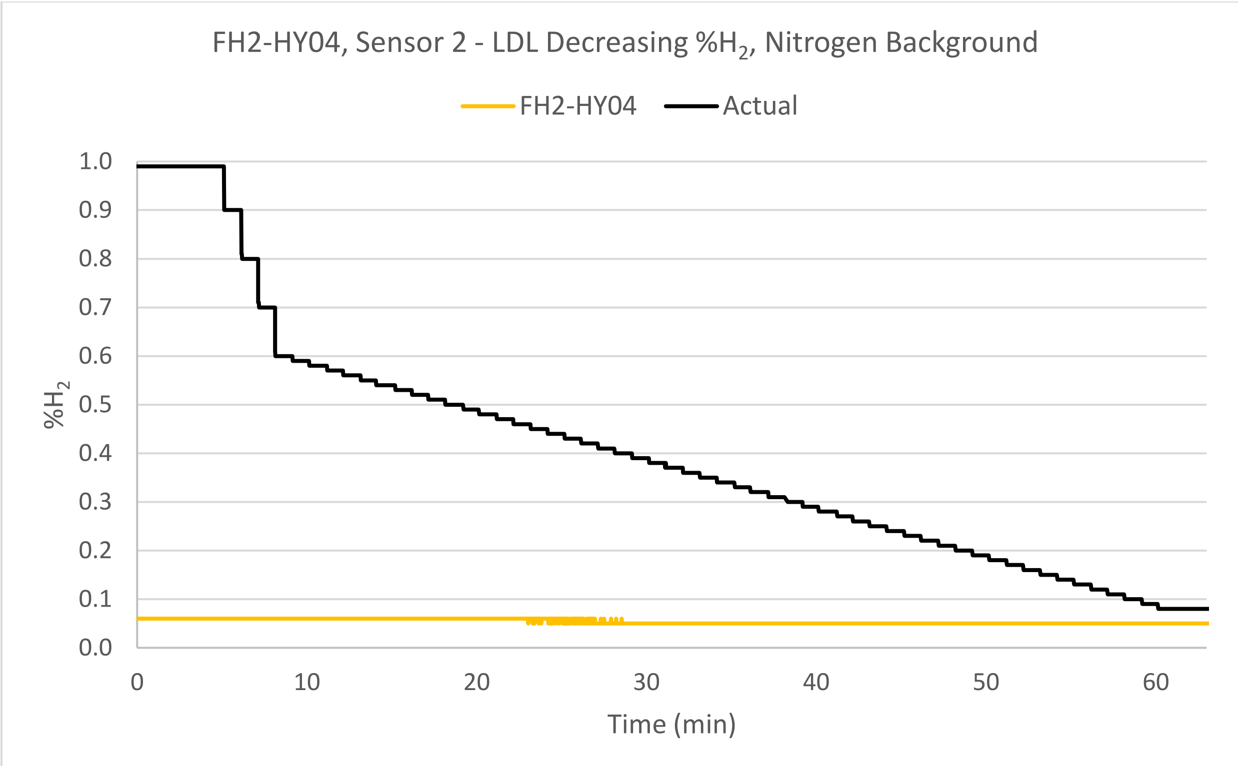

Figure 117. FH2-HY04 data for sensor 2 of the LDL test with decreasing %H_2 in a nitrogen background.

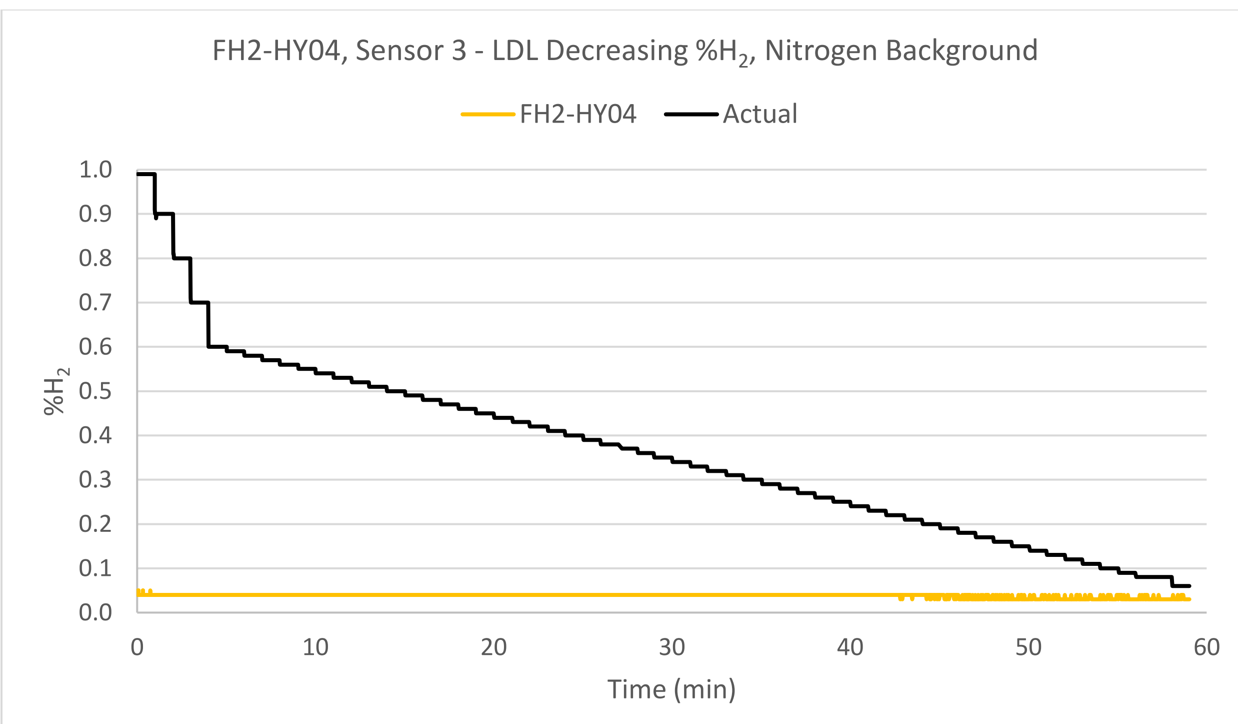

Figure 118. FH2-HY04 data for sensor 3 of the LDL test with decreasing %H_2 in a nitrogen background.

It should be noted that the concentrations specified, or shown as “actual” hydrogen 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 9 lists the lower detectible limits measured for each sensor. Because the Sense H_2® and FH2-HY04 were not functioning properly in a nitrogen background, they are omitted from the table.

Table 9. Lower Detectible Limit Test Results – Nitrogen Background.

Sensor	**Sensor/Run**	**LDL for Increasing %H_2 (%H_2)**	**LDL for Decreasing %H_2 (%H_2)**	**Average LDL (%H_2)**
H2scan 720B	1	0.50	0.50	0.50
	2	0.50	0.50	
	3	0.49	0.49	
XEN-5320	1	0.06*	0.09*	< 0.10
	2	0.07*	0.09*	
	3	0.07*	0.08*	

* minimum concentration above baseline provided during the test

Results – Helium Background

With the test setup and equipment used, the minimum concentration of hydrogen possible for each LDL test varied from 0.05% H_2 to 0.08% H_2, depending on the test. Increments of 0.01% hydrogen were used whenever possible. Due to MFC constraints, some steps were larger at the lowest values.

Figure 119 through Figure 126 show the data collected during these tests.

The LDL for the H2scan was slightly higher in a helium background than it had been in backgrounds of air or nitrogen, but it continued to respond to small changes in concentration once it reached its LDL. It is possible that the shift in LDL for a helium background reflects the need for a different calibration for this sensor in a helium background than is required for air or nitrogen.

As seen in previous tests, the XEN-5320 cannot detect hydrogen in a helium background, and the Sense H_2® and FH2-HY04 did not function anaerobically.

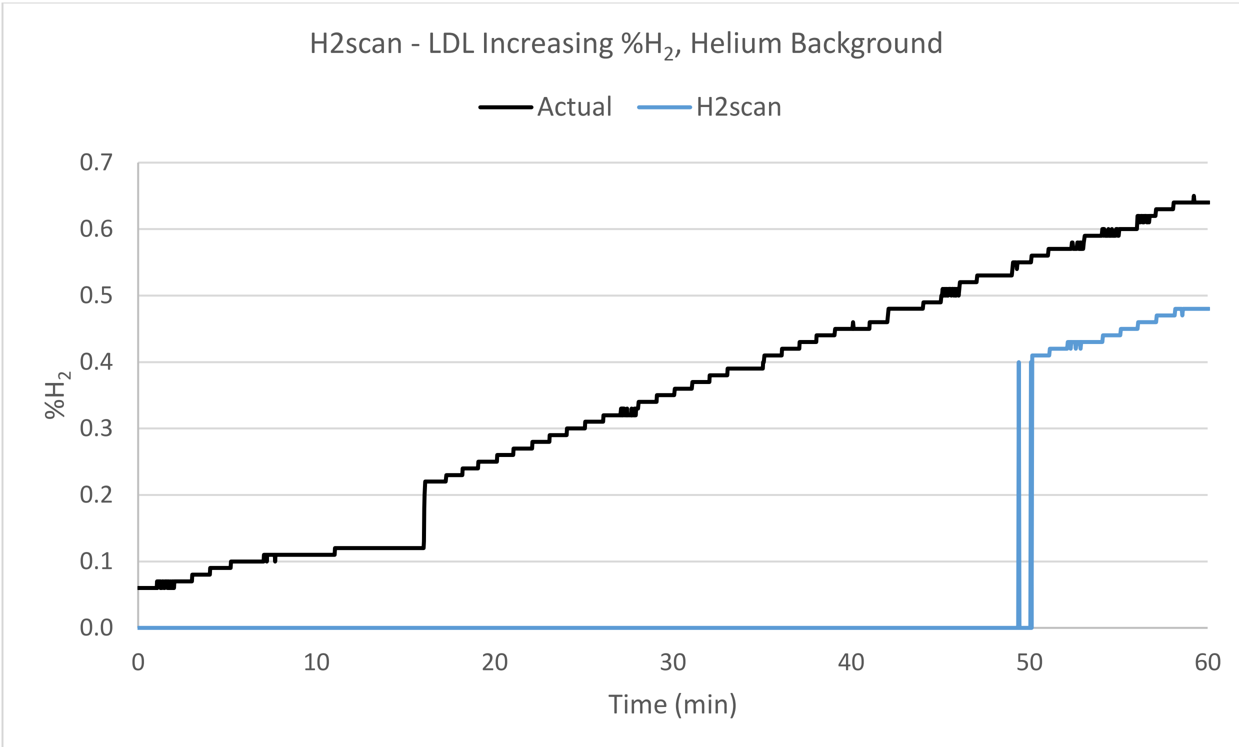

Figure 119. H2scan data for the LDL test with increasing $\%H_2$ in a helium background.

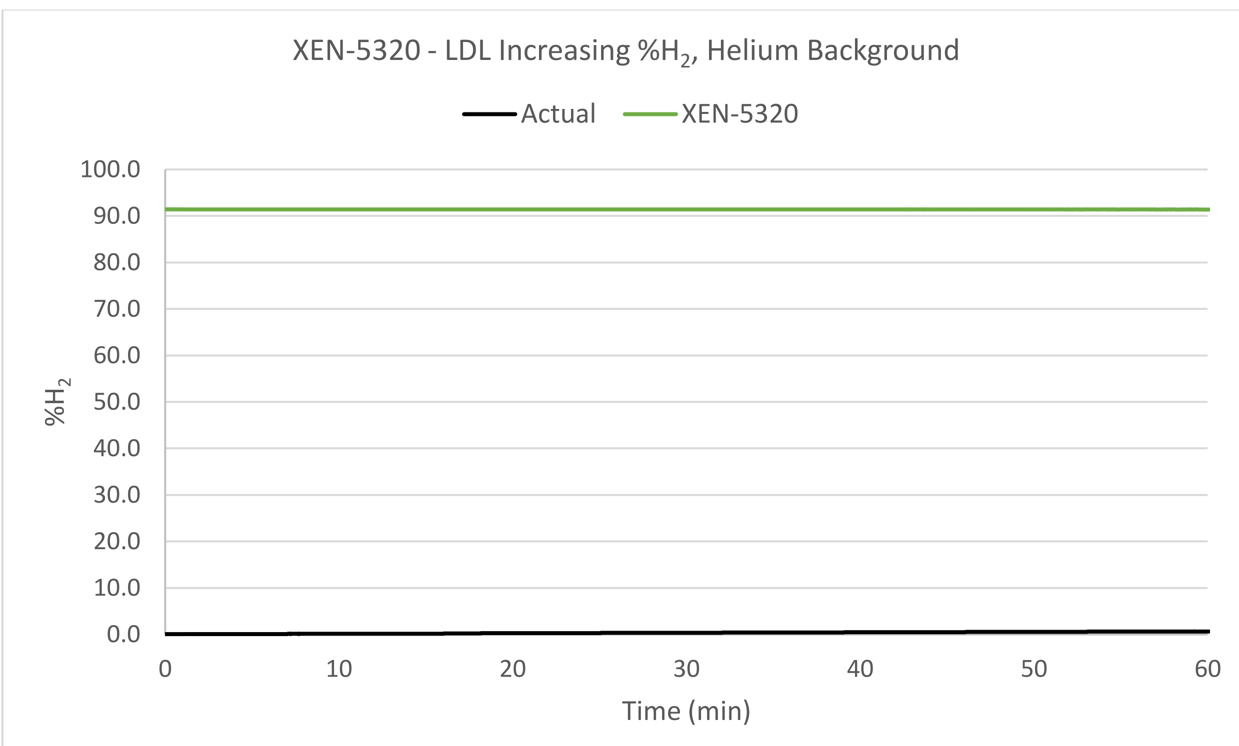

Figure 120. XEN-5320 data for the LDL test with increasing $\%H_2$ in a helium background.

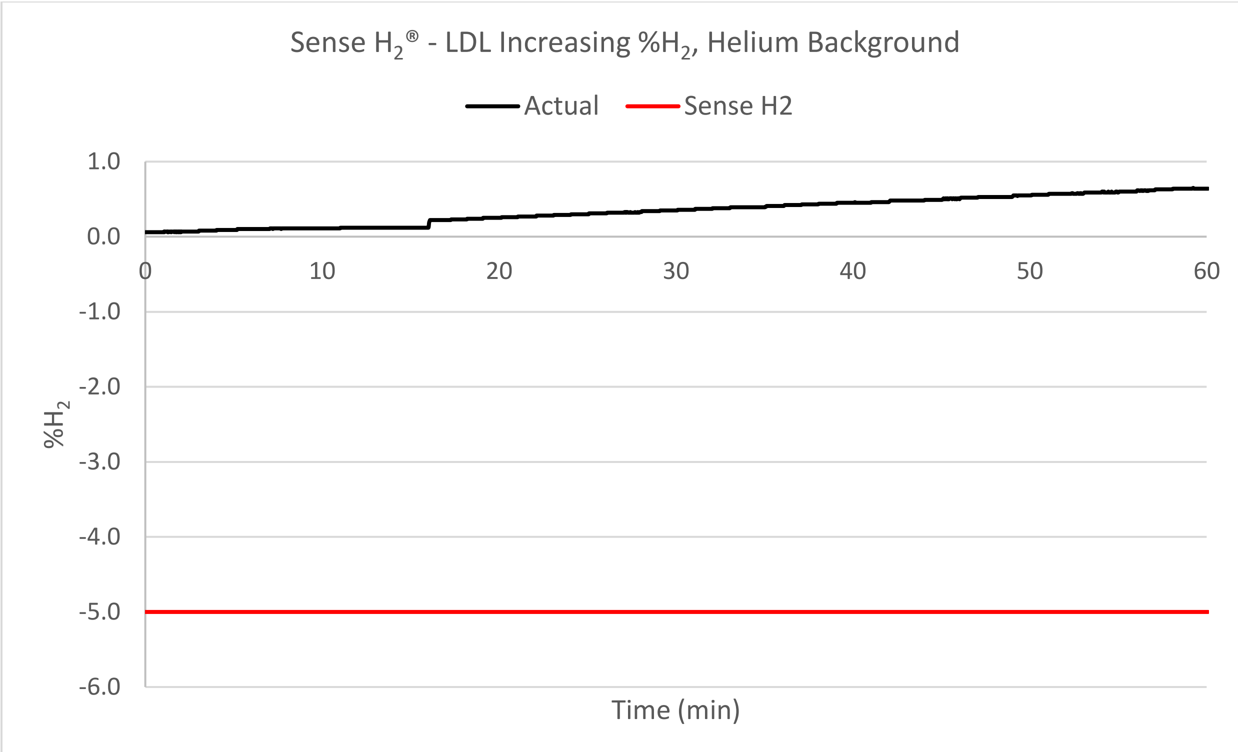

Figure 121. Sense H_2® data for the LDL test with increasing $\%H_2$ in a helium background.

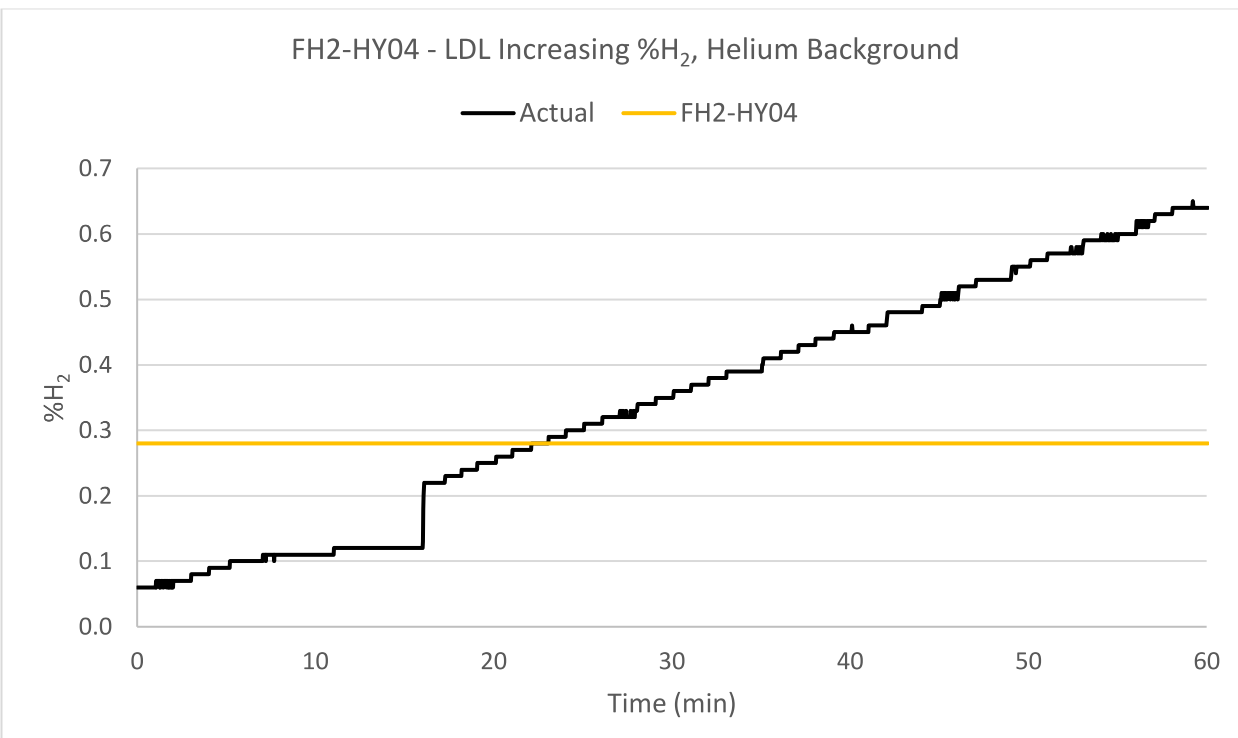

Figure 122. FH2-HY04 data for the LDL test with increasing $\%H_2$ in a helium background.

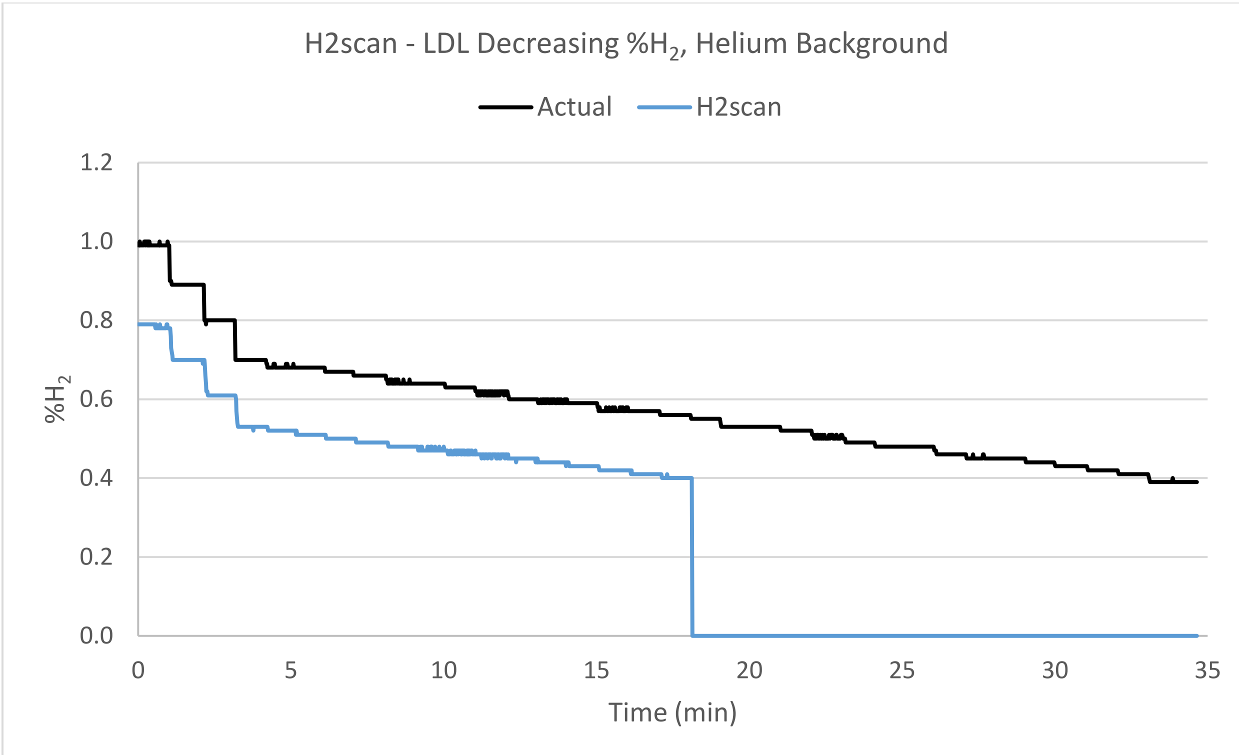

Figure 123. H2scan data for the LDL test with decreasing $\%H_2$ in a helium background.

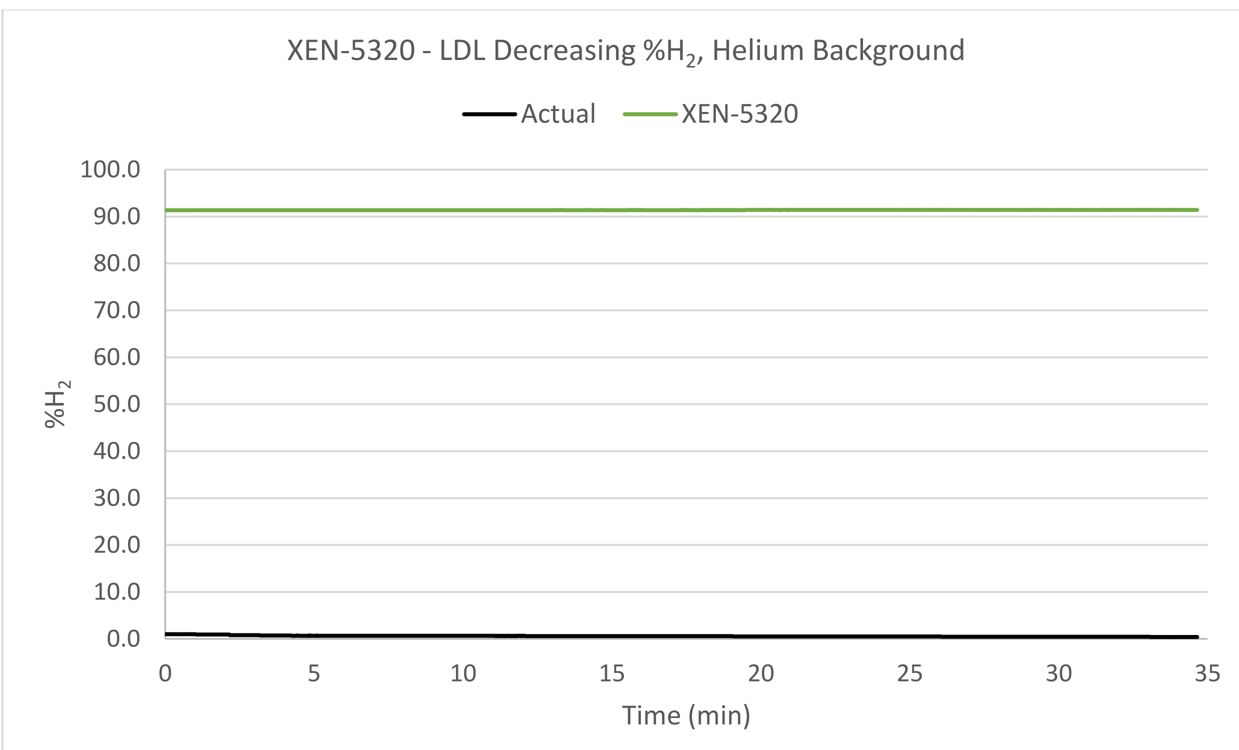

Figure 124. XEN-5320 data for the LDL test with decreasing $\%H_2$ in a helium background.

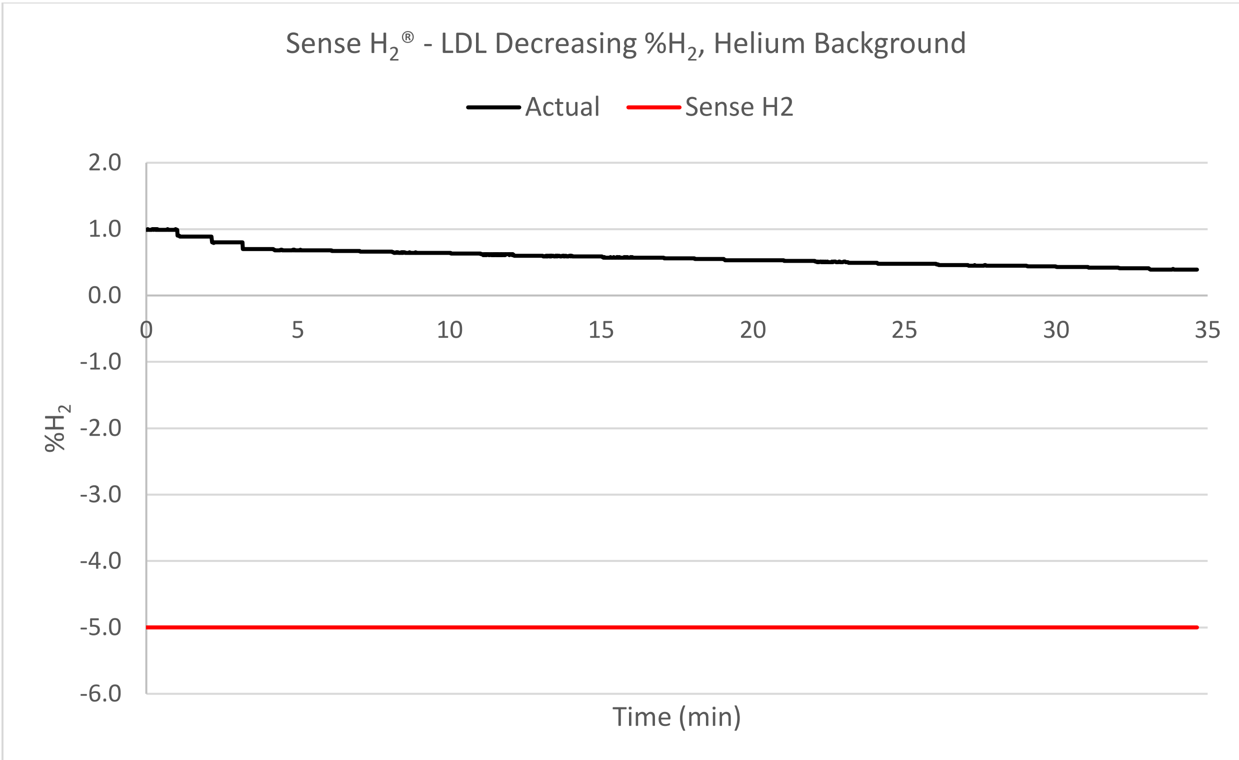

Figure 125. Sense H_2® data for the LDL test with decreasing $\%H_2$ in a helium background.

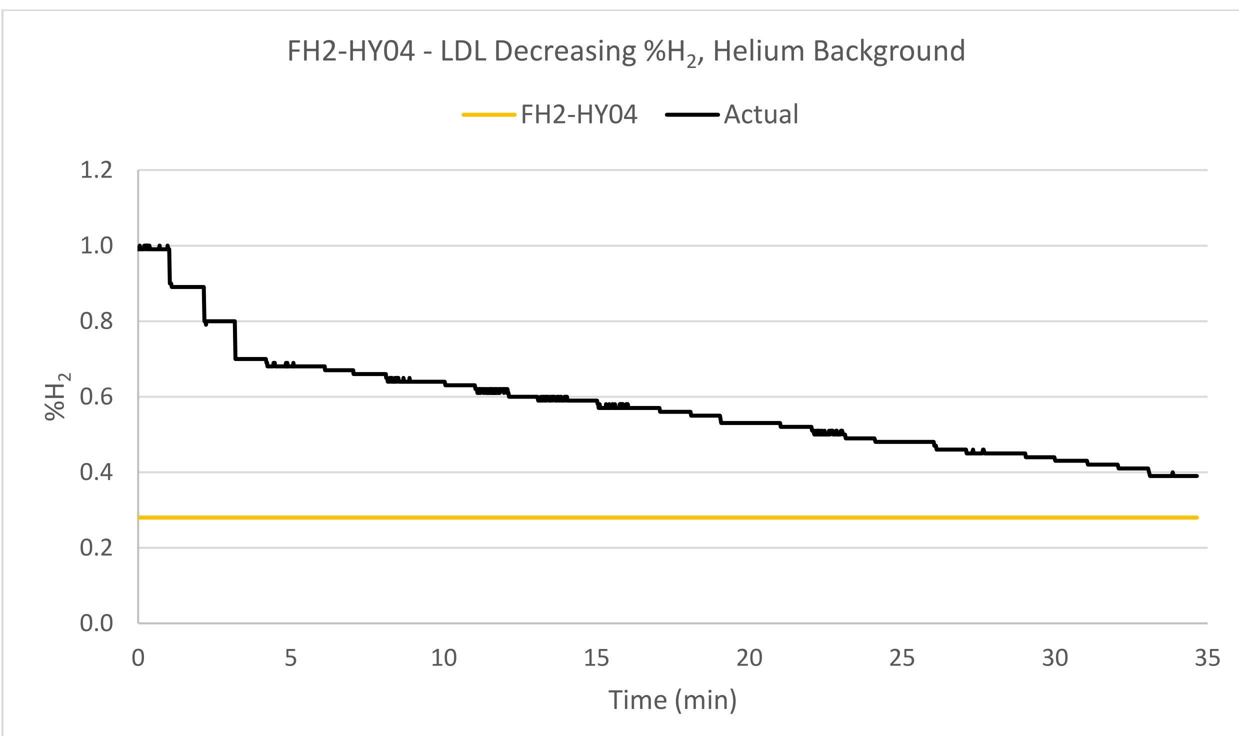

Figure 126. FH2-HY04 data for the LDL test with decreasing $\%H_2$ in a helium background.

It should be noted that the concentrations specified, or shown as "actual" hydrogen 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 lists the lower detectible limits measured for each sensor. Because none of the other sensors were functioning properly in the helium background, only the H2scan data is given on the table.

Table 10. Lower Detectible Limit Test Results – Helium Background.

Sensor	LDL for Increasing %H_2 (%H_2)	LDL for Decreasing %H_2 (%H_2)	Average LDL (%H_2)
H2scan 720B	0.56	0.56	0.56

Stair Step Test

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

Procedure

1. Connect hydrogen 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% hydrogen.
6. Allow outputs to stabilize.
7. Adjust gas flows for a hydrogen concentration of 0.5%.
8. Collect data for a sufficient time to allow outputs to stabilize.
9. Increase the hydrogen concentration in steps, going up 0.5% (or similar value, based on available hydrogen concentrations) each time, until the maximum hydrogen concentration is reached, collecting data for a sufficient duration to allow output stabilization each time.
10. Using the same hydrogen concentrations, step the concentration down incrementally back to ~0% hydrogen, 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 hydrogen concentration as follows.

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

where

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

$\overline{output}_{sensor}$ = 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 hydrogen 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

$\overline{\mathrm{output}}_{\mathrm{sensor}}$ = 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).

Results – Air Background

Figure 127 through Figure 142 show data collected during the stair step test with an air background.

The H2scan sensor did not always detect the 0.5% steps, as they were close to its LDL with the current calibration. This may improve following calibration of the sensor. Otherwise, its steps were consistent within each test. The sensor's offset from the actual hydrogen concentration would likely improve with calibration.

The XEN-5320 sensors all showed each step consistently. The sensors' offsets from the actual hydrogen concentration would likely improve with calibration.

The Sense H_2® had inconsistent results from one sensor to another. In most tests, the outputs for 2% hydrogen and 2.4% hydrogen were the same. Some tests, however, had the same output for 2.4% hydrogen and 2.8% hydrogen. In some cases, the output alternated between two values 0.5% H_2 apart while the hydrogen concentration remained constant.

The FH2-HY04 sensor had even steps and responded at all concentrations. It was consistent for all replications of the stair step pattern within each test, but did have some variation from one sensor to another. This sensor's manual does not list any calibration options, but it is possible that a correction could be applied to its outputs to at least partly improve the offset.

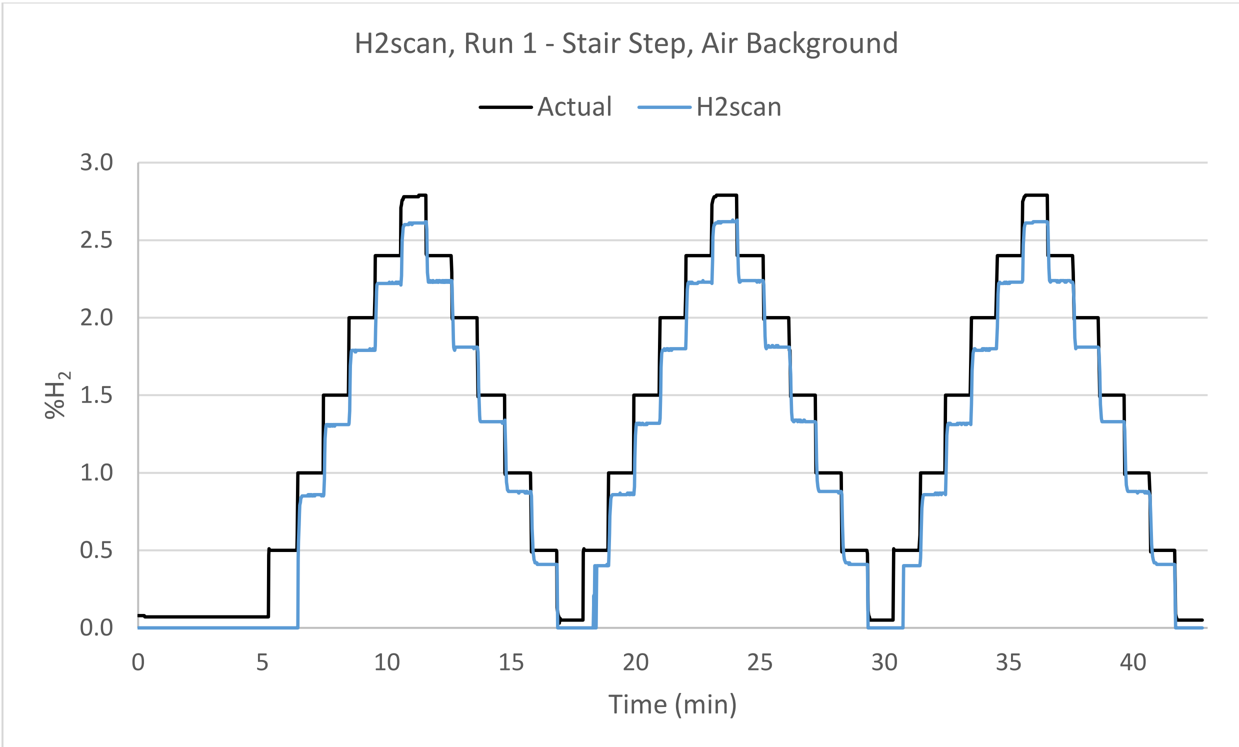

Figure 127. H2scan data for run 1 of the stair step test with an air background.

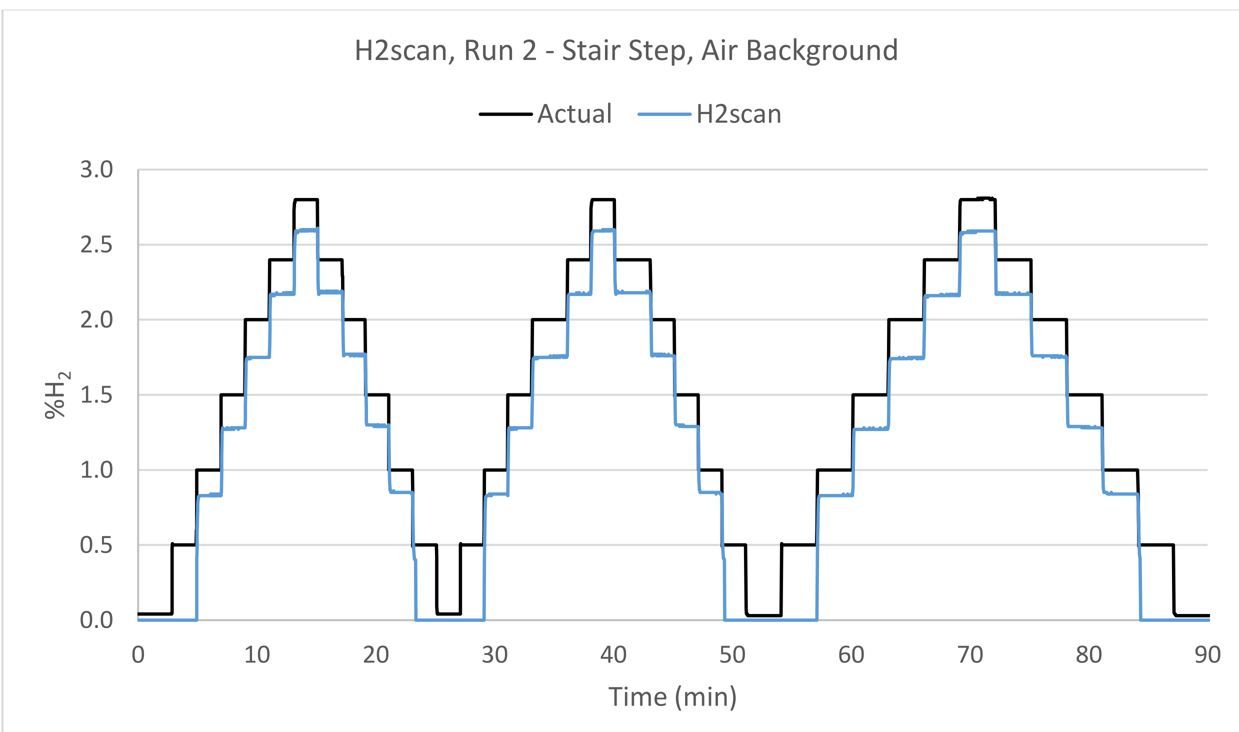

Figure 128. H2scan data for run 2 of the stair step test with an air background.

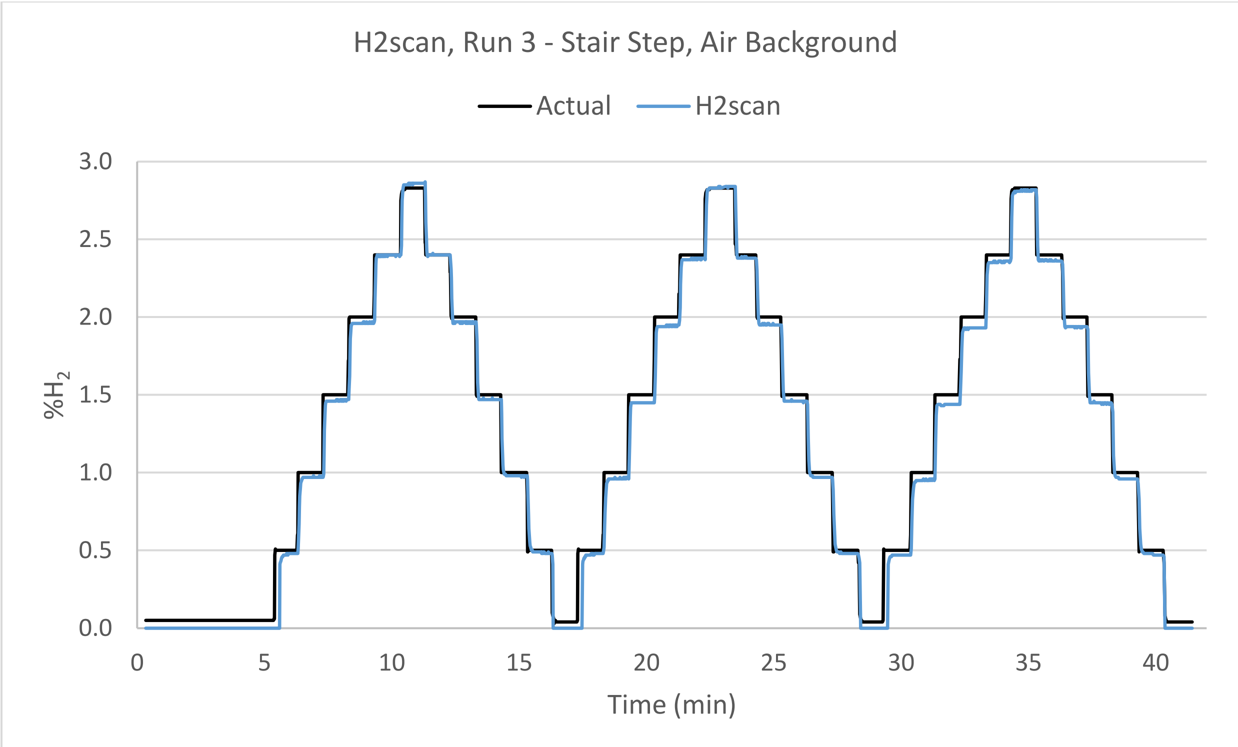

Figure 129. H2scan data for run 3 of the stair step test with an air background.

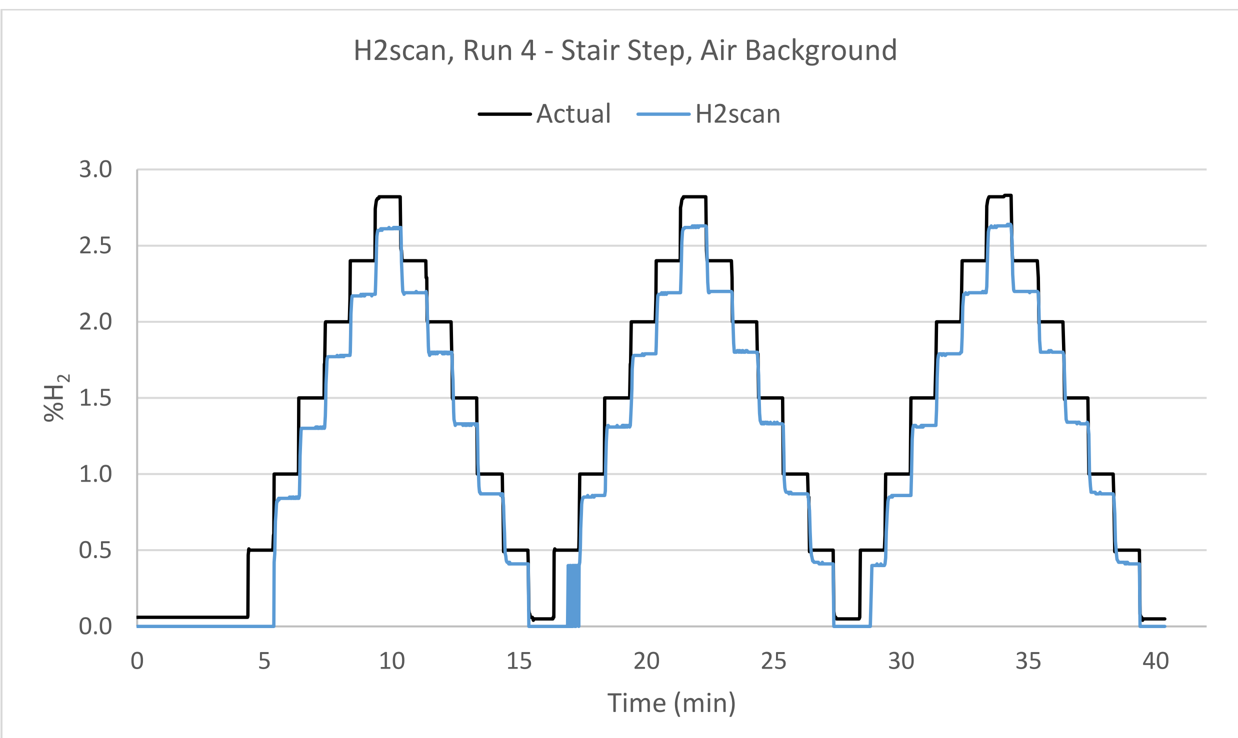

Figure 130. H2scan data for run 4 of the stair step test with an air background.

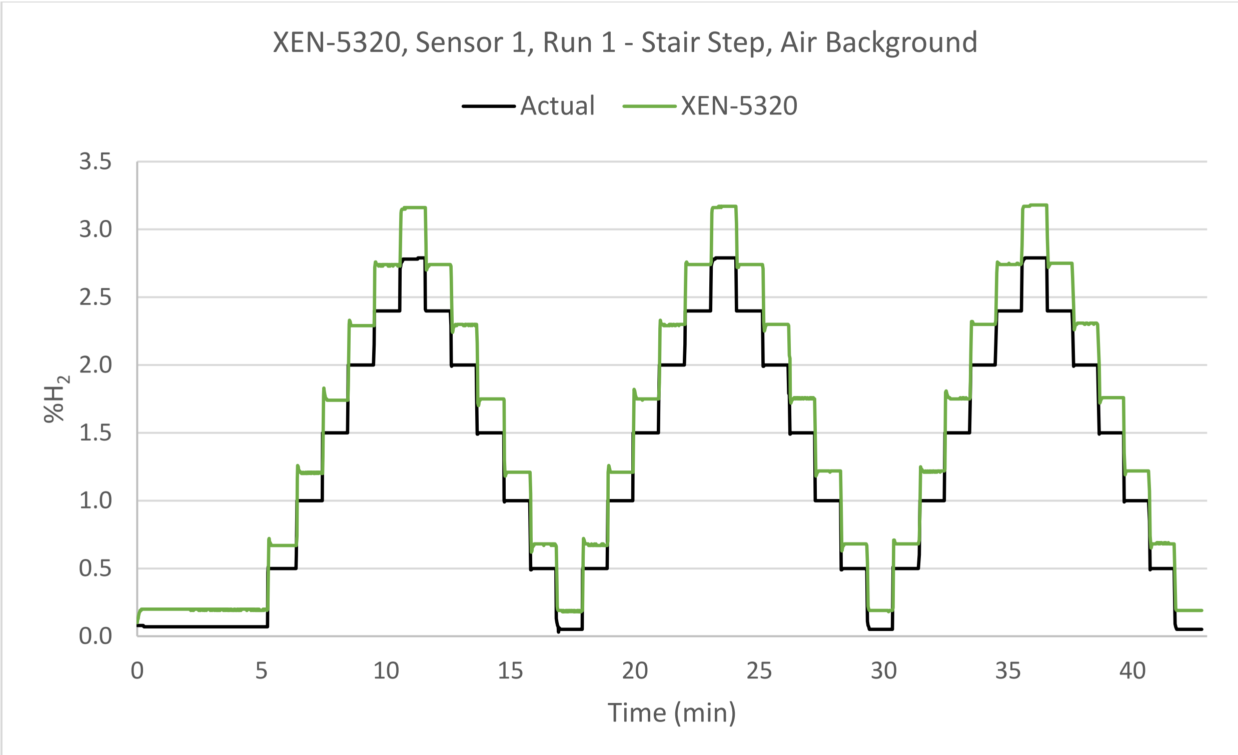

Figure 131. XEN-5320 data for sensor 1, run 1 of the stair step test with an air background.

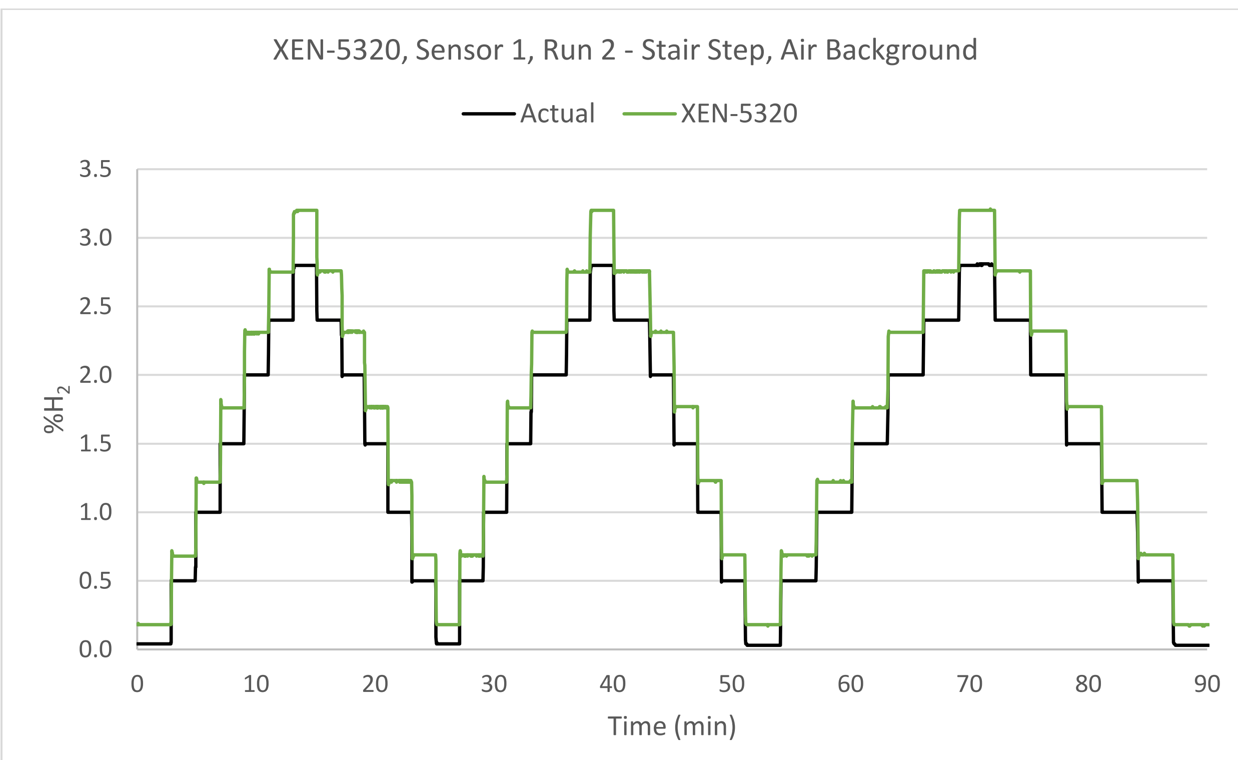

Figure 132. XEN-5320 data for sensor 1, run 2 of the stair step test with an air background.

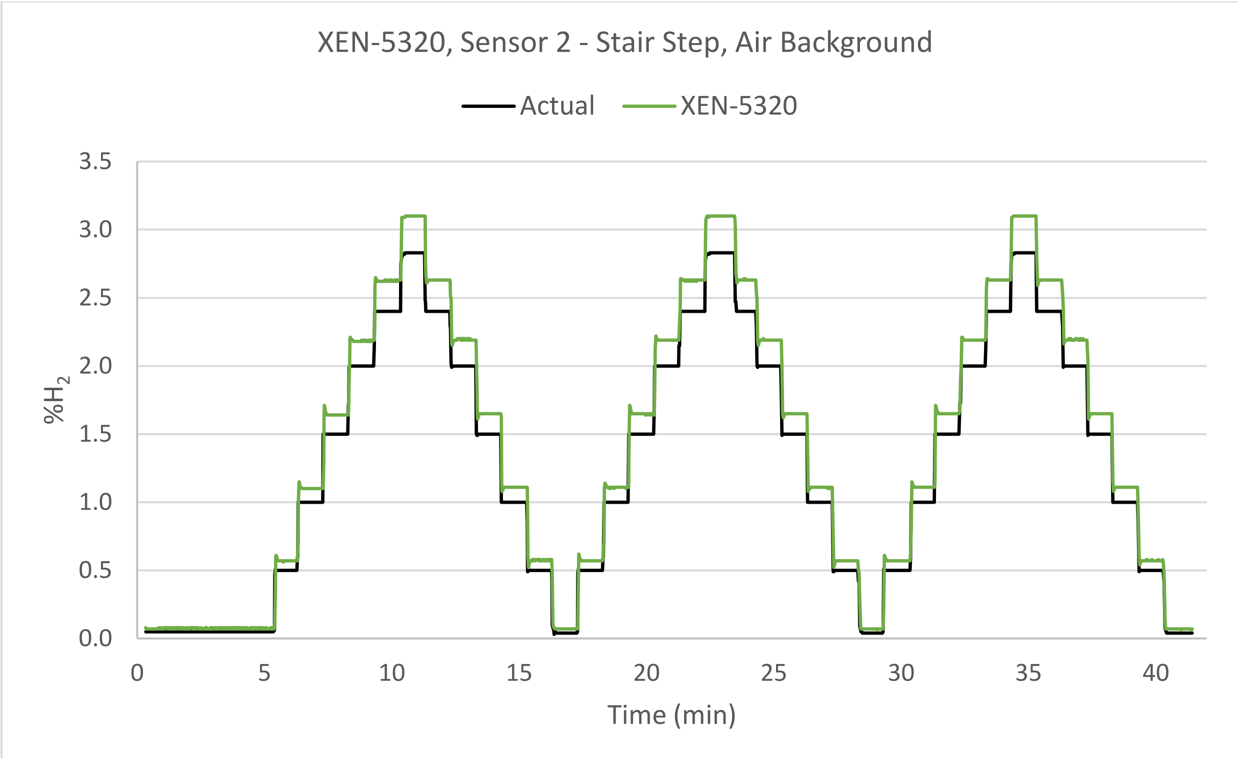

Figure 133. XEN-5320 data for sensor 2 in the stair step test with an air background.

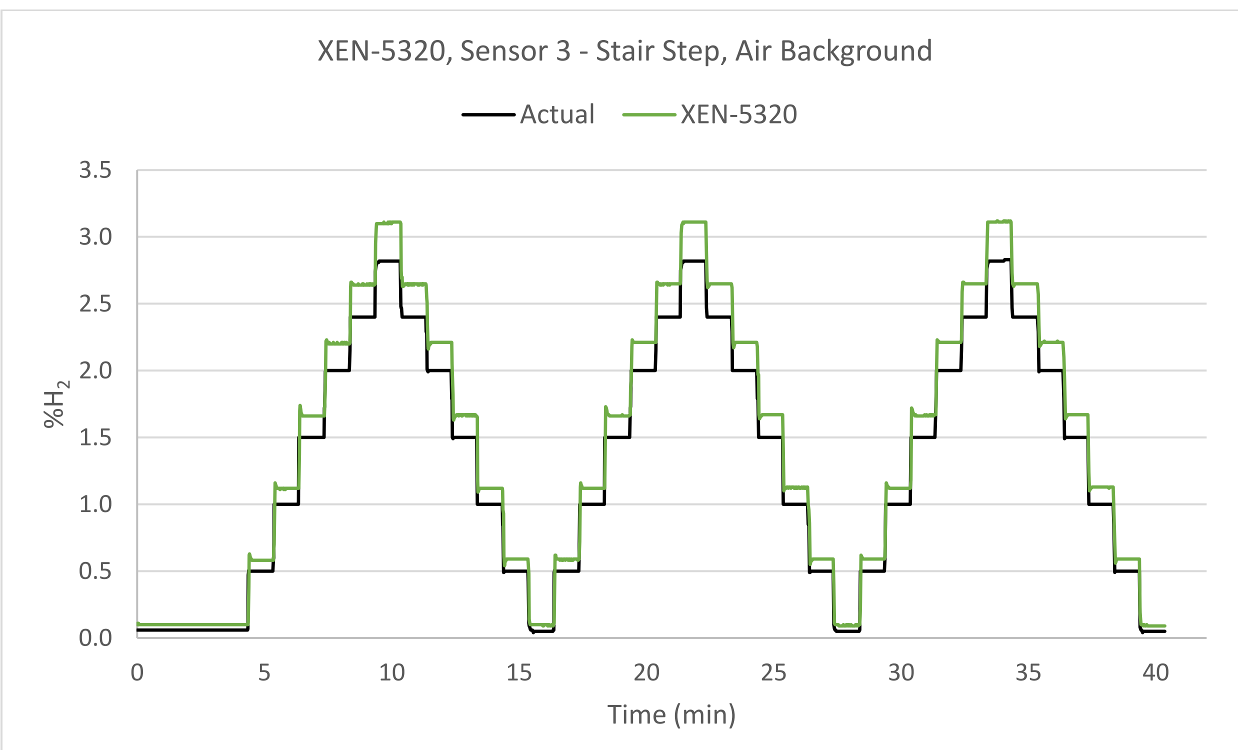

Figure 134. XEN-5320 data for sensor 3 in the stair step test with an air background.

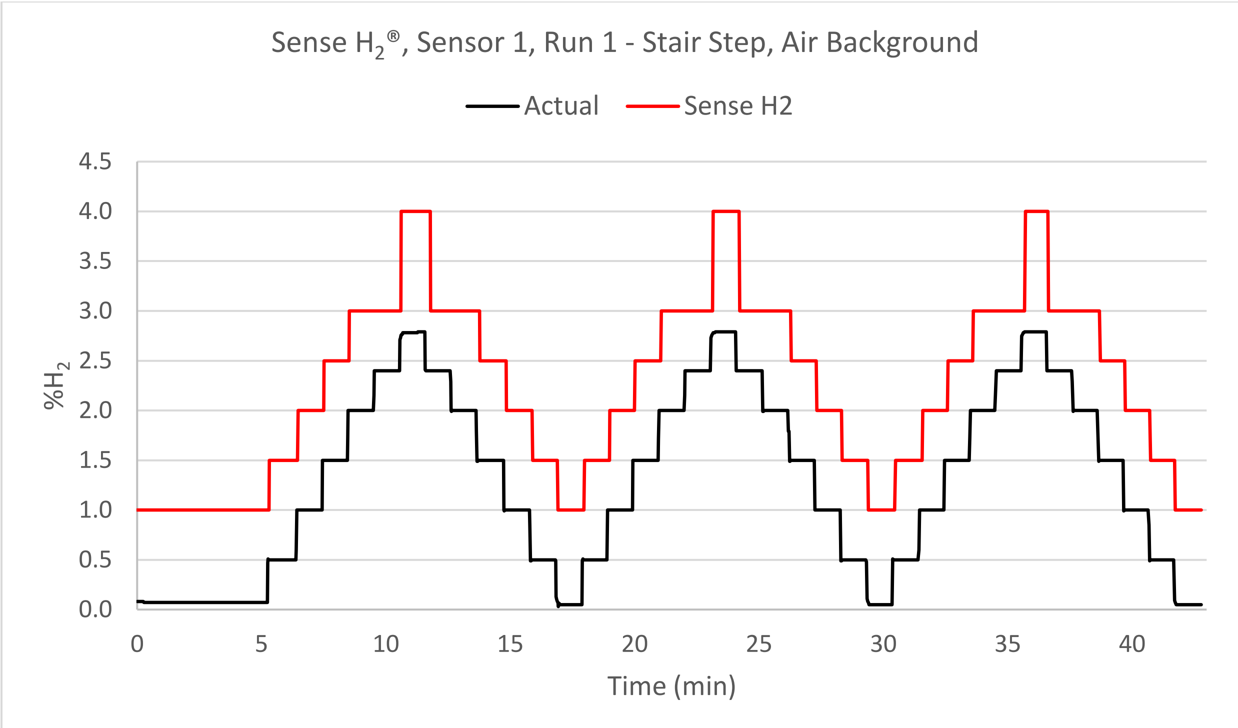

Figure 135. Sense H_2® data for sensor 1, run 1 of the stair step test with an air background.

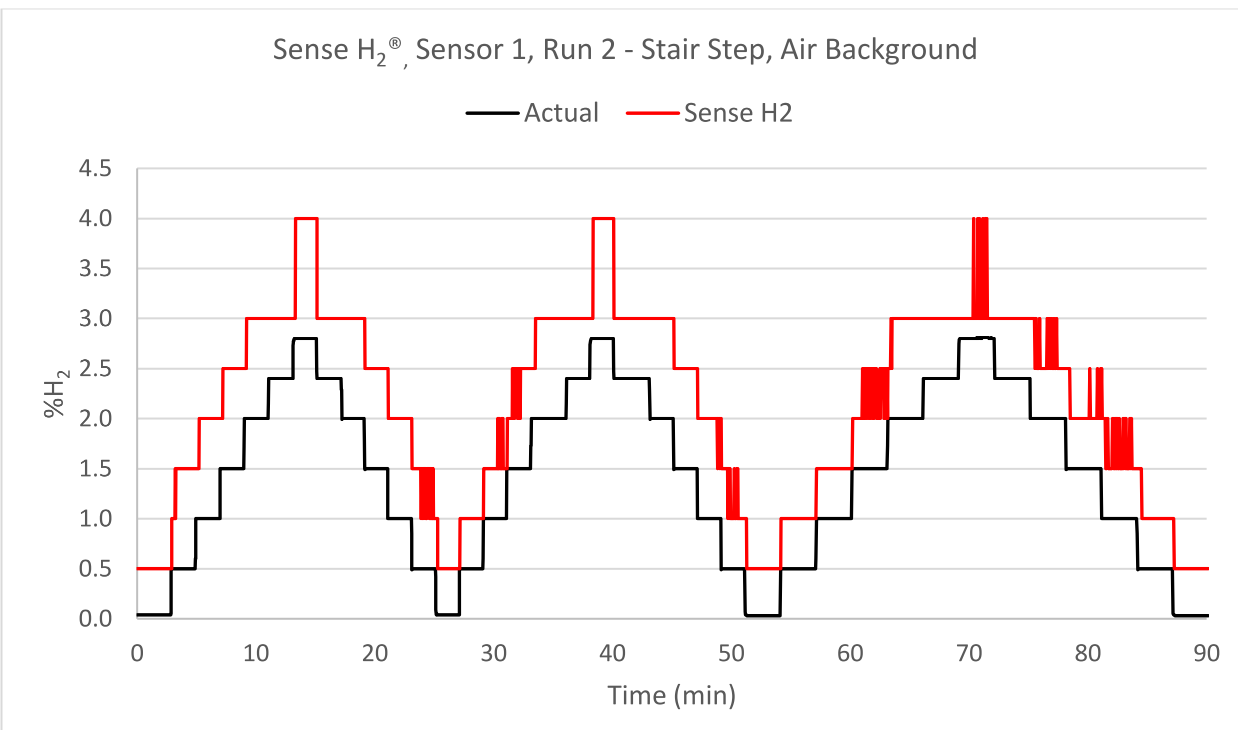

Figure 136. Sense H_2® data for sensor 1, run 2 of the stair step test with an air background.

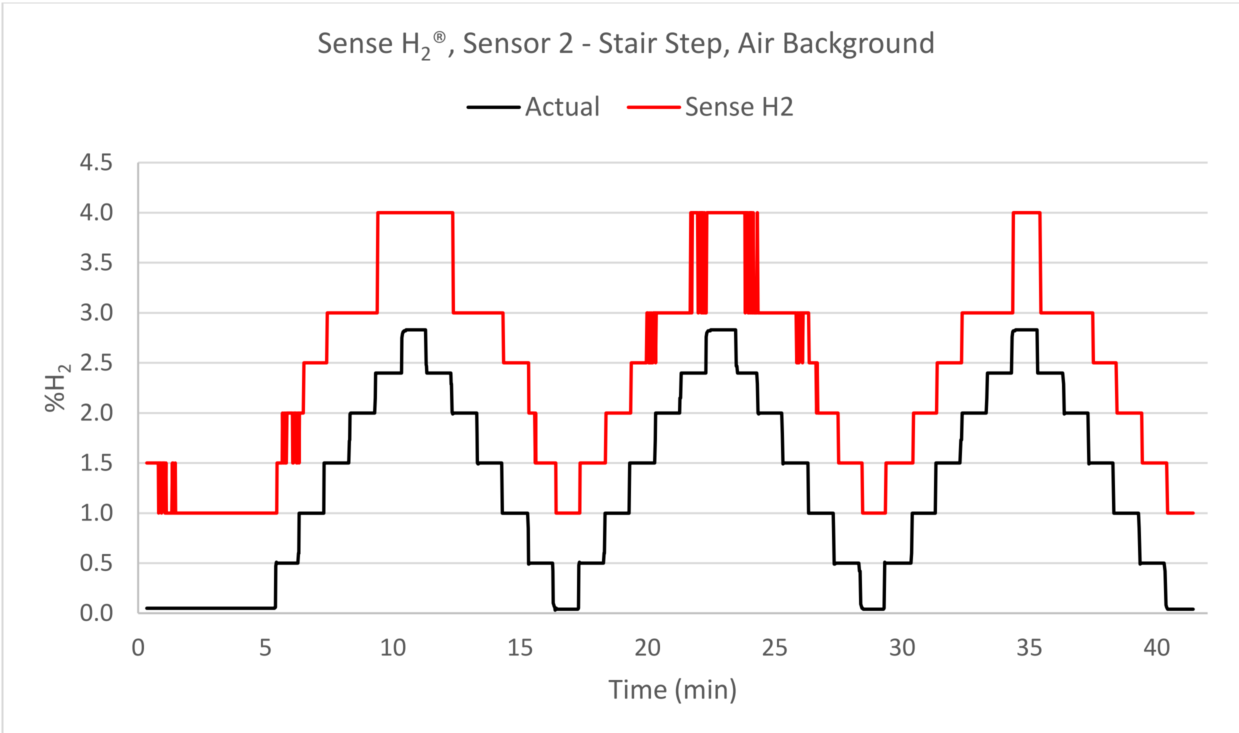

Figure 137. Sense H_2® data for sensor 2 in the stair step test with an air background.

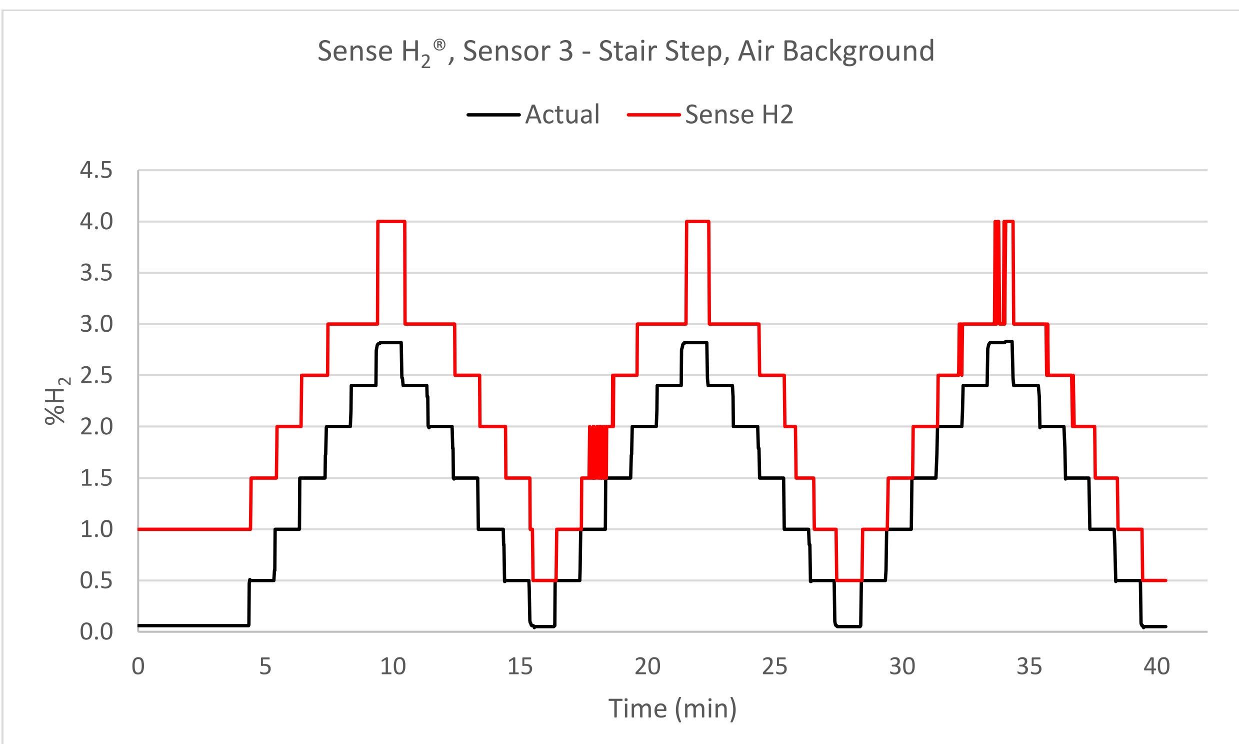

Figure 138. Sense H_2® data for sensor 3 in the stair step test with an air background.

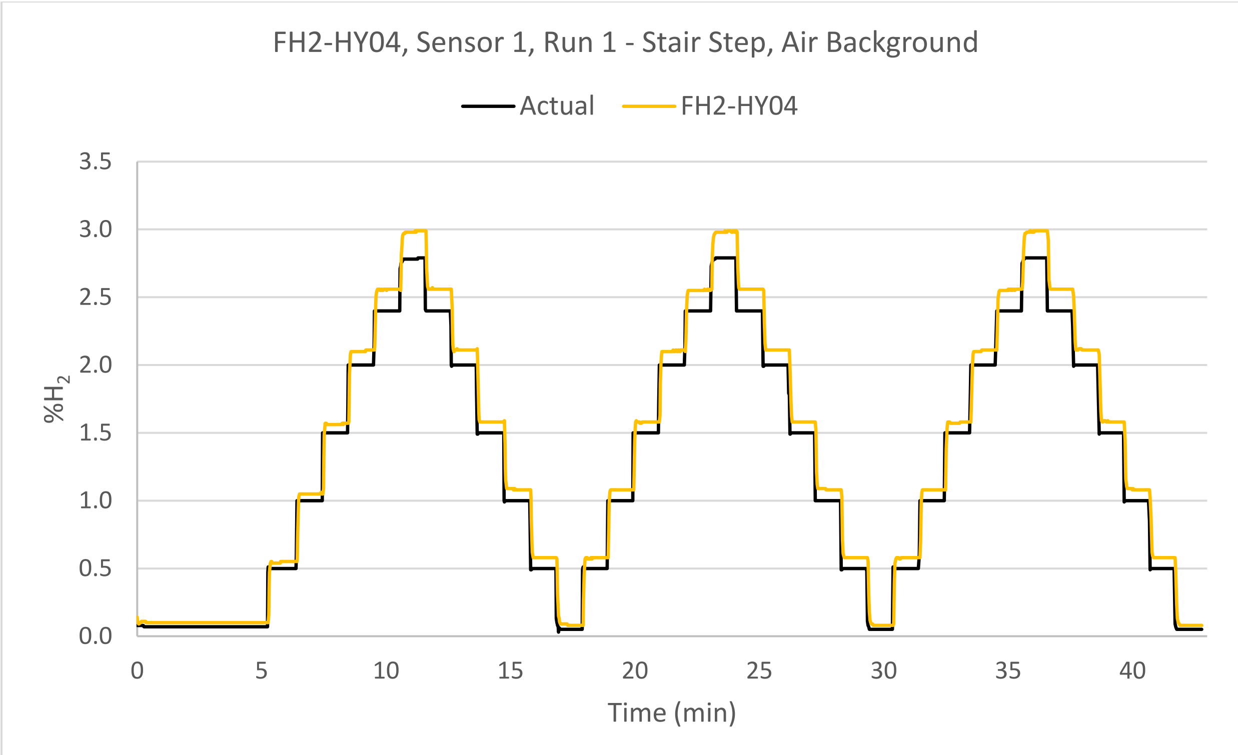

Figure 139. FH2-HY04 data for sensor 1, run 1 of the stair step test with an air background.

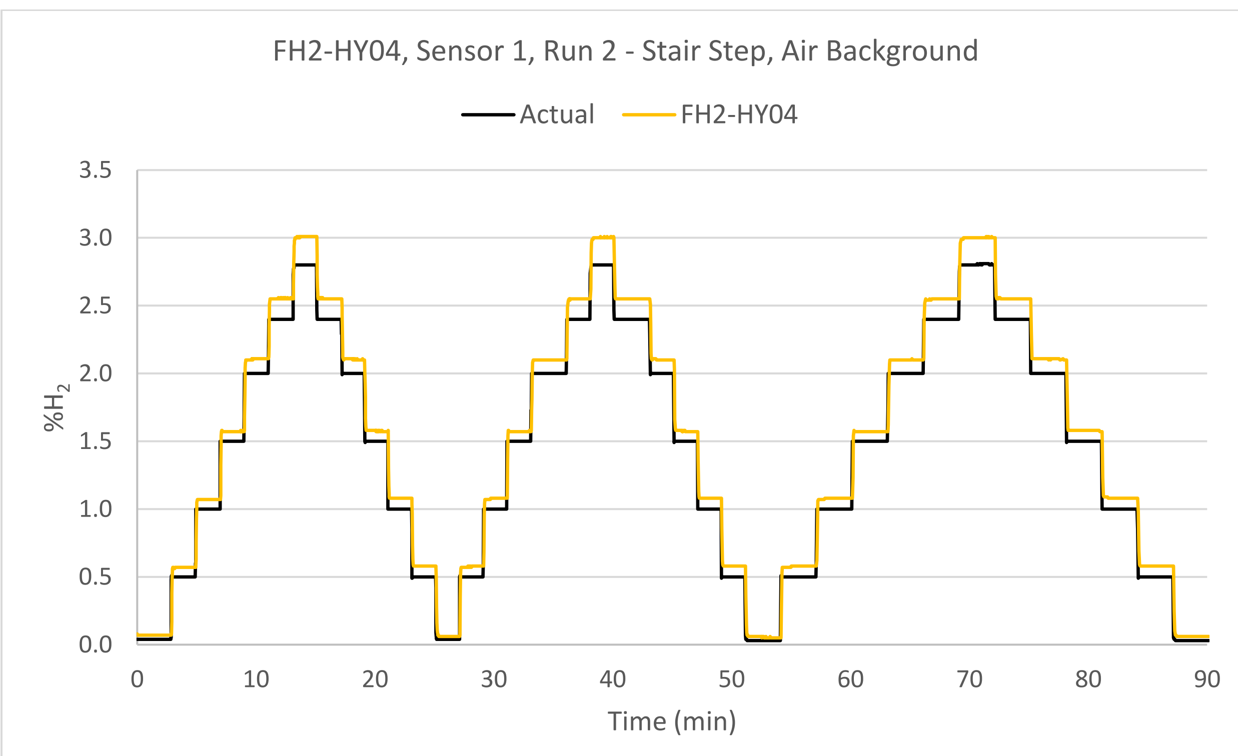

Figure 140. FH2-HY04 data for sensor 1, run 2 of the stair step test with an air background.

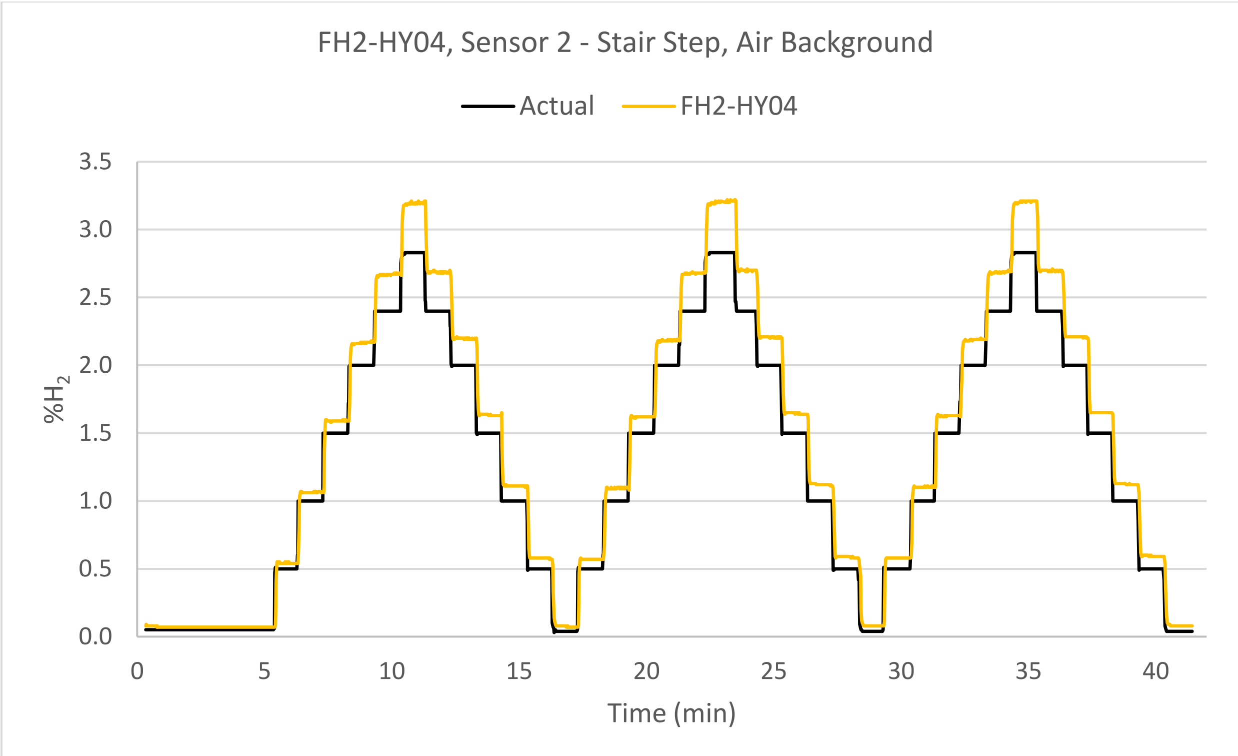

Figure 141. FH2-HY04 data for sensor 2 in the stair step test with an air background.

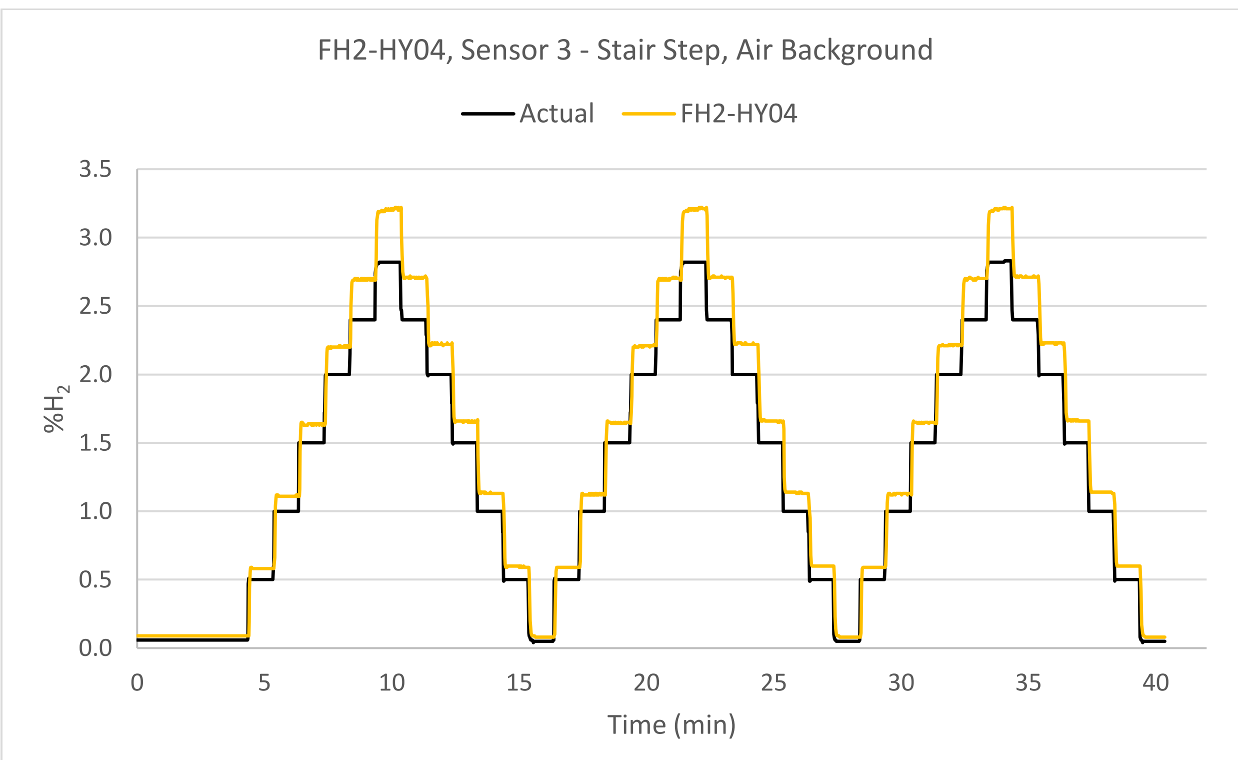

Figure 142. FH2-HY04 data for sensor 3 in the stair step test with an air background.

Table 11 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 precision values are cases of division by zero errors or values not collected. Accuracies for each value are also represented graphically in Figure 143 through Figure 146.

As previously discussed, the accuracies of the H2scan, XEN-5320, and FH2-HY04 could be improved with calibration. The accuracies were much worse for the ~0% hydrogen concentrations because the concentrations are so small.

In most cases, the precision values were very low, which is good. In one instance, the H2scan had a precision of 19% due to the sensor output toggling between 0.40% and 0.00% for a 0.50% hydrogen concentration.

For most sensors and hydrogen 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 hydrogen concentration (shown in shaded cells in the table) and another for steps which resulted from a decreased hydrogen concentration.

These individual values were averaged for each test, not including the ~0% values for accuracy, which are skewed exceptionally large due to the very small concentrations, the results of which are given in Table 12.

Table 11. Accuracy and Precision Results – Air Background.

Sensor	Sensor/ Run	%H_2	Value 1	Value 2	Value 3	Value 4	Value 5	Value 6	Average Accuracy	Average Precision
H2scan 720B	Run 1	~0.06%	0.00	0.00	0.00	0.00	-	-	-100%	-
		0.50%	0.00	0.41	0.40	0.41	0.40	0.41	-32%	0%
		1.00%	0.86	0.88	0.86	0.88	0.86	0.88	-13%	0%
		1.50%	1.31	1.33	1.32	1.33	1.32	1.33	-12%	0%
		2.00%	1.79	1.81	1.80	1.81	1.80	1.81	-10%	0%
		2.40%	2.22	2.23	2.23	2.24	2.23	2.24	-7%	0%
		~2.79%	2.61	2.62	2.62	-	-	-	-6%	0%
	Run 2	~0.04%	0.00	0.00	0.00	0.00	-	-	-100%	-
		0.50%	0.00	0.00	0.00	0.00	0.00	0.00	-100%	-
		1.00%	0.83	0.85	0.84	0.85	0.83	0.84	-16%	0%
		1.50%	1.28	1.30	1.28	1.29	1.27	1.29	-14%	0%
		2.00%	1.75	1.77	1.75	1.76	1.74	1.76	-12%	0%
		2.40%	2.17	2.18	2.17	2.18	2.16	2.17	-9%	0%
		2.80%	2.59	2.59	2.59	-	-	-	-7%	0%
	Run 3	~0.04%	0.00	0.00	0.00	0.00	-	-	-100%	-
		0.50%	0.47	0.49	0.47	0.48	0.47	0.48	-5%	2%
		1.00%	0.97	0.98	0.96	0.97	0.95	0.96	-3%	0%
		1.50%	1.46	1.47	1.45	1.46	1.44	1.45	-3%	0%
		2.00%	1.96	1.97	1.94	1.95	1.93	1.94	-3%	0%
		2.40%	2.40	2.40	2.37	2.38	2.35	2.36	-1%	0%
		2.83%	2.86	2.84	2.81	-	-	-	0%	0%
	Run 4	~0.05%	0.00	0.00	0.00	0.00	-	-	-100%	-

		0.50%	0.00	0.41	0.23	0.41	0.40	0.41	-38%	19%
		1.00%	0.84	0.87	0.86	0.87	0.86	0.87	-14%	1%
		1.50%	1.30	1.33	1.31	1.33	1.32	1.34	-12%	0%
		2.00%	1.77	1.80	1.79	1.80	1.79	1.80	-10%	0%
		2.40%	2.18	2.19	2.19	2.20	2.19	2.20	-9%	0%
		2.82%	2.61	2.63	2.63	-	-	-	-7%	0%
XEN-5320	Sensor 1 Run 1	~0.06%	0.20	0.19	0.19	0.19	-	-	247%	1%
		0.50%	0.67	0.68	0.67	0.68	0.68	0.68	35%	0%
		1.00%	1.21	1.21	1.21	1.22	1.22	1.22	21%	0%
		1.50%	1.74	1.75	1.75	1.75	1.75	1.76	17%	1%
		2.00%	2.29	2.30	2.30	2.30	2.30	2.31	15%	0%
		2.40%	2.74	2.74	2.74	2.74	2.74	2.75	14%	0%
		~2.79%	3.16	3.17	3.18	-	-	-	14%	0%
	Sensor 1 Run 2	~0.04%	0.18	0.18	0.18	0.18	-	-	414%	1%
		0.50%	0.68	0.69	0.69	0.69	0.69	0.69	38%	0%
		1.00%	1.22	1.23	1.22	1.23	1.22	1.23	22%	0%
		1.50%	1.76	1.77	1.76	1.77	1.76	1.77	18%	0%
		2.00%	2.31	2.31	2.31	2.31	2.31	2.32	16%	0%
		2.40%	2.75	2.76	2.75	2.76	2.76	2.76	15%	0%
		2.80%	3.20	3.20	3.20	-	-	-	14%	0%
	Sensor 2	~0.04%	0.07	0.07	0.07	0.07	-	-	66%	3%
		0.50%	0.57	0.57	0.57	0.57	0.57	0.57	14%	0%
		1.00%	1.10	1.11	1.11	1.11	1.11	1.11	11%	0%
		1.50%	1.64	1.65	1.65	1.65	1.65	1.65	10%	0%
		2.00%	2.18	2.19	2.19	2.19	2.19	2.19	9%	0%
		2.40%	2.62	2.63	2.63	2.63	2.63	2.63	10%	0%
		2.83%	3.10	3.10	3.10	-	-	-	10%	0%
	Sensor 3	~0.05%	0.10	0.10	0.09	0.09	-	-	82%	3%
		0.50%	0.58	0.59	0.59	0.59	0.59	0.59	18%	0%
		1.00%	1.12	1.12	1.12	1.13	1.12	1.13	12%	0%
		1.50%	1.66	1.67	1.66	1.67	1.66	1.67	11%	0%
		2.00%	2.20	2.21	2.21	2.21	2.21	2.21	10%	0%
		2.40%	2.64	2.65	2.65	2.65	2.65	2.65	10%	0%
		2.82%	3.11	3.11	3.11	-	-	-	10%	0%
Sense H_2®	Sensor 1 Run 1	~0.06%	1.0	1.0	1.0	1.0	-	-	1718%	0%
		0.50%	1.5	1.5	1.5	1.5	1.5	1.5	200%	0%
		1.00%	2.0	2.0	2.0	2.0	2.0	2.0	100%	0%
		1.50%	2.5	2.5	2.5	2.5	2.5	2.5	67%	0%
		2.00%	3.0	3.0	3.0	3.0	3.0	3.0	50%	0%
		2.40%	3.0	3.0	3.0	3.0	3.0	3.0	25%	0%
		~2.79%	4.0	4.0	4.0	-	-	-	43%	0%
	Sensor 1 Run 2	~0.04%	0.5	0.5	0.5	0.5	-	-	1329%	0%
		0.50%	1.5	1.4	1.0	1.2	1.0	1.0	136%	6%
		1.00%	1.9	2.0	1.6	1.9	1.5	1.7	77%	6%
		1.50%	2.5	2.5	2.3	2.5	2.2	2.0	56%	5%
		2.00%	3.0	3.0	3.0	3.0	3.0	2.7	47%	1%

		2.40%	3.0	3.0	3.0	3.0	3.0	3.0	25%	0%
		2.80%	4.0	4.0	3.1	-	-	-	32%	3%
	Sensor 2	~0.04%	1.1	1.0	1.0	1.0	-	-	2297%	4%
		0.50%	1.8	1.6	1.5	1.5	1.5	1.5	213%	4%
		1.00%	2.5	2.5	2.0	2.1	2.0	2.0	119%	2%
		1.50%	3.0	3.0	2.6	2.9	2.5	2.5	84%	2%
		2.00%	3.0	3.0	3.0	3.0	3.0	3.0	50%	0%
		2.40%	4.0	4.0	3.5	3.6	3.0	3.0	46%	5%
		2.83%	4.0	4.0	4.0	-	-	-	41%	0%
	Sensor 3	~0.05%	1.0	0.5	0.5	0.5	-	-	1090%	0%
		0.50%	1.5	1.5	1.0	1.0	1.0	1.0	133%	0%
		1.00%	2.0	2.0	1.6	1.7	1.5	1.6	73%	7%
		1.50%	2.5	2.5	2.4	2.5	2.0	2.1	56%	3%
		2.00%	3.0	3.0	2.9	3.0	2.5	2.6	42%	3%
		2.40%	3.0	3.0	3.0	3.0	3.0	3.0	25%	0%
		2.82%	4.0	4.0	3.5	-	-	-	36%	5%
FH2-HY04	Sensor 1 Run 1	~0.06%	0.10	0.08	0.08	0.08	-	-	56%	1%
		0.50%	0.55	0.58	0.58	0.58	0.58	0.58	15%	0%
		1.00%	1.05	1.08	1.08	1.08	1.08	1.08	8%	0%
		1.50%	1.56	1.58	1.58	1.58	1.58	1.58	5%	0%
		2.00%	2.10	2.11	2.10	2.11	2.11	2.11	5%	0%
		2.40%	2.56	2.56	2.55	2.56	2.55	2.56	7%	0%
		~2.79%	2.98	2.98	2.99	-	-	-	7%	0%
	Sensor 1 Run 2	~0.04%	0.07	0.06	0.06	0.06	-	-	75%	2%
		0.50%	0.57	0.58	0.58	0.58	0.58	0.58	15%	0%
		1.00%	1.07	1.08	1.08	1.08	1.08	1.08	8%	0%
		1.50%	1.57	1.58	1.57	1.57	1.57	1.58	5%	0%
		2.00%	2.11	2.11	2.10	2.11	2.10	2.12	5%	1%
		2.40%	2.55	2.55	2.55	2.55	2.55	2.55	6%	0%
		2.80%	3.01	3.00	3.00	-	-	-	7%	0%
	Sensor 2	~0.04%	0.07	0.08	0.08	0.08	-	-	81%	4%
		0.50%	0.54	0.58	0.57	0.59	0.58	0.59	15%	0%
		1.00%	1.06	1.11	1.10	1.12	1.10	1.13	10%	0%
		1.50%	1.59	1.63	1.62	1.65	1.63	1.65	9%	0%
		2.00%	2.17	2.20	2.18	2.21	2.19	2.21	10%	0%
		2.40%	2.67	2.69	2.68	2.70	2.69	2.70	12%	0%
		2.83%	3.20	3.20	3.21	-	-	-	13%	0%
	Sensor 3	~0.05%	0.09	0.08	0.08	0.08	-	-	57%	0%
		0.50%	0.58	0.60	0.59	0.60	0.59	0.60	19%	0%
		1.00%	1.11	1.13	1.12	1.14	1.13	1.14	13%	0%
		1.50%	1.64	1.66	1.65	1.66	1.65	1.66	10%	0%
		2.00%	2.20	2.22	2.21	2.22	2.21	2.23	11%	0%
		2.40%	2.69	2.71	2.70	2.71	2.70	2.71	13%	0%
		2.82%	3.20	3.21	3.21	-	-	-	14%	0%

Note: Shaded cells indicate values for which the concentration was increasing to reach the value. Unshaded cells are values for which the concentration was decreasing to reach the value.

Table 12. Average Accuracy and Precision Values – Air Background

Sensor	Sensor/Run	Overall Average Accuracy	Overall Average Precision
H2scan 720B	Run 1	-13%	0%
	Run 2	-27%	0%
	Run 3	-2%	0%
	Run 4	-15%	3%
	Sensor/Run Average	-14%	1%
XEN-5320	Sensor 1, Run 1	19%	0%
	Sensor 1, Run 2	20%	0%
	Sensor 2	11%	1%
	Sensor 3	12%	1%
	Sensor/Run Average	16%	1%
Sense H_2®	Sensor 1, Run 1	81%	0%
	Sensor 1, Run 2	62%	3%
	Sensor 2	92%	2%
	Sensor 3	61%	3%
	Sensor/Run Average	74%	2%
FH2-HY04	Sensor 1, Run 1	8%	0%
	Sensor 1, Run 2	8%	1%
	Sensor 2	11%	1%
	Sensor 3	13%	0%
	Sensor/Run Average	10%	1%

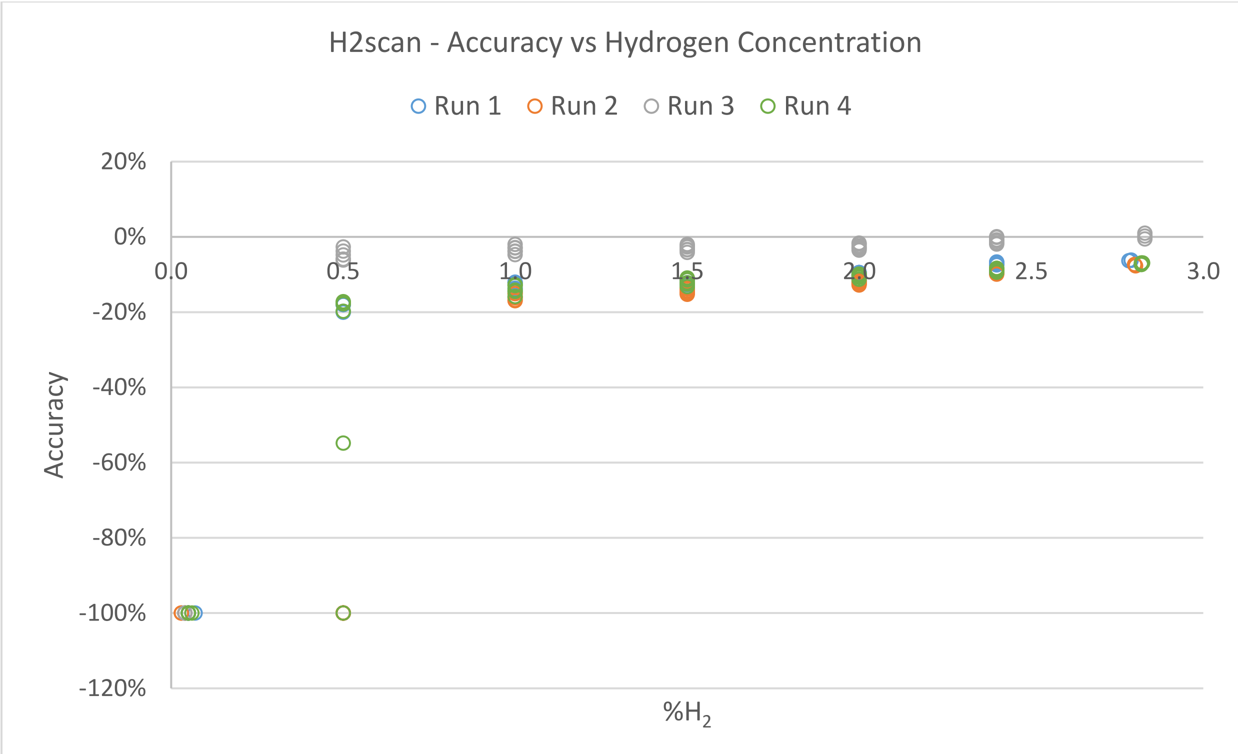

Figure 143. Accuracy of H2scan outputs for each hydrogen concentration, in an air background.

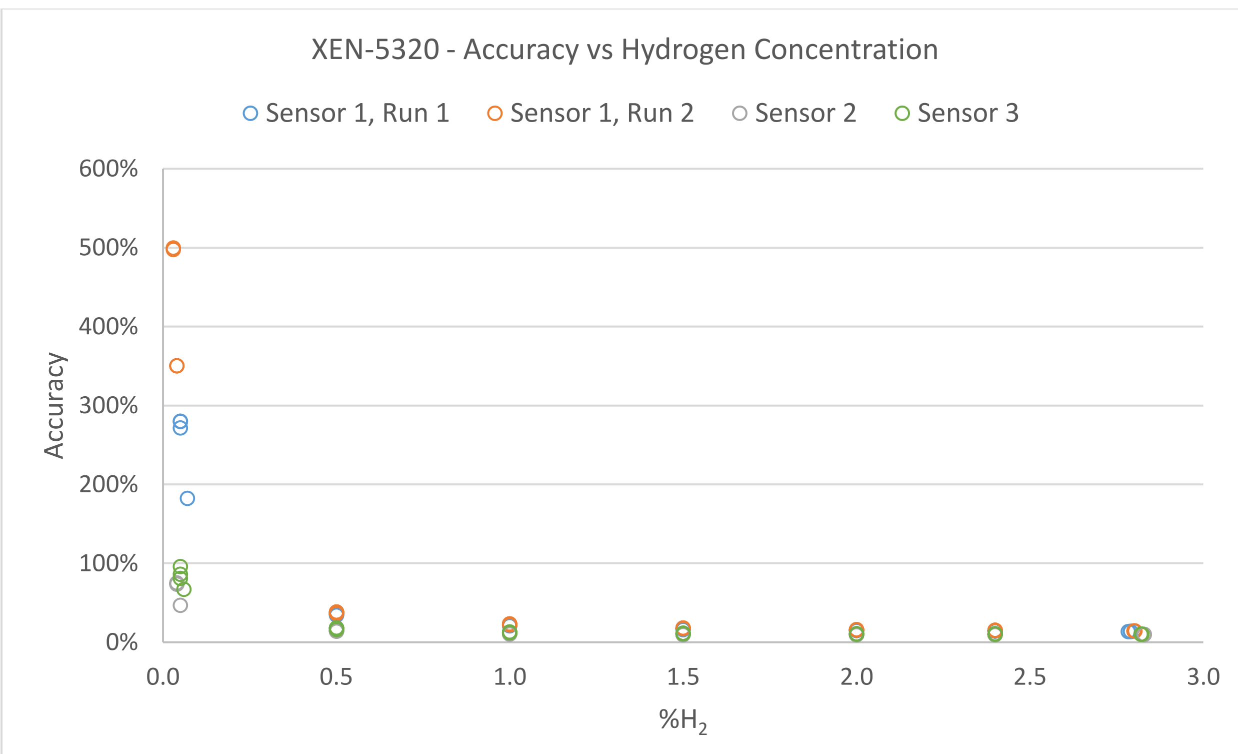

Figure 144. Accuracy of XEN-5320 outputs for each hydrogen concentration, in an air background.

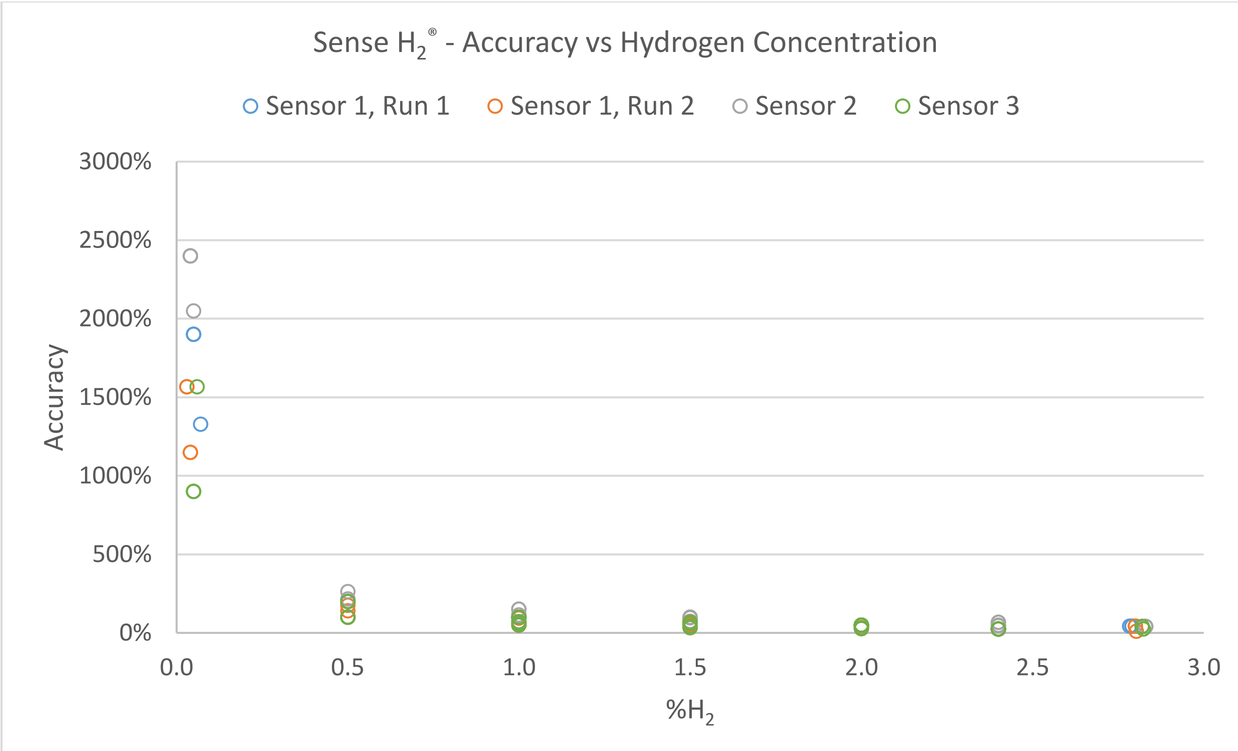

Figure 145. Accuracy of Sense H_2® outputs for each hydrogen concentration, in an air background.

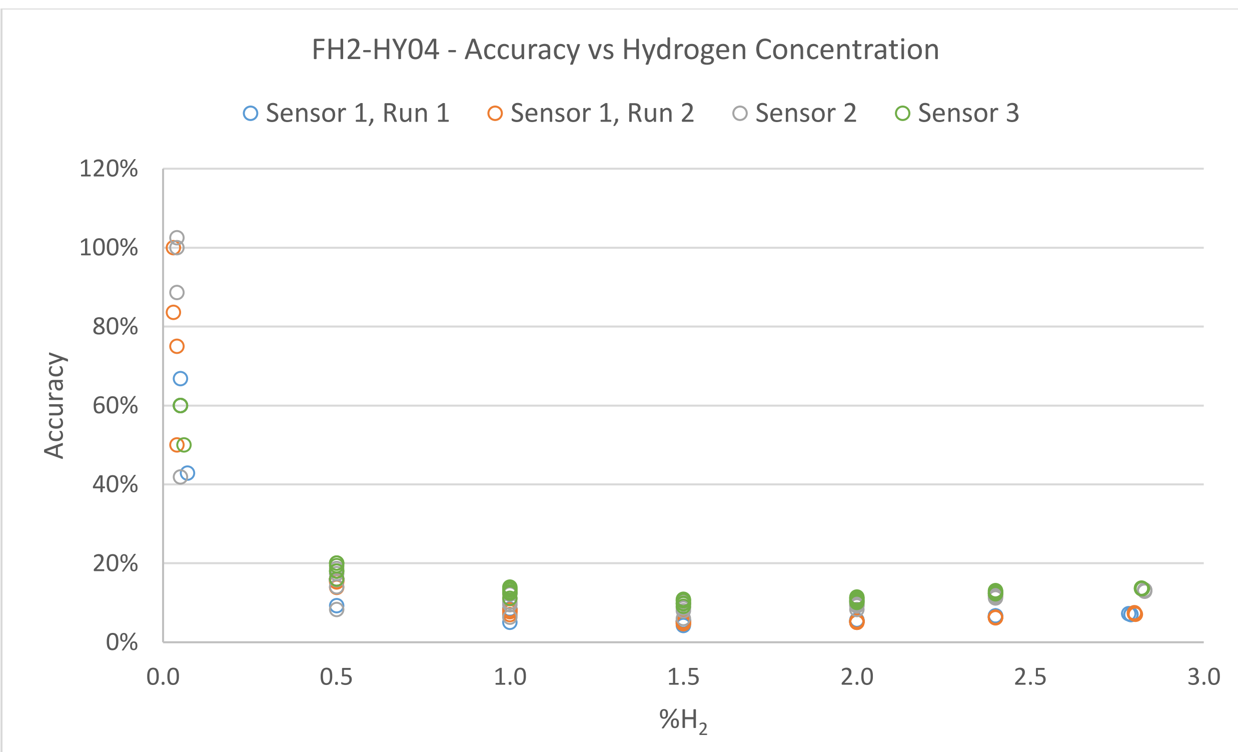

Figure 146. Accuracy of FH2-HY04 outputs for each hydrogen concentration, in an air background.

Results – Nitrogen Background

Figure 147 through Figure 158 show data collected during the stair step test with a nitrogen background.

Both the H2scan and the XEN-5320 sensors performed similarly in a nitrogen background to their performance in an air background. The offsets were different than in air background testing, indicating that a different calibration would likely be needed for a nitrogen background than an air background.

As with previous tests, the Sense H_2® and FH2-HY04 did not function anaerobically.

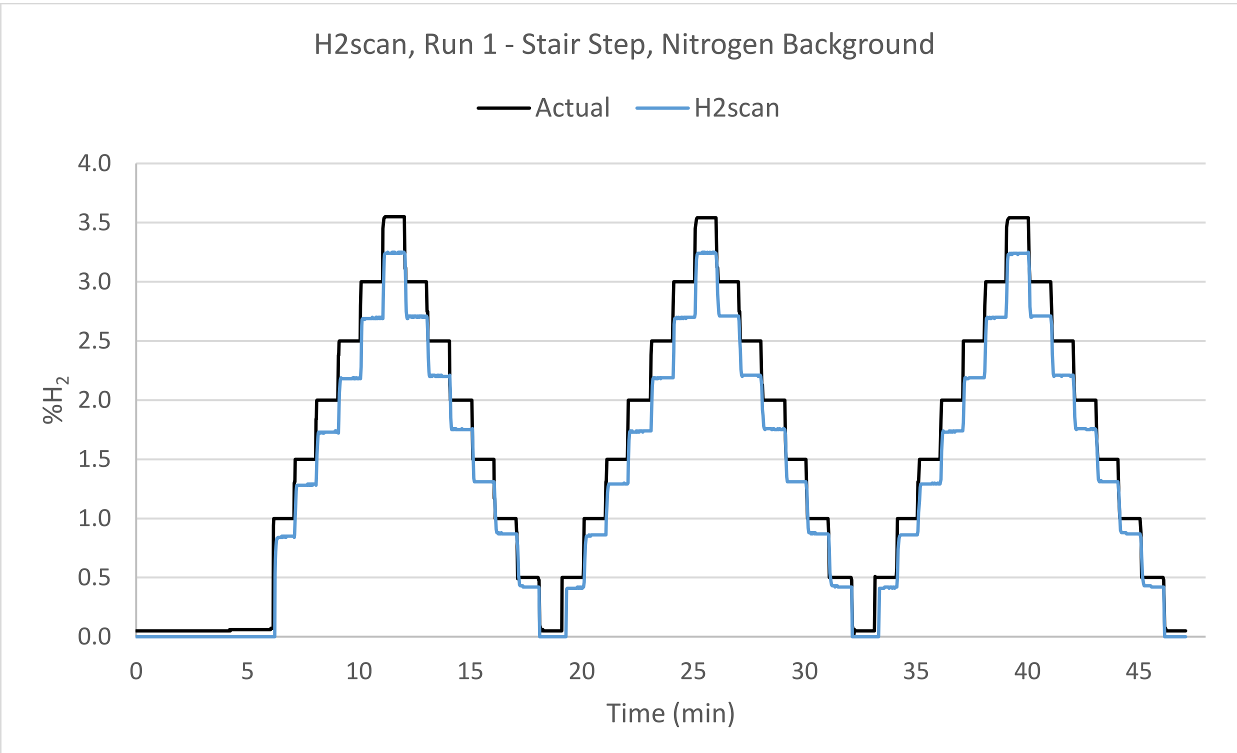

Figure 147. H2scan data for run 1 of the stair step test with a nitrogen background.

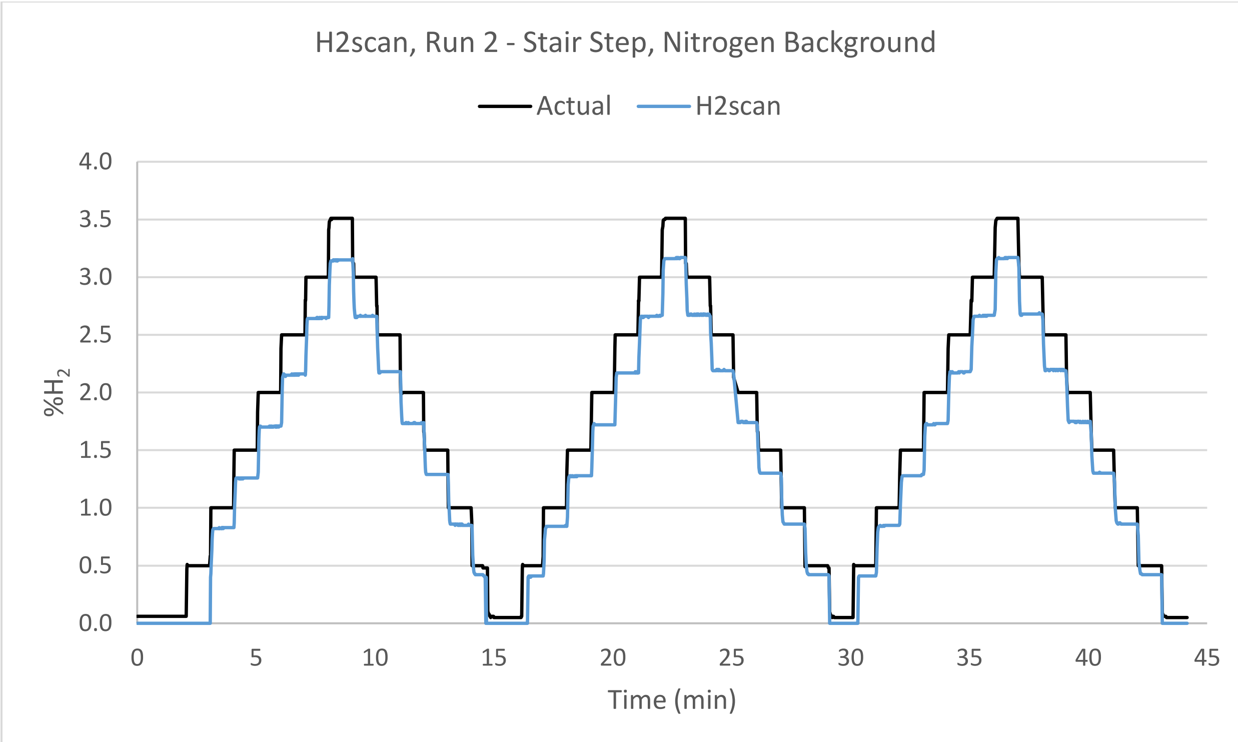

Figure 148. H2scan data for run 2 of the stair step test with a nitrogen background.

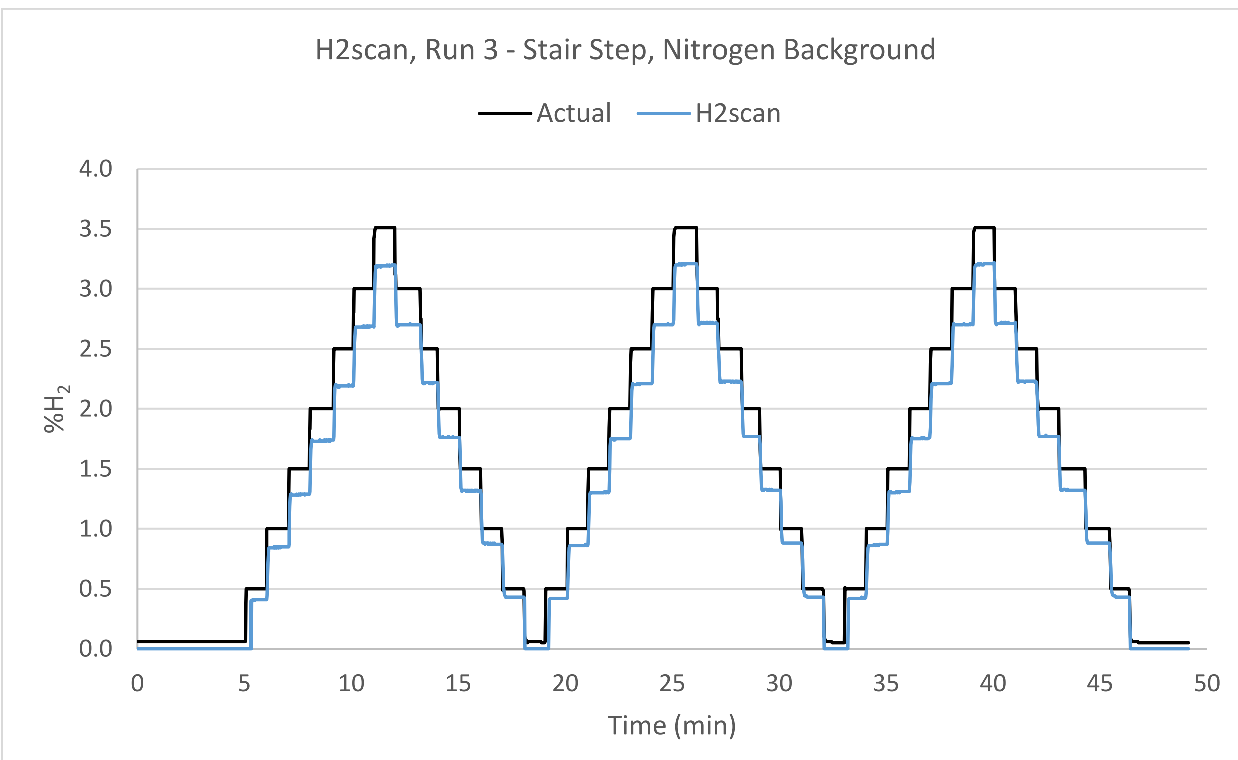

Figure 149. H2scan data for run 3 of the stair step test with a nitrogen background.

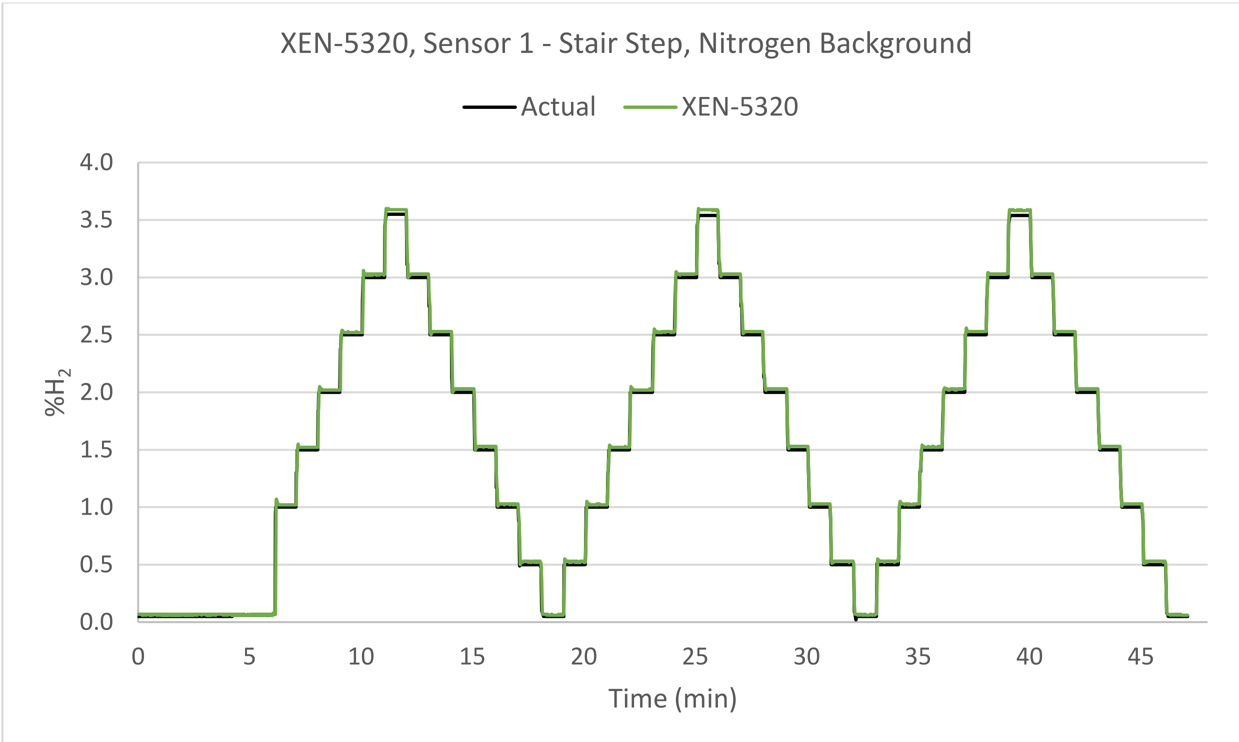

Figure 150. XEN-5320 data for sensor 1 in the stair step test with a nitrogen background.

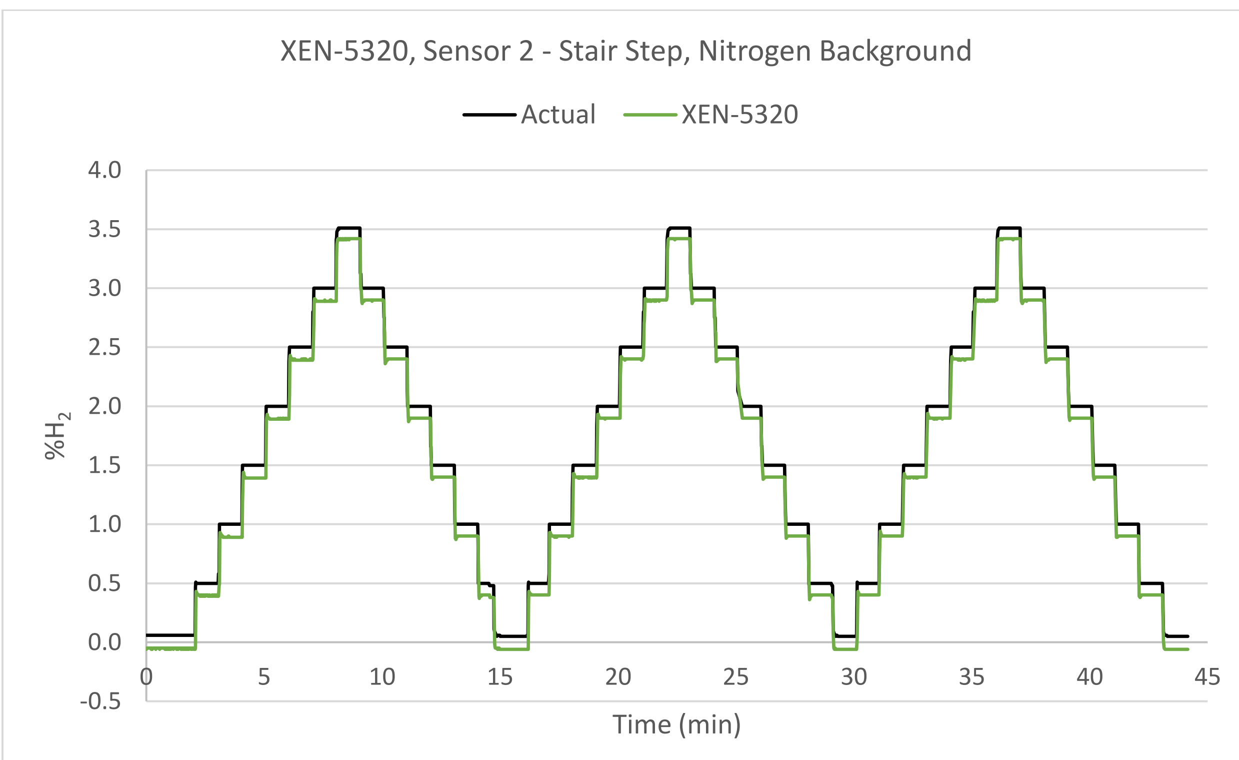

Figure 151. XEN-5320 data for sensor 2 in the stair step test with a nitrogen background.

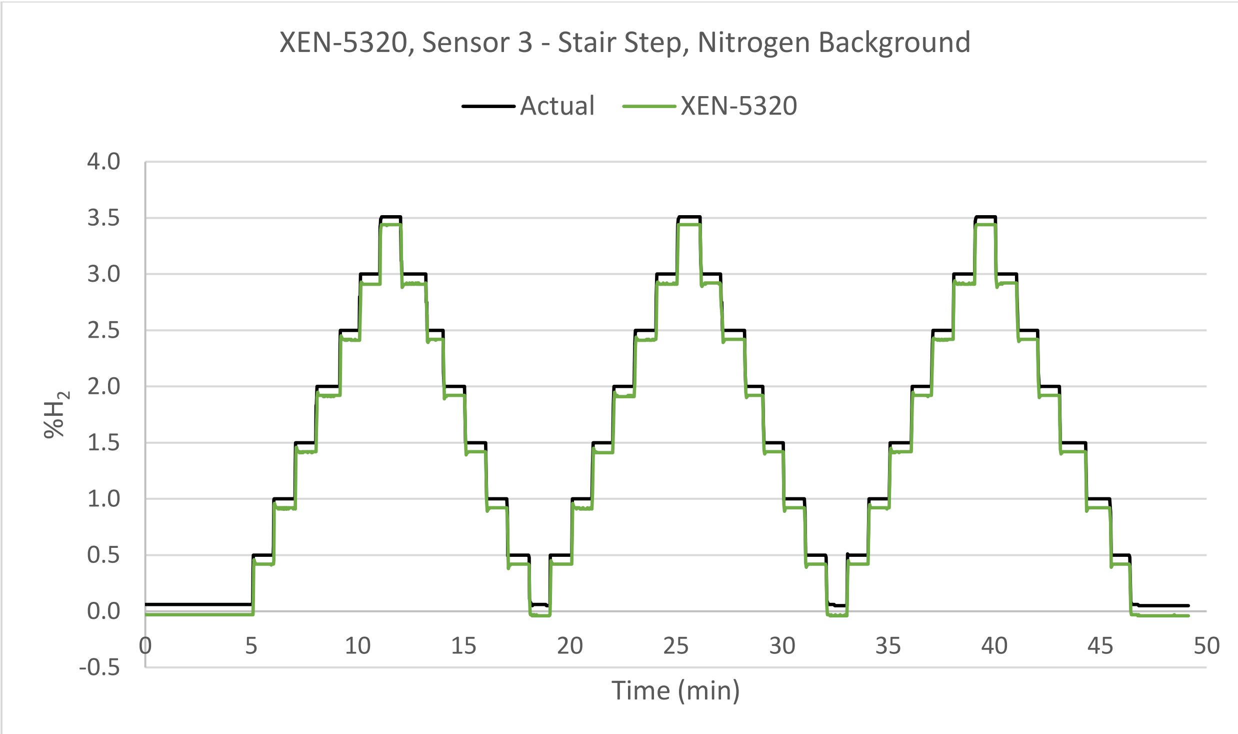

Figure 152. XEN-5320 data for sensor 3 in the stair step test with a nitrogen background.

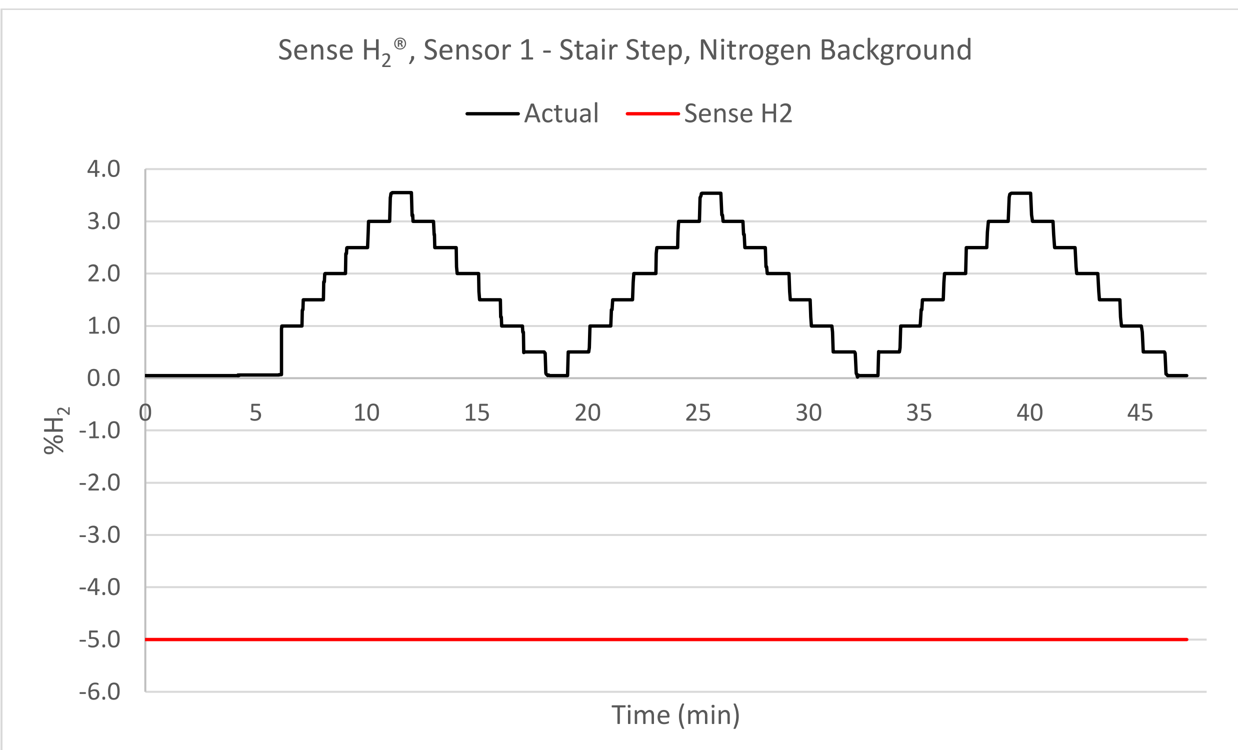

Figure 153. Sense H_2® data for sensor 1 in the stair step test with a nitrogen background.

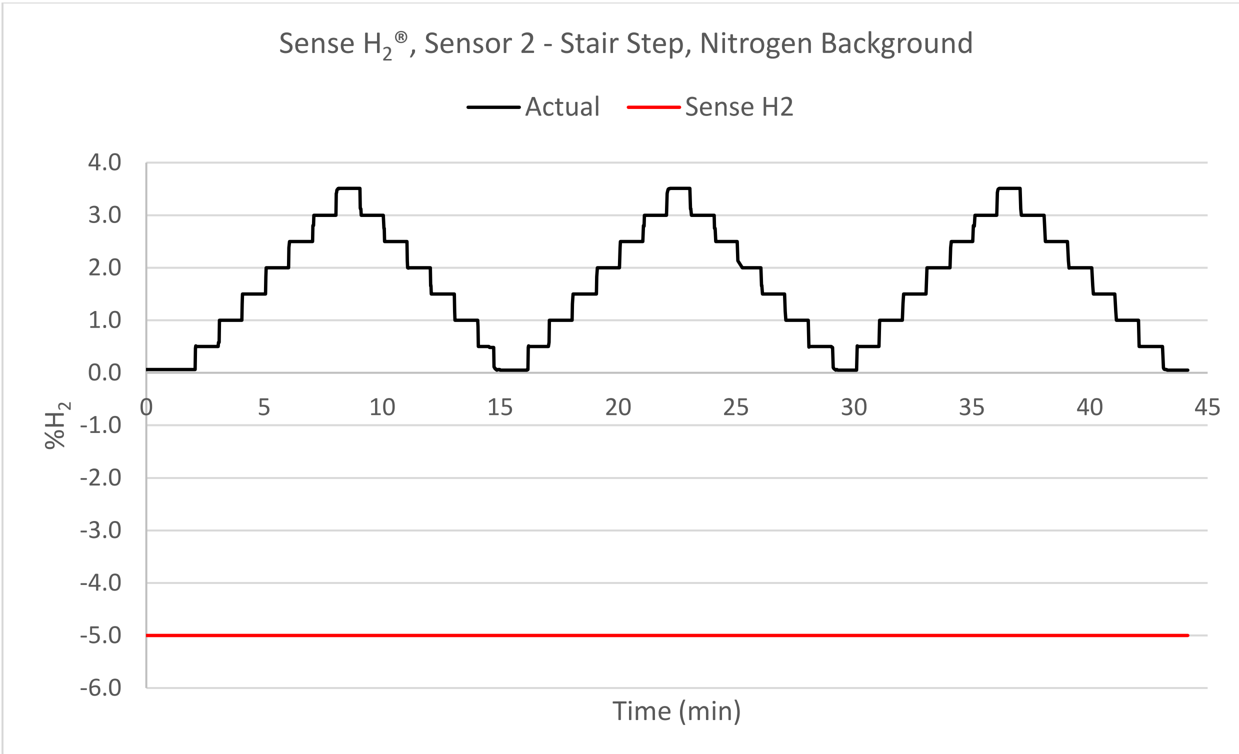

Figure 154. Sense H_2® data for sensor 2 in the stair step test with a nitrogen background.

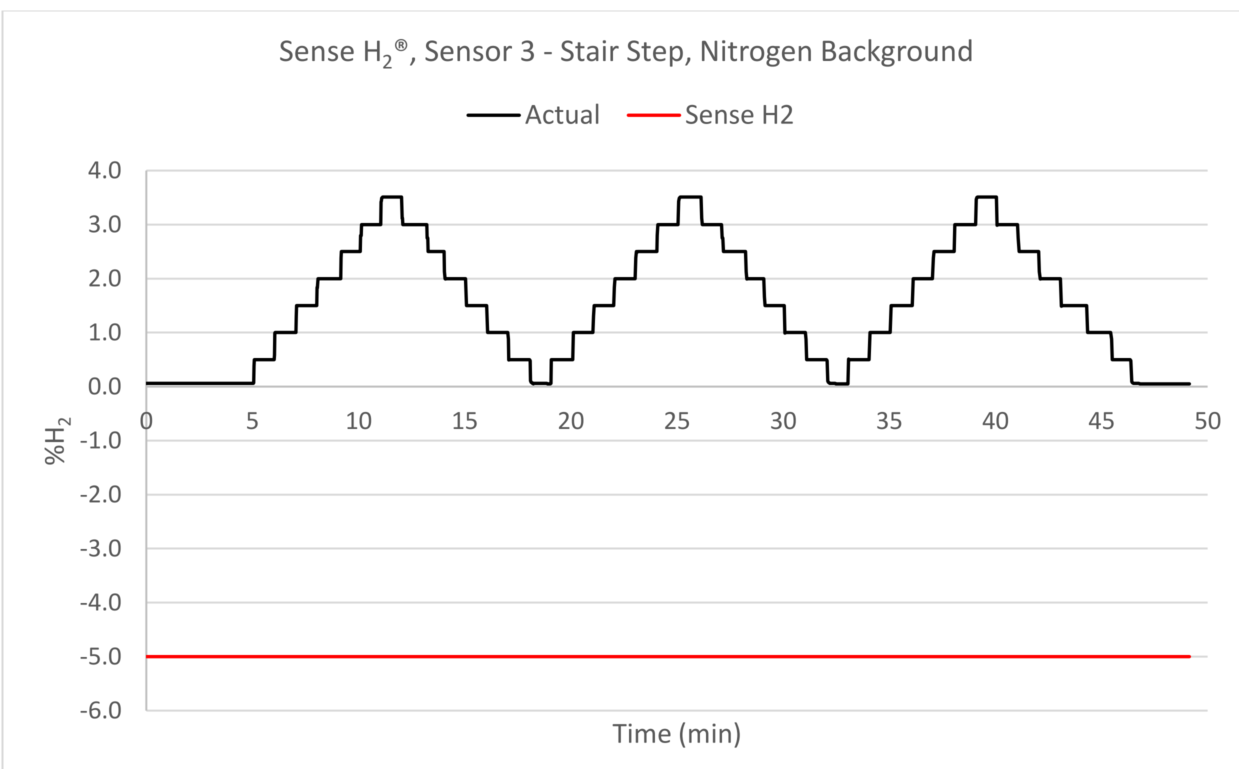

Figure 155. Sense H_2® data for sensor 3 in the stair step test with a nitrogen background.

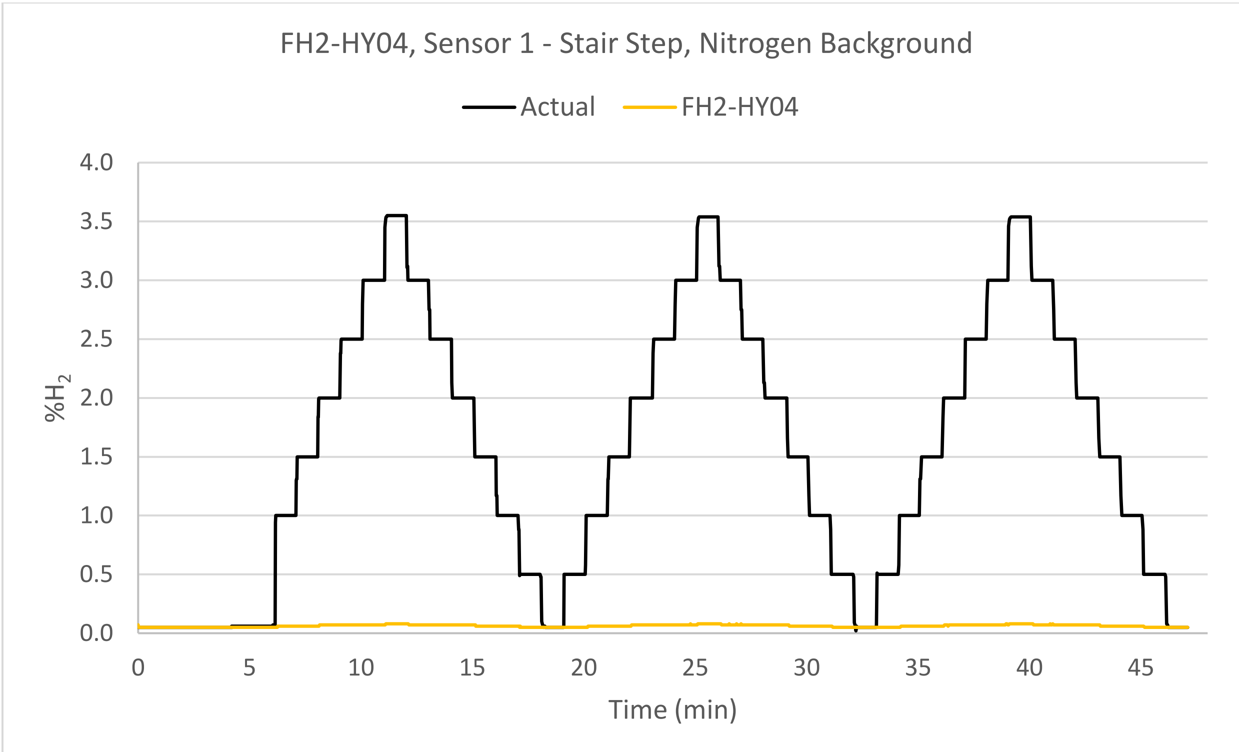

Figure 156. FH2-HY04 data for sensor 1 in the stair step test with a nitrogen background.

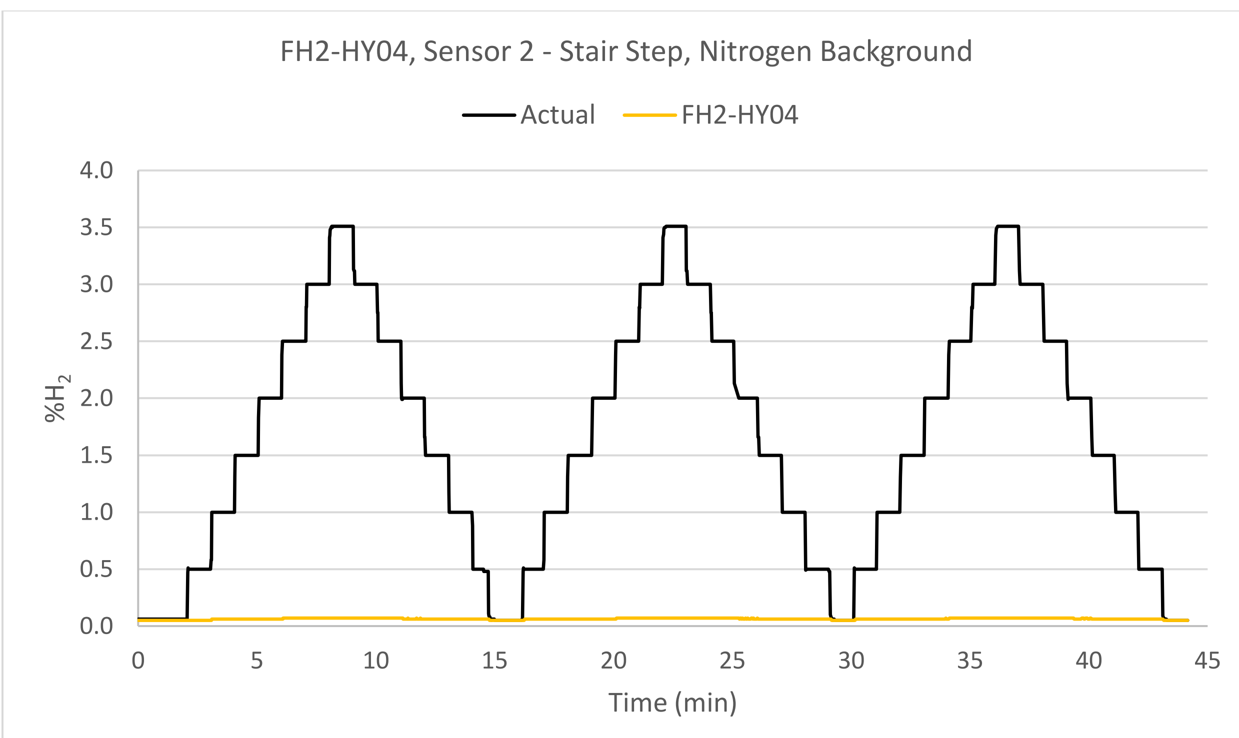

Figure 157. FH2-HY04 data for sensor 2 in the stair step test with a nitrogen background.

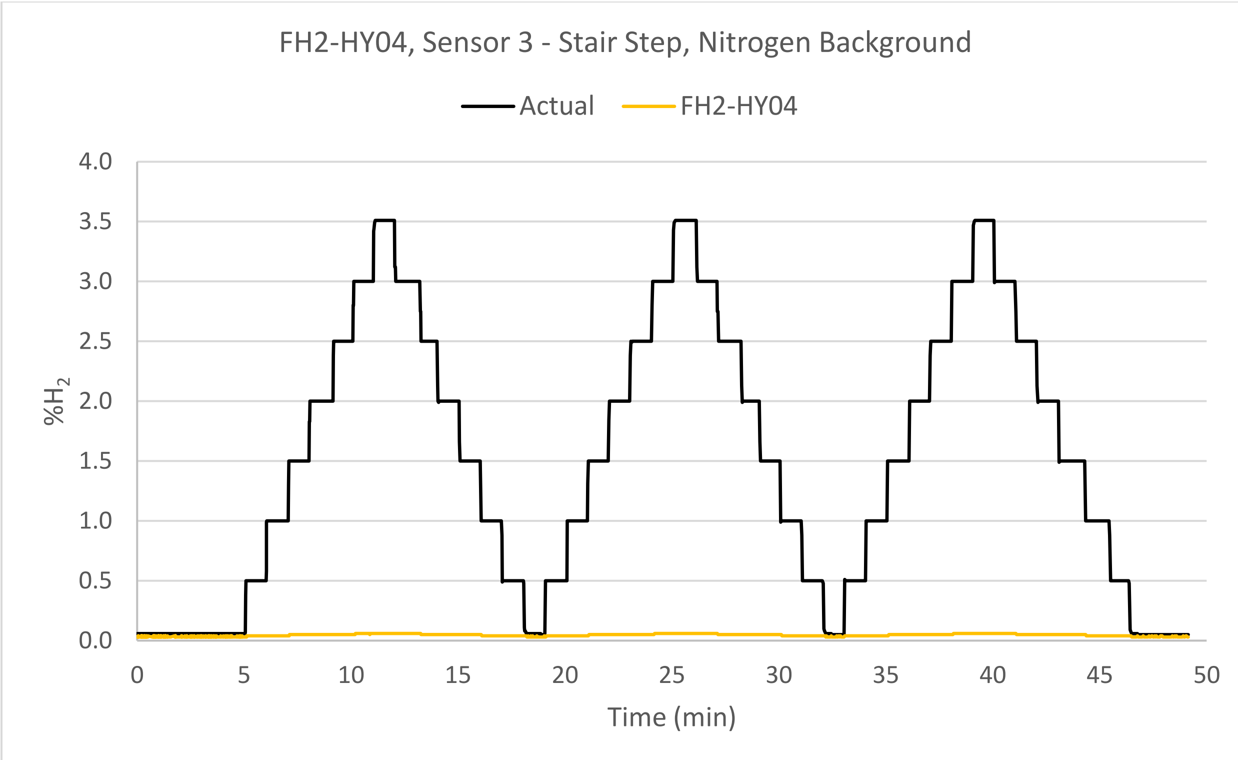

Figure 158. FH2-HY04 data for sensor 3 in the stair step test with a nitrogen background.

Table 13 lists the average output value for each time the sensor reached a particular “step,” along with the accuracy and precision calculated from those steps. These individual values were averaged for the entire test, the results of which are given in Table 14. Because the Sense H_2® and FH2-HY04 were not functioning properly in a nitrogen background, they are omitted from the tables. Accuracies for each value are also represented graphically in Figure 159 and Figure 160.

Both sensors had improved accuracies and precisions in the nitrogen background versus the air background. This could be due to the conditions under which they were calibrated. As with previous tests, a new calibration would likely improve these results.

Table 13. Accuracy and Precision Results – Nitrogen Background.

Sensor	Sensor/ Run	% H_2	Value 1	Value 2	Value 3	Value 4	Value 5	Value 6	Average Accuracy	Average Precision
H2scan 720B	1	0.05%	0.00	0.00	0.00	0.00	-	-	-100%	-
		0.50%	-	0.42	0.41	0.42	0.42	0.42	-16%	1%
		1.00%	0.85	0.87	0.86	0.87	0.86	0.87	-14%	0%
		1.50%	1.28	1.31	1.29	1.31	1.29	1.31	-13%	0%
		2.00%	1.73	1.75	1.74	1.76	1.74	1.76	-13%	0%
		2.50%	2.18	2.20	2.19	2.21	2.19	2.21	-12%	0%
		3.00%	2.69	2.71	2.70	2.71	2.70	2.71	-10%	0%
		~3.54%	3.24	3.24	3.24	-	-	-	-9%	0%
	2	~0.05%	0.00	0.00	0.00	0.00	-	-	-100%	-
		0.50%	0.00	0.42	0.41	0.42	0.41	0.42	-31%	0%
		1.00%	0.83	0.85	0.84	0.86	0.85	0.86	-15%	0%
		1.50%	1.26	1.29	1.28	1.30	1.28	1.30	-14%	0%
		2.00%	1.70	1.73	1.72	1.74	1.73	1.75	-14%	0%
		2.50%	2.15	2.18	2.17	2.19	2.18	2.20	-13%	0%
		3.00%	2.64	2.66	2.66	2.67	2.67	2.68	-11%	0%
		3.51%	3.15	3.16	3.17	-	-	-	-10%	0%
	3	~0.06%	0.00	0.00	0.00	0.00	-	-	-100%	-
		0.50%	0.41	0.43	0.42	0.43	0.42	0.43	-15%	1%
		1.00%	0.85	0.87	0.86	0.88	0.87	0.88	-13%	0%
		1.50%	1.29	1.32	1.30	1.32	1.31	1.32	-13%	0%
		2.00%	1.73	1.76	1.75	1.77	1.75	1.77	-12%	0%
		2.50%	2.19	2.22	2.21	2.23	2.21	2.23	-11%	0%
		3.00%	2.68	2.70	2.70	2.71	2.70	2.71	-10%	0%
		3.51%	3.19	3.21	3.21	-	-	-	-9%	0%
XEN-5320	1	0.05%	0.07	0.06	0.06	0.06	-	-	29%	7%
		0.50%	-	0.53	0.53	0.53	0.53	0.53	6%	1%
		1.00%	1.02	1.03	1.02	1.03	1.03	1.03	3%	0%
		1.50%	1.52	1.53	1.52	1.53	1.52	1.53	2%	0%
		2.00%	2.02	2.03	2.02	2.03	2.03	2.03	1%	0%
		2.50%	2.52	2.53	2.53	2.53	2.53	2.53	1%	0%
		3.00%	3.03	3.03	3.03	3.03	3.03	3.03	1%	1%
		~3.54%	3.59	3.59	3.58	-	-	-	1%	0%
	2	~0.05%	-0.05	-0.06	-0.06	-0.06	-	-	-216%	-4%
		0.50%	0.40	0.40	0.40	0.40	0.40	0.40	-20%	0%
		1.00%	0.89	0.90	0.90	0.90	0.90	0.90	-10%	0%
		1.50%	1.39	1.40	1.40	1.40	1.40	1.40	-7%	0%
		2.00%	1.89	1.90	1.90	1.90	1.90	1.90	-5%	0%
		2.50%	2.39	2.40	2.40	2.40	2.40	2.40	-4%	0%
		3.00%	2.89	2.90	2.90	2.90	2.90	2.90	-3%	0%
		3.51%	3.42	3.42	3.42	-	-	-	-3%	0%
	3	~0.06%	-0.03	-0.04	-0.04	-0.04	-	-	-160%	-7%
		0.50%	0.42	0.42	0.42	0.42	0.42	0.42	-16%	0%
		1.00%	0.92	0.92	0.91	0.92	0.92	0.92	-8%	0%

		1.50%	1.42	1.42	1.41	1.42	1.42	1.42	-5%	0%
		2.00%	1.92	1.92	1.91	1.92	1.92	1.92	-4%	0%
		2.50%	2.41	2.42	2.41	2.42	2.42	2.42	-3%	0%
		3.00%	2.91	2.91	2.91	2.92	2.91	2.92	-3%	0%
		3.51%	3.44	3.44	3.44	-	-	-	-2%	0%

Note: Shaded cells indicate values for which the concentration was increasing to reach the value. Unshaded cells are values for which the concentration was decreasing to reach the value.

Table 14. Average Accuracy and Precision Values – Nitrogen Background

Sensor	Sensor/Run	Overall Average Accuracy	Overall Average Precision
H2scan 720B	1	-12%	0%
	2	-15%	0%
	3	-12%	0%
	Sensor/Run Average	-13%	0%
XEN-5320	1	2%	1%
	2	-7%	0%
	3	-6%	-1%
	Sensor/Run Average	-4%	0%

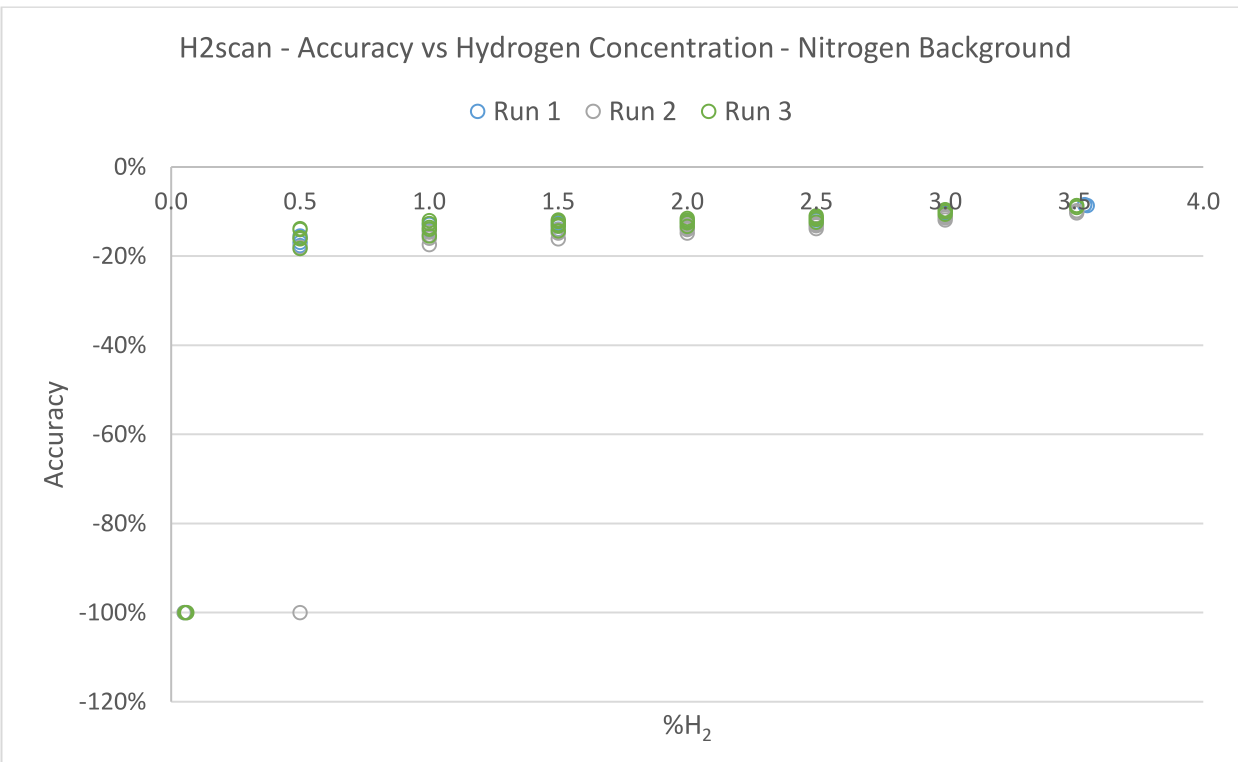

Figure 159. Accuracy of H2scan outputs for each hydrogen concentration, in a nitrogen background.

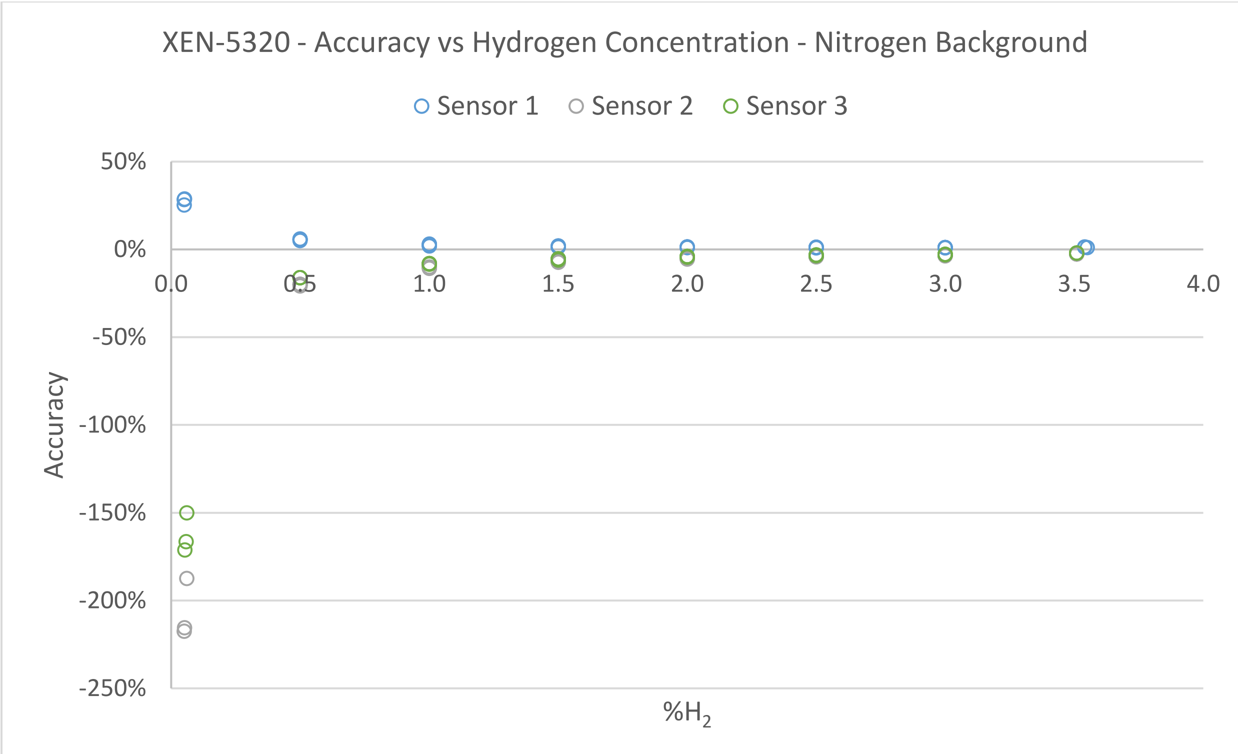

Figure 160. Accuracy of XEN-5320 outputs for each hydrogen concentration, in a nitrogen background.

Results – Helium Background

Figure 161 through Figure 164 show data collected during the stair step test with a helium background.

The H2scan's performance remained similar to that which was seen in air and nitrogen backgrounds. It did not register any of the 0.5% hydrogen steps in a helium background, which is consistent with this sensor having a higher LDL in helium. This could possibly also be remedied, along with improvements to the sensor's accuracy and precision, by calibrating the sensor under these conditions.

As seen in previous tests, the XEN-5320 cannot detect hydrogen in a helium background, and the Sense H_2® and FH2-HY04 did not function anaerobically.

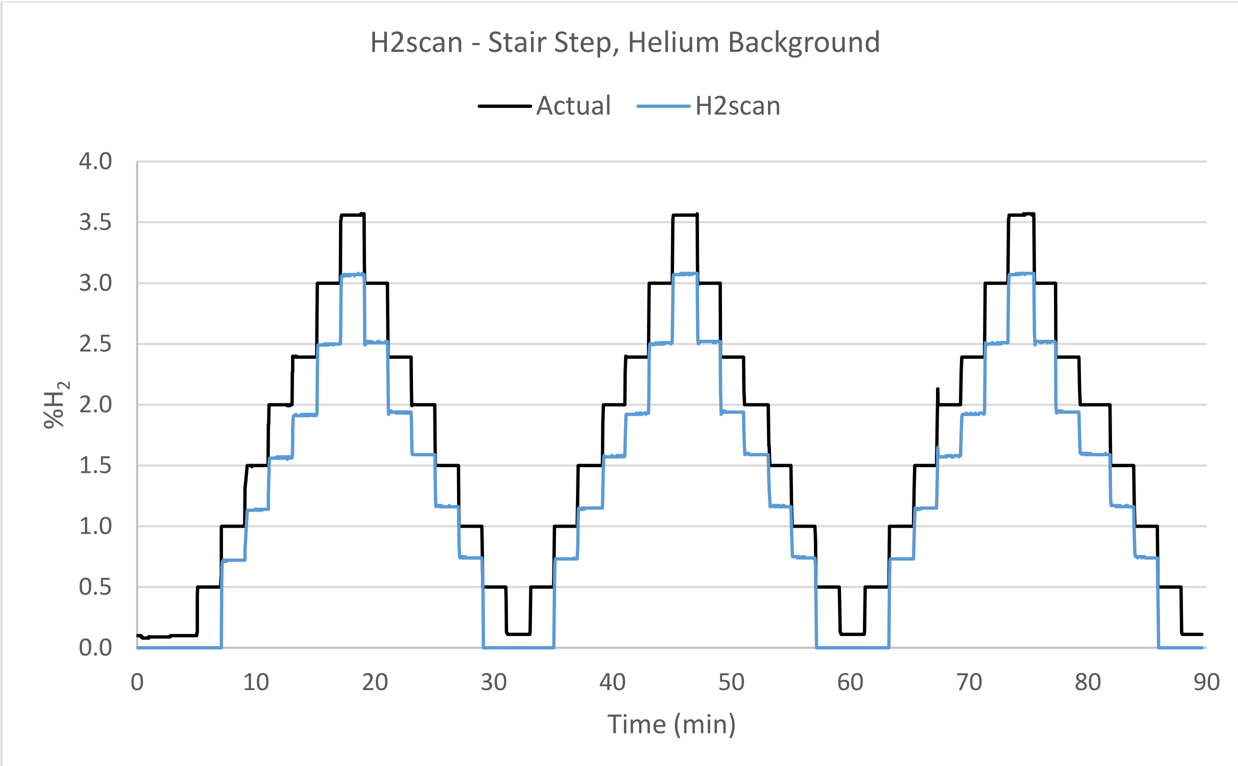

Figure 161. H2scan data for the stair step test with a helium background.

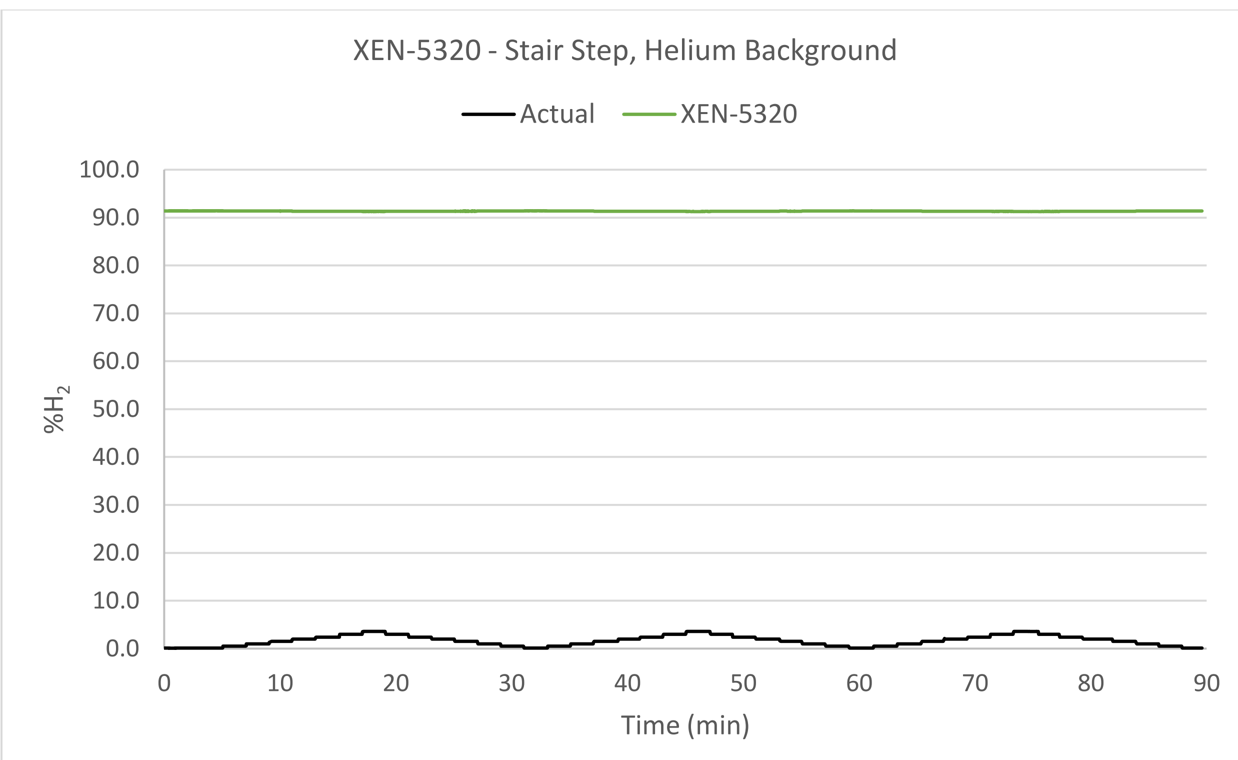

Figure 162. XEN-5320 data for the stair step test with a helium background.

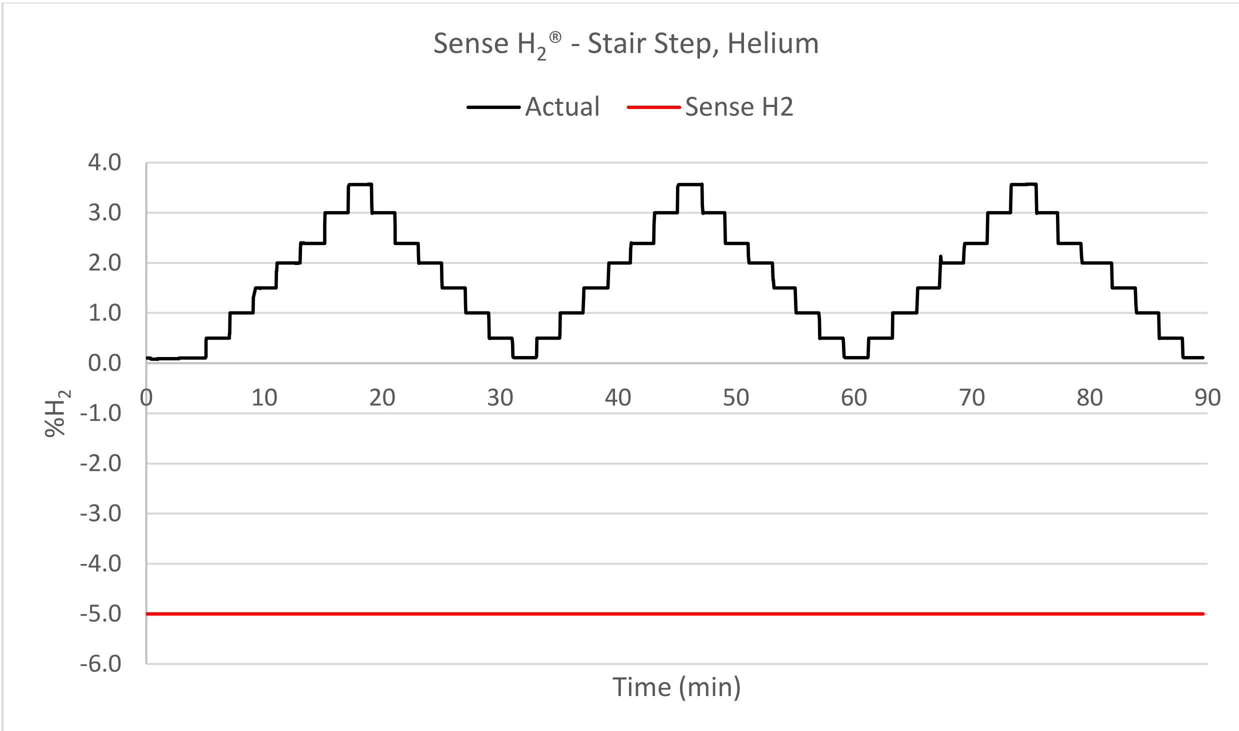

Figure 163. Sense H_2® data for the stair step test with a helium background.

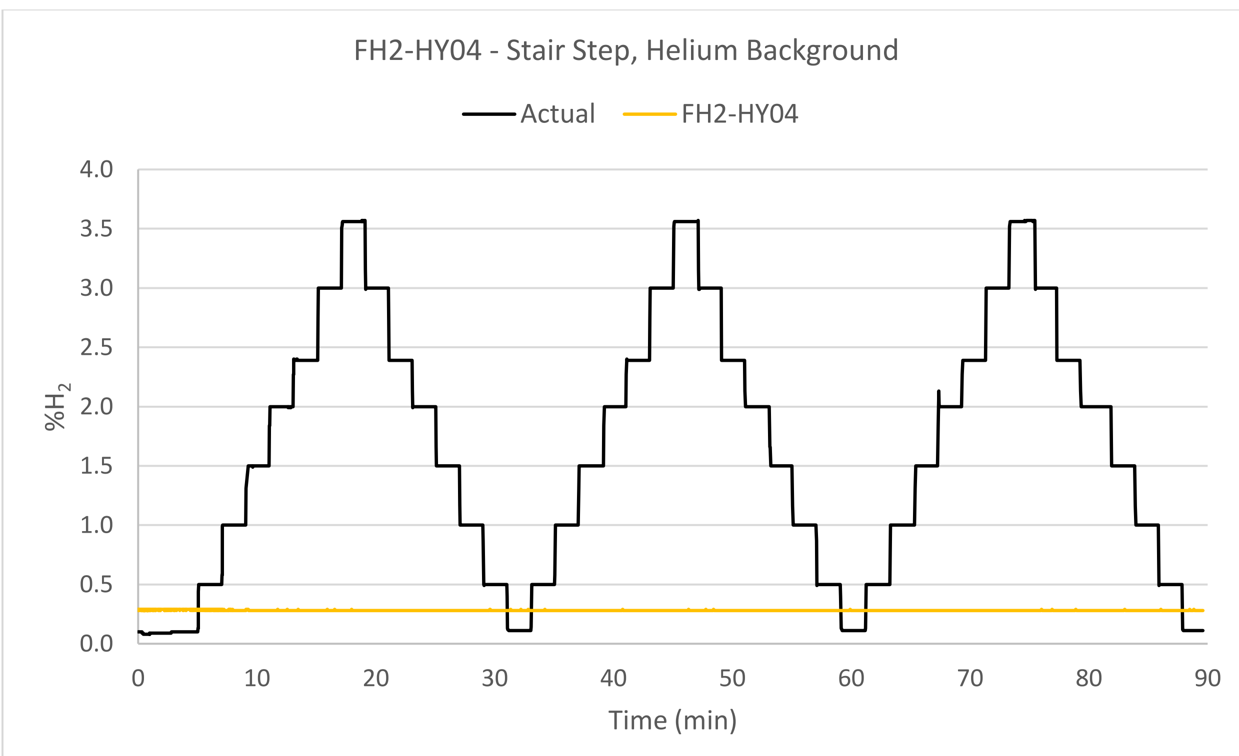

Figure 164. FH2-HY04 data for the stair step test with a helium background.

Table 15 lists the average output value for each time the sensor reached a particular "step," along with the accuracy and precision calculated from those steps. These individual values were averaged for the entire test, the results of which are given in Table 16. Because none of the other sensors were functioning properly in the helium background, only the H2scan data is given on the table. Accuracies for each value are also represented graphically in Figure 165.

The overall accuracy of the sensor was worse in a helium background than nitrogen or air, but that could be due to the helium background having a greater variation from its calibration conditions.

Table 15. Accuracy and Precision Results – Helium Background.

Sensor	%H_2	Value 1	Value 2	Value 3	Value 4	Value 5	Value 6	Average Accuracy	Average Precision
H2scan 720B	~0.11%	0.00	0.00	0.00	0.00	-	-	-100%	-
	0.50%	0.00	0.00	0.00	0.00	0.00	0.00	-100%	-
	1.00%	0.72	0.74	0.73	0.74	0.73	0.74	-27%	0%
	1.50%	1.14	1.16	1.15	1.16	1.15	1.16	-23%	0%
	2.00%	1.56	1.59	1.57	1.59	1.57	1.59	-21%	0%
	2.39%	1.91	1.94	1.92	1.94	1.92	1.94	-19%	0%
	3.00%	2.50	2.51	2.50	2.52	2.50	2.52	-16%	0%
	3.56%	3.07	3.08	3.08	-	-	-	-14%	0%

Note: Shaded cells indicate values for which the concentration was increasing to reach the value. Unshaded cells are values for which the concentration was decreasing to reach the value.

Table 16. Average Accuracy and Precision Values – Helium Background

Sensor	Overall Accuracy	Overall Precision
H2scan 720B	-31%	0%

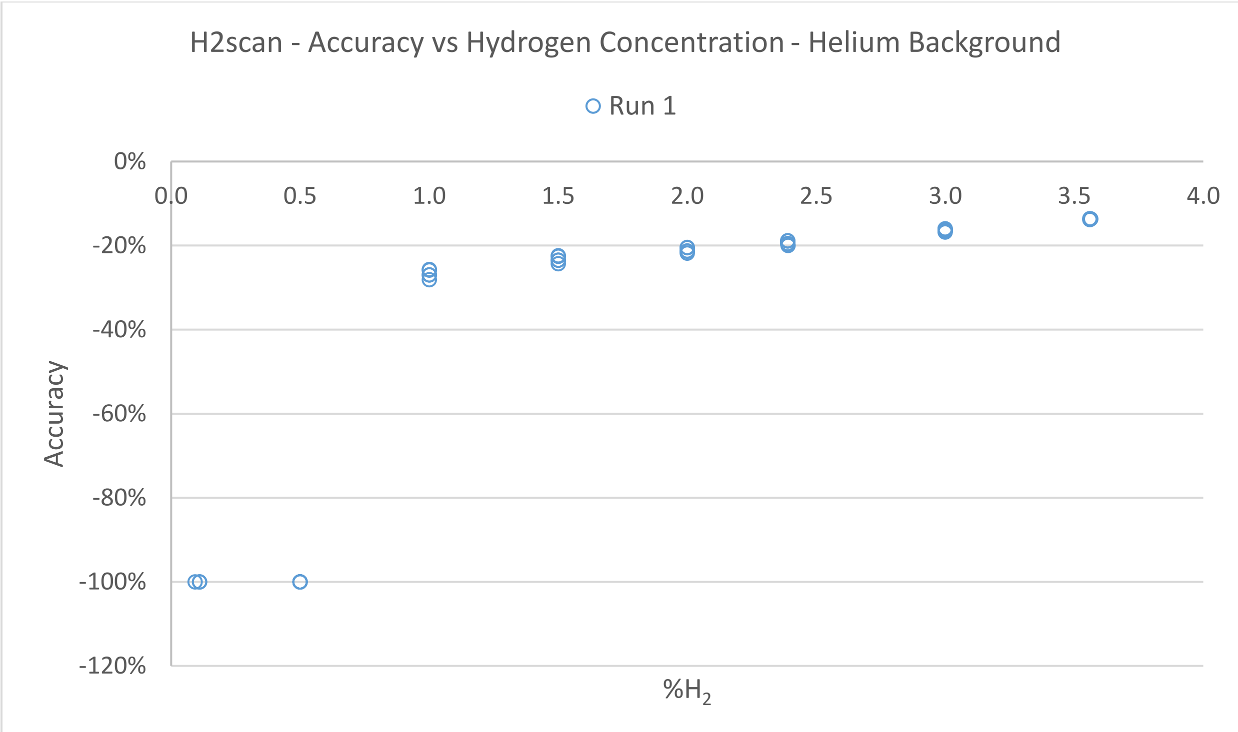

Figure 165. Accuracy of H2scan outputs for each hydrogen concentration, in a helium background.

Square Wave Test

This test was used to determine the repeatability of the sensors. Hydrogen concentrations were changed in a series of square waves, from ~0% to a given hydrogen 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 hydrogen 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% hydrogen.
6. Allow outputs to stabilize.
7. Adjust gas flows for a hydrogen concentration of 0.5%.
8. Allow outputs to stabilize.
9. Adjust gas flows for a hydrogen 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 hydrogen 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 hydrogen concentration change. Repeatability is given in terms of the difference in hydrogen concentrations reported by the sensors, $\%H_2$. 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 hydrogen concentration.

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

Results – Air Background

Figure 166 through Figure 181 show the data collected for the square wave test with an air background.

In each case, the three repetitions of each hydrogen concentration had very similar responses, indicating good repeatability. The Sense H_2® did have multiple instances where two of the concentrations had the same outputs, but even the incorrect values were consistent within each sensor.

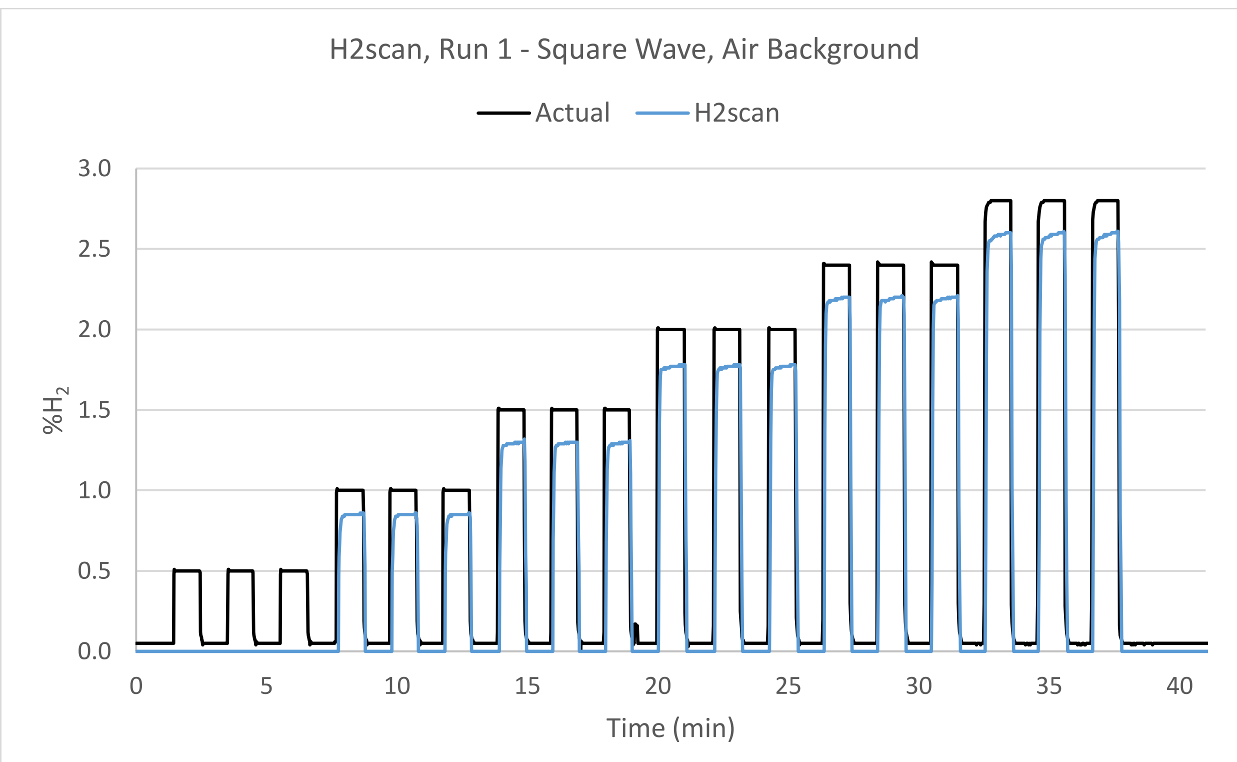

Figure 166. H2scan data for run 1 of the square wave test with an air background.

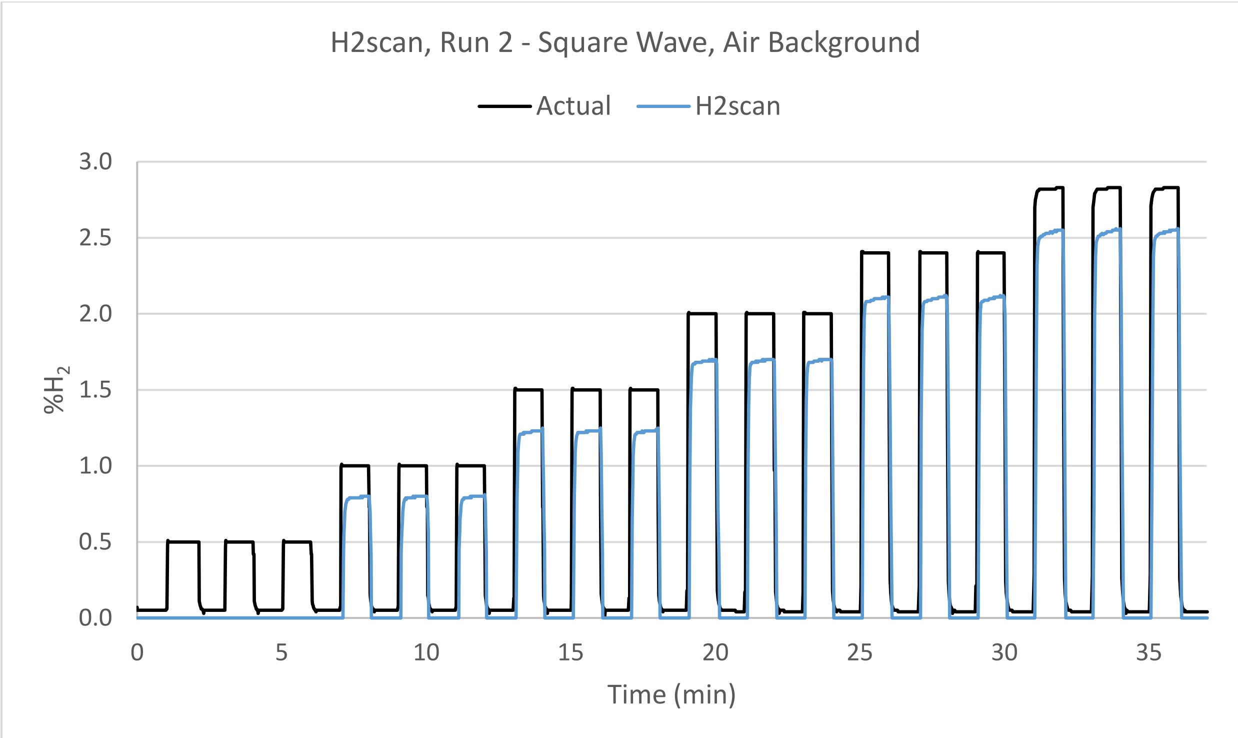

Figure 167. H2scan data for run 2 of the square wave test with an air background.

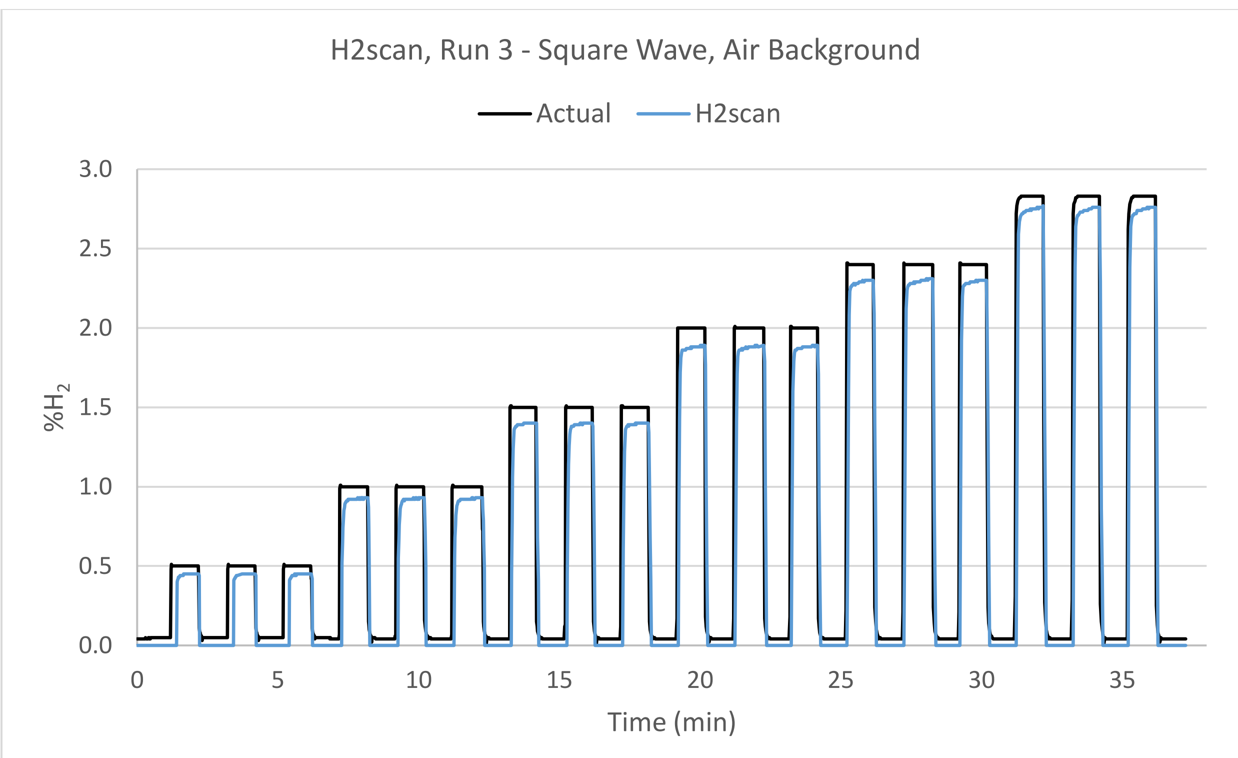

Figure 168. H2scan data for run 3 of the square wave test with an air background.

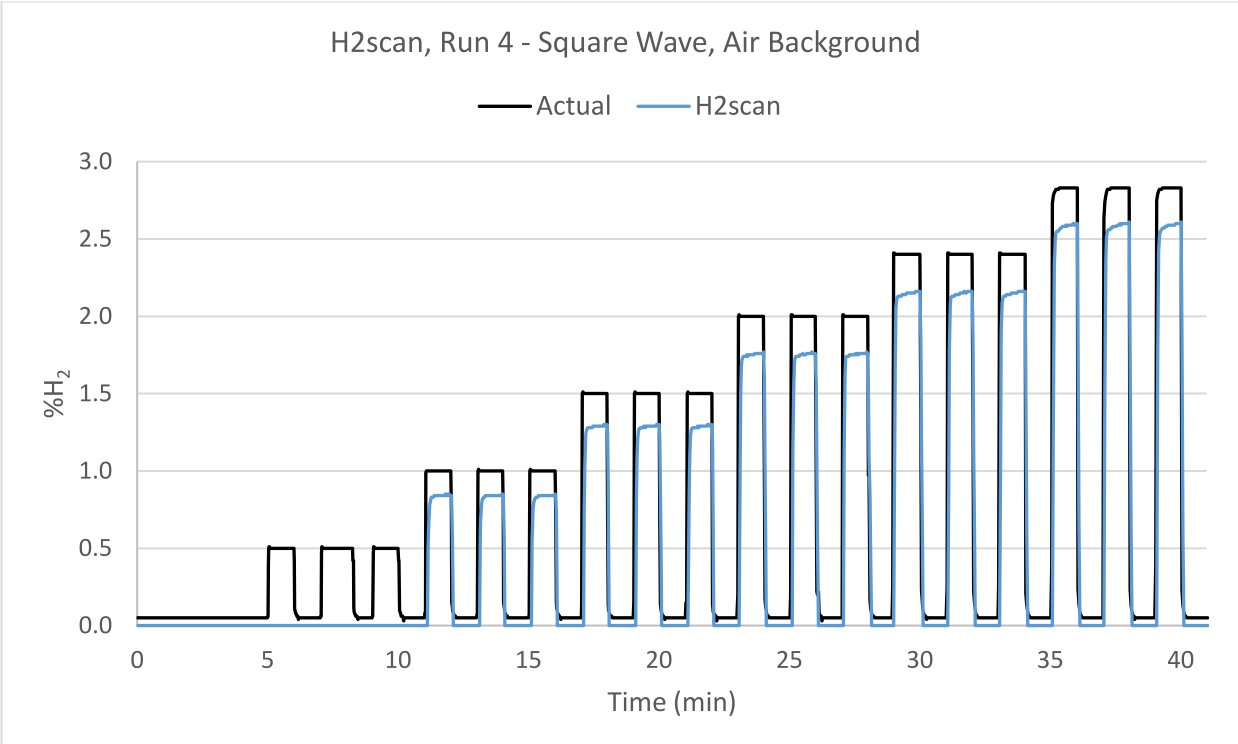

Figure 169. H2scan data for run 4 of the square wave test with an air background.

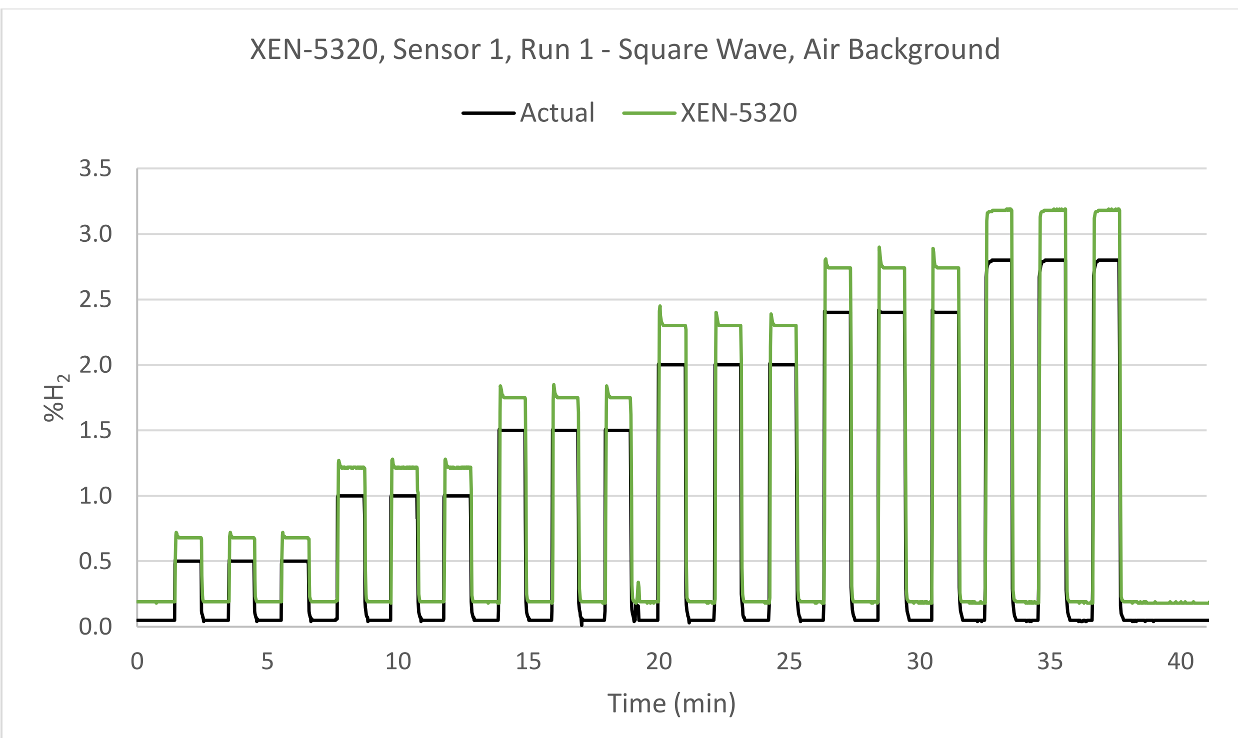

Figure 170. XEN-5320 data for sensor 1, run 1 of the square wave test with an air background.

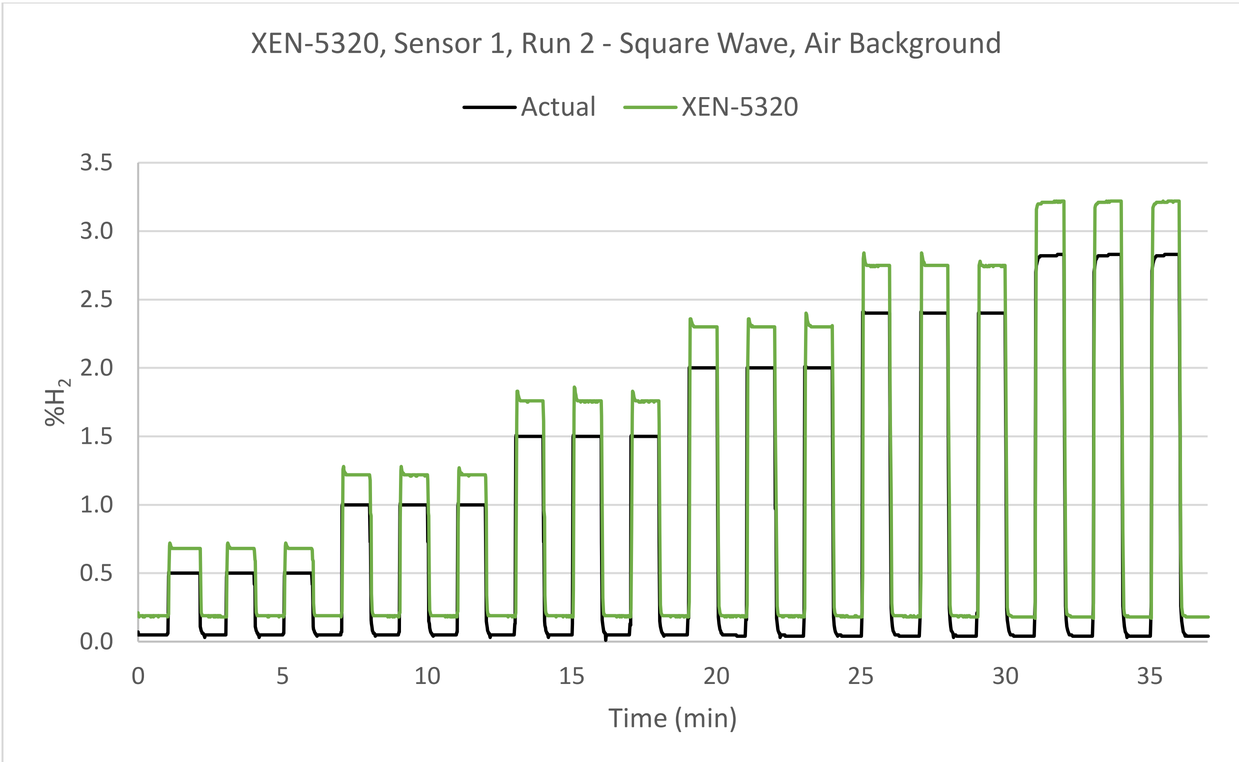

Figure 171. XEN-5320 data for sensor 1, run 2 of the square wave test with an air background.

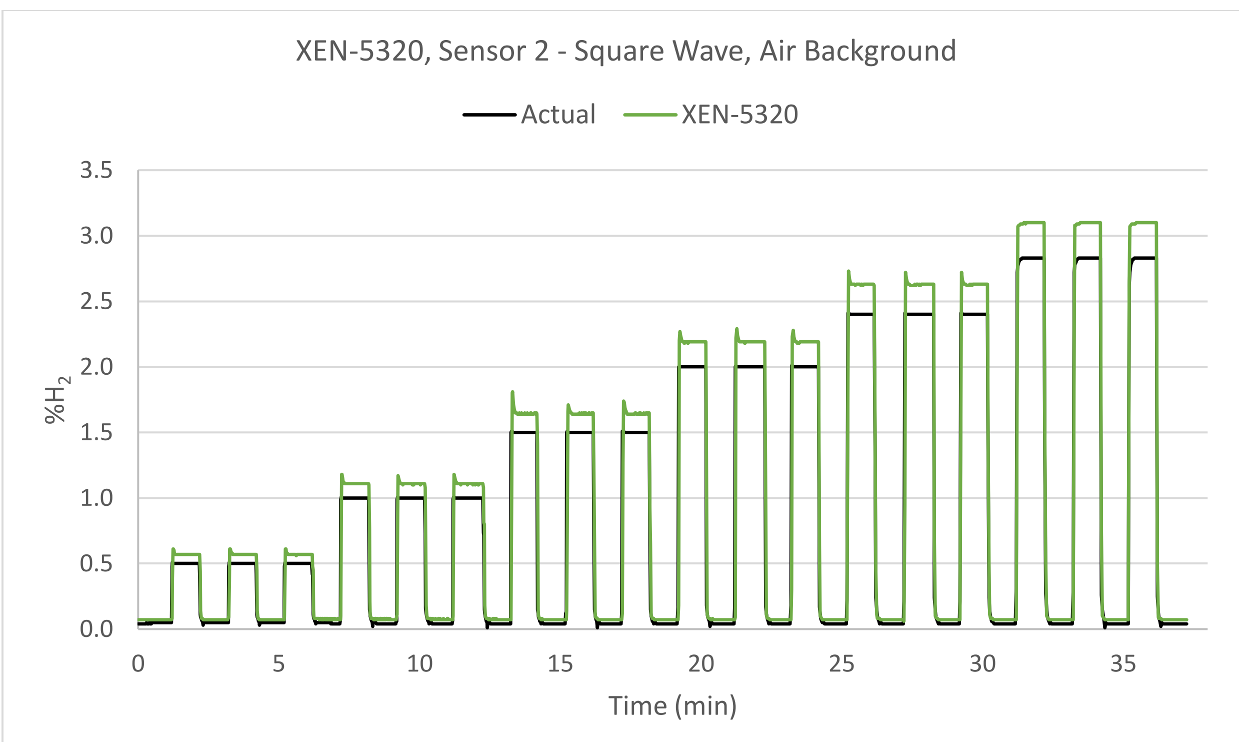

Figure 172. XEN-5320 data for sensor 2 in the square wave test with an air background.

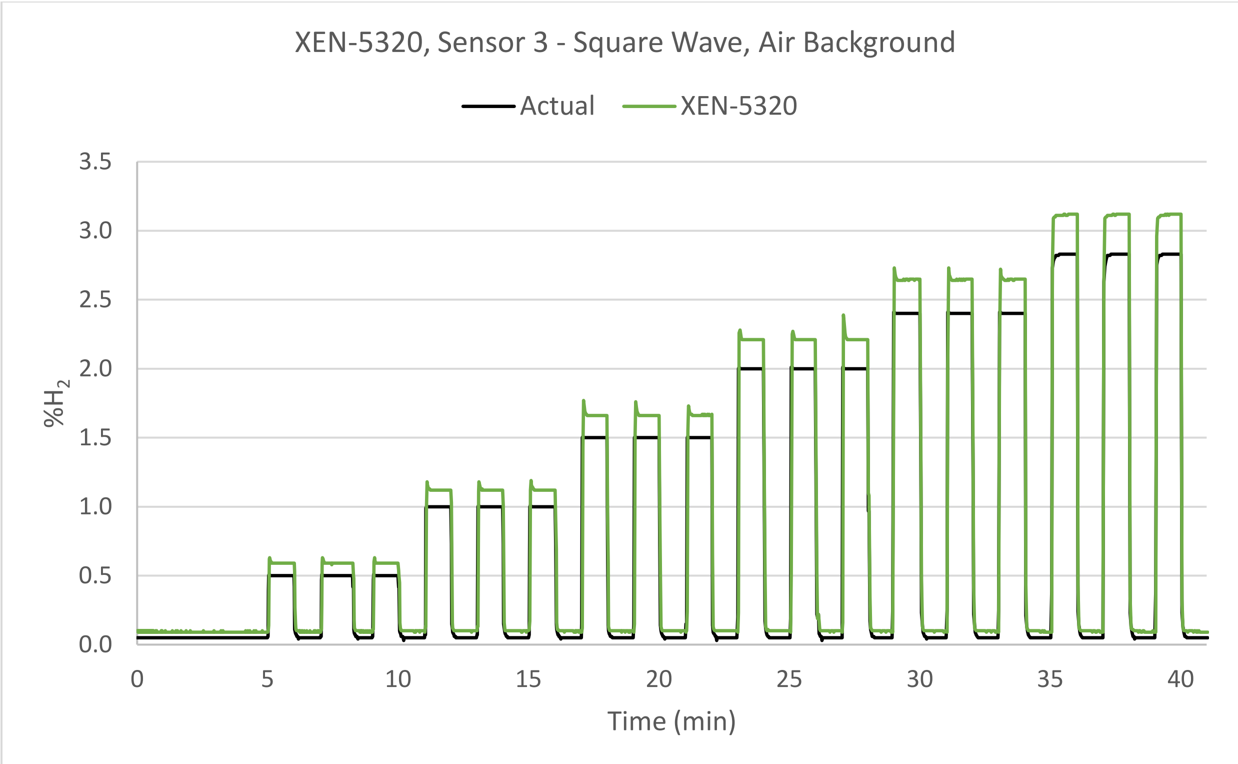

Figure 173. XEN-5320 data for sensor 3 in the square wave test with an air background.

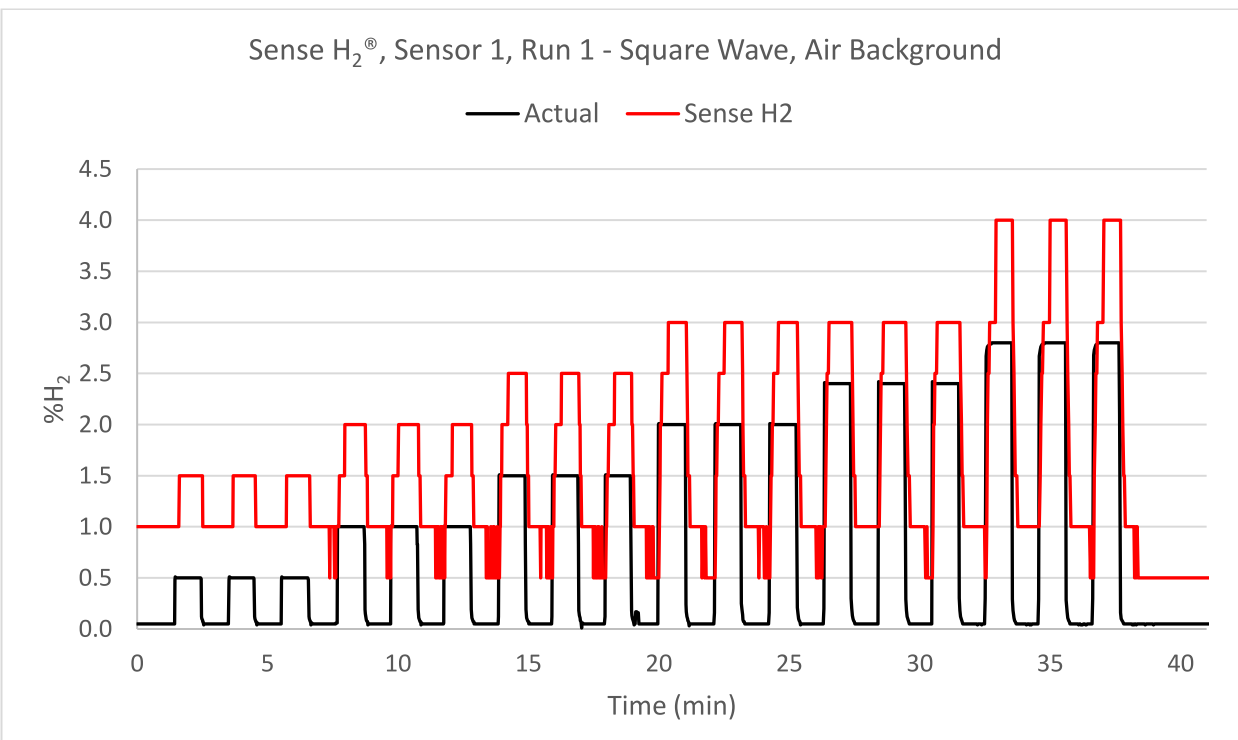

Figure 174. Sense H_2® data for sensor 1, run 1 of the square wave test with an air background.

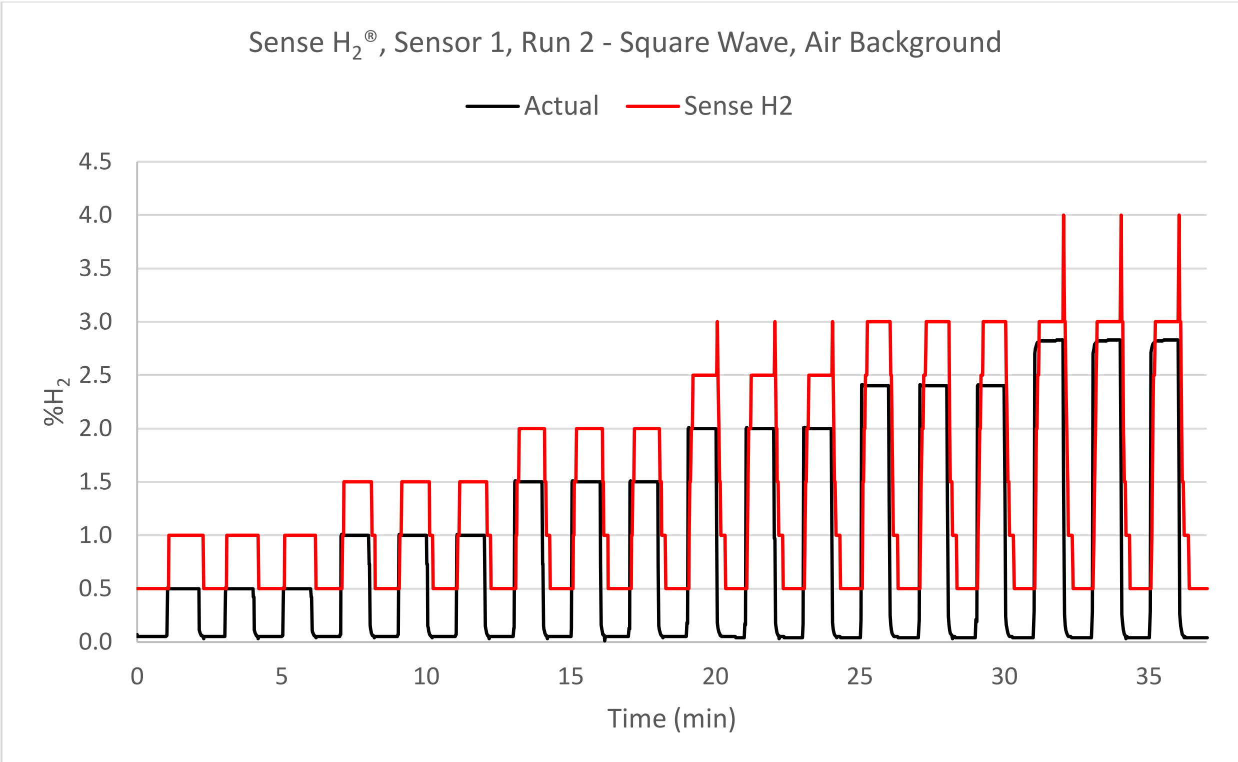

Figure 175. Sense H_2® data for sensor 1, run 2 of the square wave test with an air background.

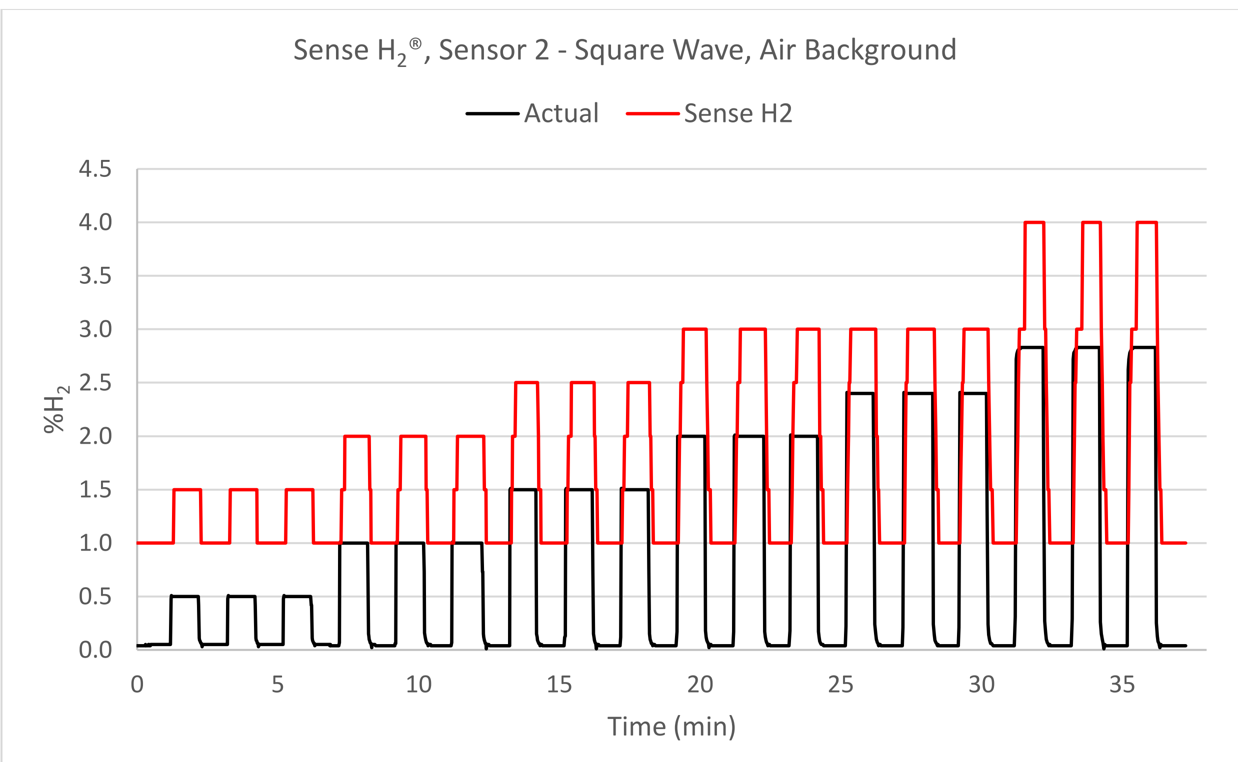

Figure 176. Sense H_2® data for sensor 2 in the square wave test with an air background.

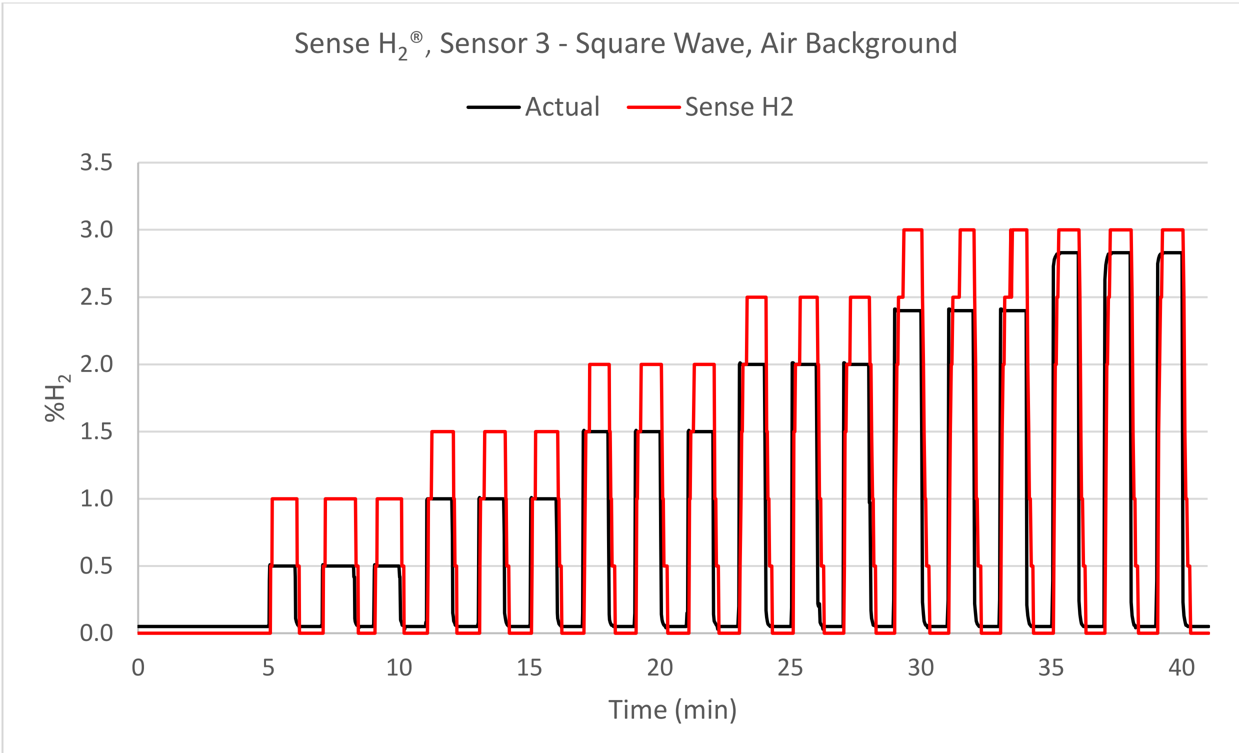

Figure 177. Sense H_2® data for sensor 3 in the square wave test with an air background.

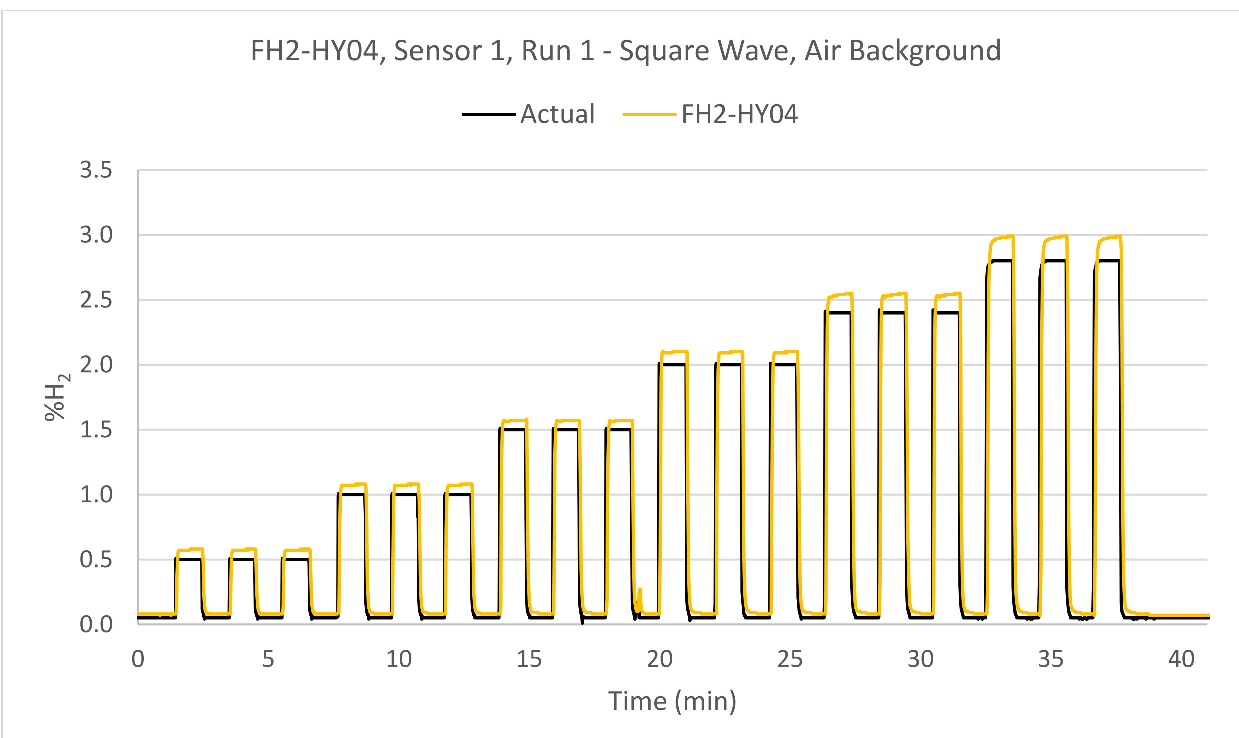

Figure 178. FH2-HY04 data for sensor 1, run 1 of the square wave test with an air background.

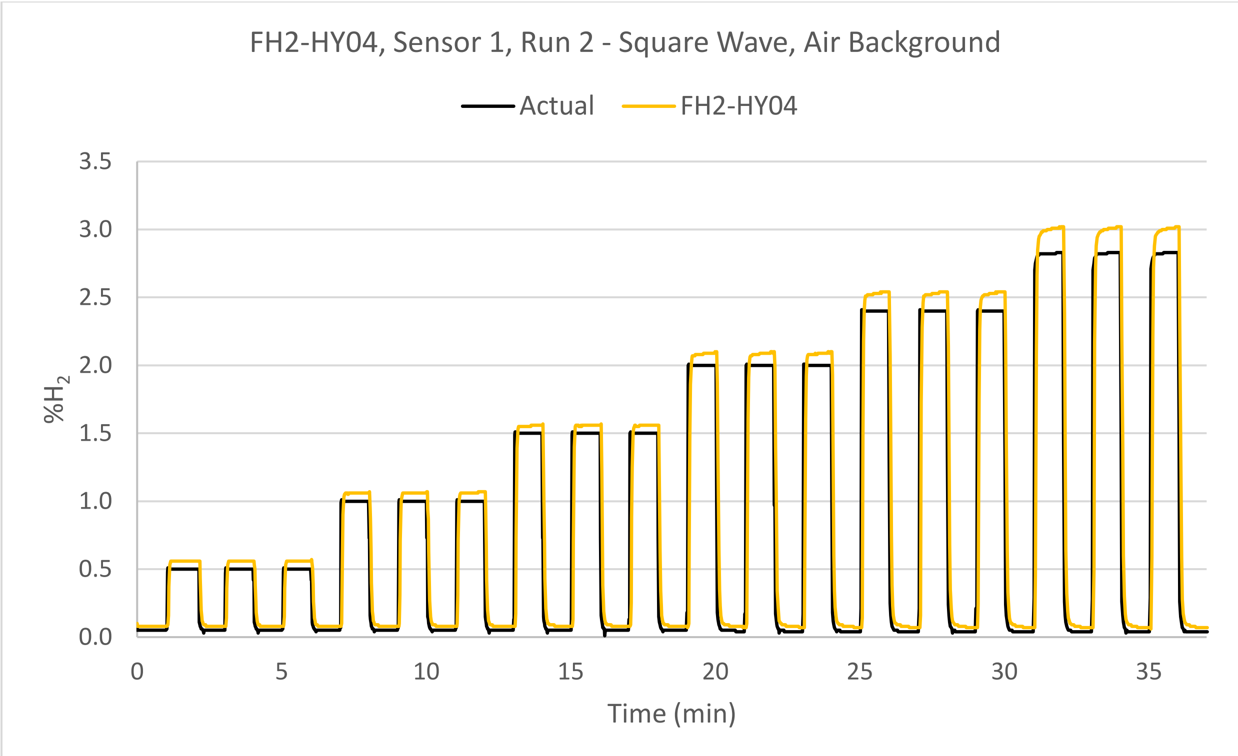

Figure 179. FH2-HY04 data for sensor 1, run 2 of the square wave test with an air background.

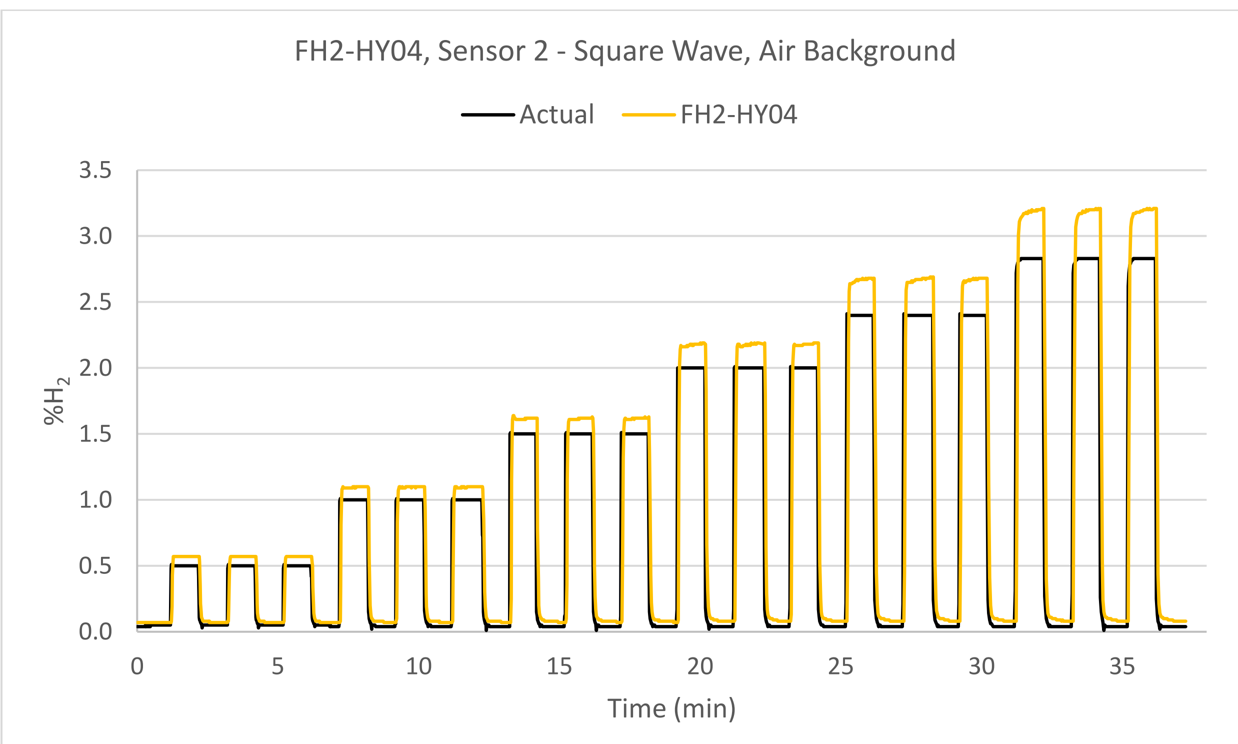

Figure 180. FH2-HY04 data for sensor 2 in the square wave test with an air background.

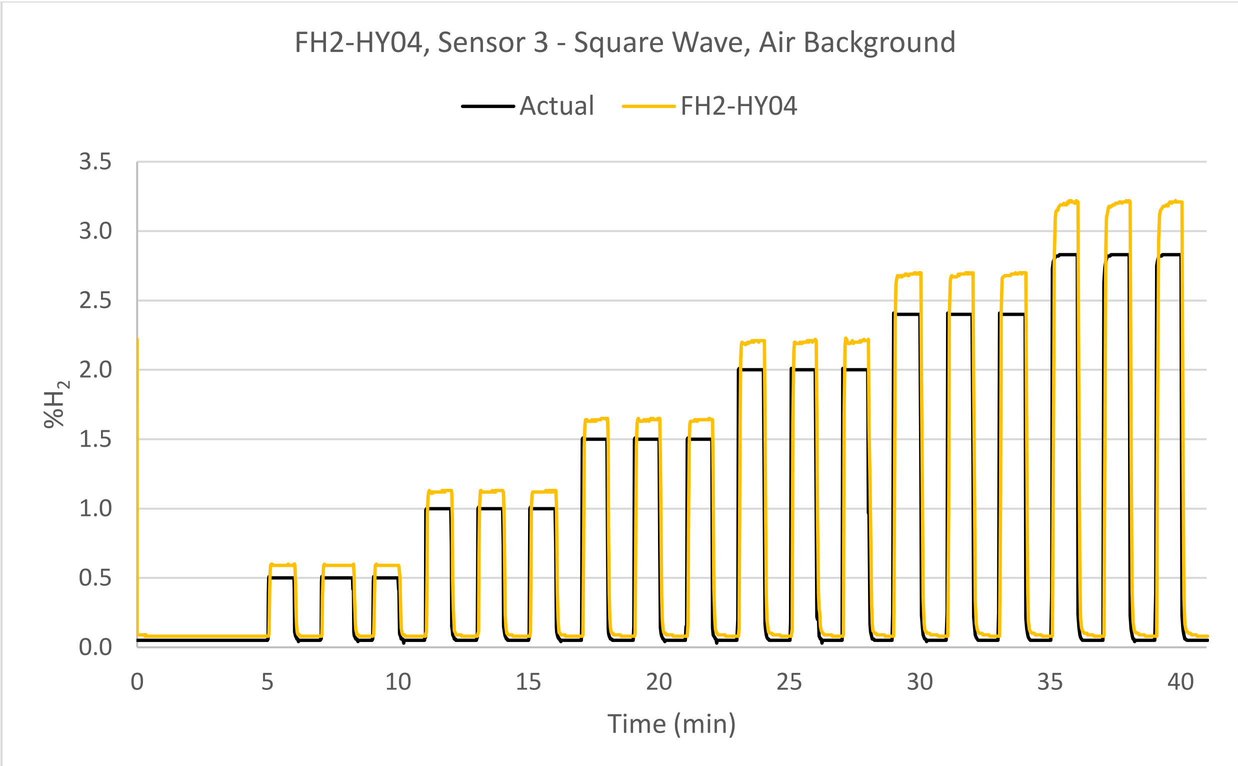

Figure 181. FH2-HY04 data for sensor 3 of the square wave test with an air background.

For each hydrogen concentration, the average value after a sensor had stabilized was calculated. Those values, as well as the repeatability (the difference between the maximum and minimum values for each hydrogen concentration) are given in Table 17.

None of the four sensors showed a large change between repeated cycling to a given set point.

Table 17. Repeatability Results – Air Background

Sensor	**Sensor/ Run**	**%H_2**	**Value 1 (%H_2)**	**Value 2 (%H_2)**	**Value 3 (%H_2)**	**Repeatability (%H_2)**	**Average Repeatability**
H2scan 720B	Run 1	0.50%	0.00	0.00	0.00	0.00	0.00% H_2
		1.00%	0.85	0.85	0.85	0.00	
		1.50%	1.29	1.29	1.29	0.00	
		2.00%	1.77	1.77	1.77	0.00	
		2.40%	2.19	2.19	2.19	0.00	
		2.80%	2.59	2.59	2.59	0.00	
	Run 2	0.50%	0.00	0.00	0.00	0.00	0.00% H_2
		1.00%	0.79	0.80	0.80	0.01	
		1.50%	1.22	1.23	1.23	0.01	
		2.00%	1.69	1.69	1.69	0.00	
		2.40%	2.10	2.10	2.10	0.00	
		2.80%	2.54	2.54	2.54	0.00	
	Run 3	0.50%	0.45	0.39	0.39	0.06	0.01% H_2

		1.00%	0.92	0.92	0.92	0.00	
		1.50%	1.40	1.39	1.40	0.01	
		2.00%	1.88	1.88	1.88	0.00	
		2.40%	2.29	2.29	2.29	0.00	
		2.80%	2.75	2.75	2.75	0.00	
	Run 4	0.50%	0.00	0.00	0.00	0.00	0.00% H_2
		1.00%	0.84	0.84	0.84	0.00	
		1.50%	1.29	1.29	1.29	0.00	
		2.00%	1.75	1.75	1.76	0.01	
		2.40%	2.15	2.15	2.16	0.01	
		2.80%	2.59	2.59	2.59	0.00	
XEN-5320	Sensor 1 Run 1	0.50%	0.68	0.68	0.68	0.00	0.00% H_2
		1.00%	1.22	1.22	1.22	0.00	
		1.50%	1.75	1.75	1.75	0.00	
		2.00%	2.30	2.30	2.30	0.00	
		2.40%	2.74	2.74	2.74	0.00	
		2.80%	3.18	3.18	3.18	0.00	
	Sensor 1 Run 2	0.50%	0.68	0.68	0.68	0.00	0.00% H_2
		1.00%	1.22	1.22	1.22	0.00	
		1.50%	1.76	1.76	1.76	0.00	
		2.00%	2.30	2.30	2.30	0.00	
		2.40%	2.75	2.75	2.75	0.00	
		2.80%	3.21	3.22	3.22	0.01	
	Sensor 2	0.50%	0.57	0.57	0.57	0.00	0.00% H_2
		1.00%	1.11	1.11	1.11	0.00	
		1.50%	1.64	1.64	1.64	0.00	
		2.00%	2.19	2.19	2.19	0.00	
		2.40%	2.63	2.63	2.63	0.00	
		2.80%	3.10	3.10	3.10	0.00	
	Sensor 3	0.50%	0.59	0.59	0.59	0.00	0.00% H_2
		1.00%	1.12	1.12	1.12	0.00	
		1.50%	1.66	1.66	1.66	0.00	
		2.00%	2.21	2.21	2.21	0.00	
		2.40%	2.65	2.65	2.65	0.00	
		2.80%	3.12	3.12	3.12	0.00	
Sense H_2®	Sensor 1 Run 1	0.50%	1.5	1.5	1.5	0.0	0.02% H_2
		1.00%	2.0	2.0	2.0	0.0	
		1.50%	2.4	2.4	2.4	0.0	
		2.00%	2.9	2.9	3.0	0.1	
		2.40%	3.0	3.0	3.0	0.0	
		2.80%	4.0	4.0	4.0	0.0	
	Sensor 1 Run 2	0.50%	1.0	1.0	1.0	0.0	0.00% H_2
		1.00%	1.5	1.5	1.5	0.0	
		1.50%	2.0	2.0	2.0	0.0	
		2.00%	2.5	2.5	2.5	0.0	

		2.40%	3.0	3.0	3.0	0.0	
		2.80%	3.0	3.0	3.0	0.0	
	Sensor 2	0.50%	1.5	1.5	1.5	0.0	0.00% H_2
		1.00%	2.0	2.0	2.0	0.0	
		1.50%	2.5	2.5	2.5	0.0	
		2.00%	3.0	3.0	3.0	0.0	
		2.40%	3.0	3.0	3.0	0.0	
		2.80%	4.0	4.0	4.0	0.0	
	Sensor 3	0.50%	1.0	1.0	1.0	0.0	0.02% H_2
		1.00%	1.5	1.5	1.5	0.0	
		1.50%	2.0	2.0	2.0	0.0	
		2.00%	2.4	2.4	2.5	0.1	
		2.40%	3.0	3.0	3.0	0.0	
		2.80%	3.0	3.0	3.0	0.0	
FH2-HY04	Sensor 1 Run 1	0.50%	0.57	0.57	0.57	0.00	0.00% H_2
		1.00%	1.07	1.08	1.08	0.01	
		1.50%	1.57	1.57	1.57	0.00	
		2.00%	2.10	2.10	2.10	0.00	
		2.40%	2.54	2.54	2.54	0.00	
		2.80%	2.98	2.98	2.98	0.00	
	Sensor 1 Run 2	0.50%	0.56	0.56	0.56	0.00	0.00% H_2
		1.00%	1.06	1.06	1.06	0.00	
		1.50%	1.56	1.56	1.56	0.00	
		2.00%	2.08	2.09	2.09	0.01	
		2.40%	2.53	2.53	2.53	0.00	
		2.80%	3.01	3.01	3.01	0.00	
	Sensor 2	0.50%	0.57	0.57	0.57	0.00	0.00% H_2
		1.00%	1.10	1.10	1.10	0.00	
		1.50%	1.62	1.62	1.62	0.00	
		2.00%	2.18	2.18	2.18	0.00	
		2.40%	2.67	2.67	2.67	0.00	
		2.80%	3.19	3.20	3.20	0.01	
	Sensor 3	0.50%	0.59	0.59	0.59	0.00	0.00% H_2
		1.00%	1.12	1.12	1.12	0.00	
		1.50%	1.64	1.64	1.64	0.00	
		2.00%	2.20	2.20	2.20	0.00	
		2.40%	2.69	2.69	2.69	0.00	
		2.80%	3.20	3.21	3.20	0.01	

Results – Nitrogen Background

Figure 182 through Figure 193 show the data collected for the square wave test with a nitrogen background.

As seen with the air background tests, both the H2scan and the XEN-5320 had consistent results for each repetition at each concentration in a nitrogen background.

As with previous tests, the Sense H_2® and FH2-HY04 did not function anaerobically.

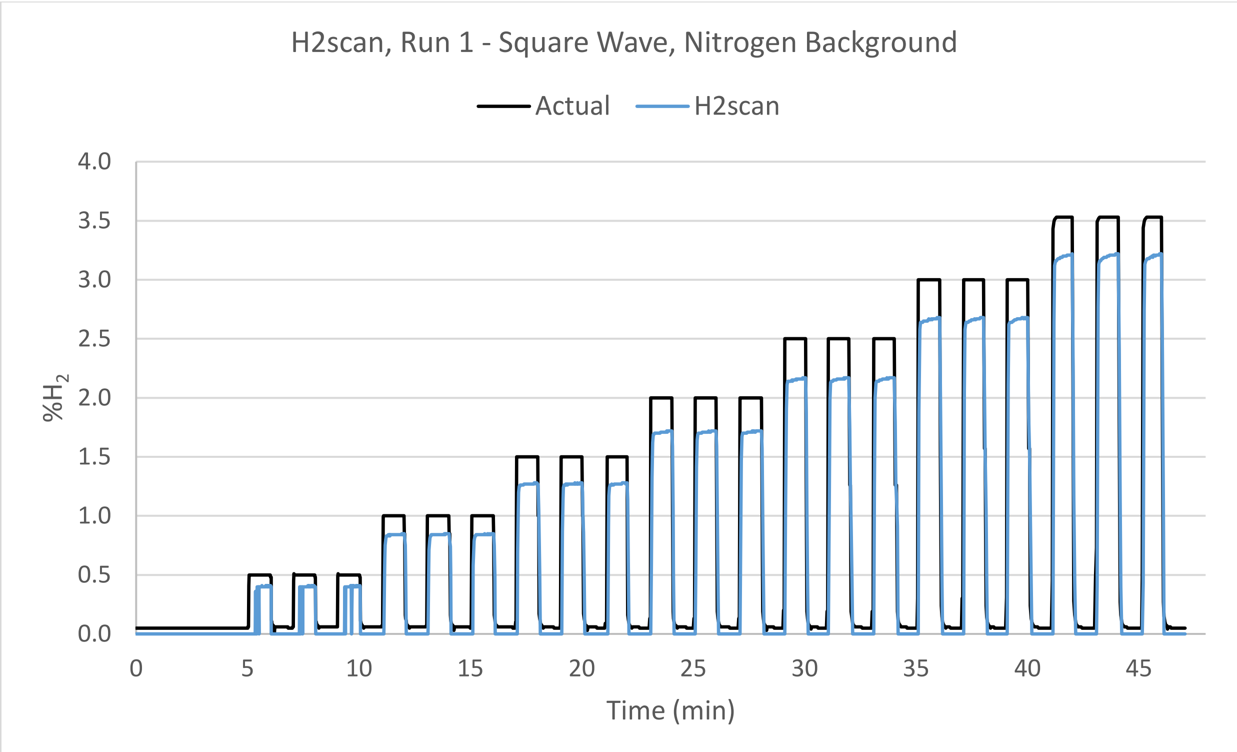

Figure 182. H2scan data for run 1 of the square wave test with a nitrogen background.

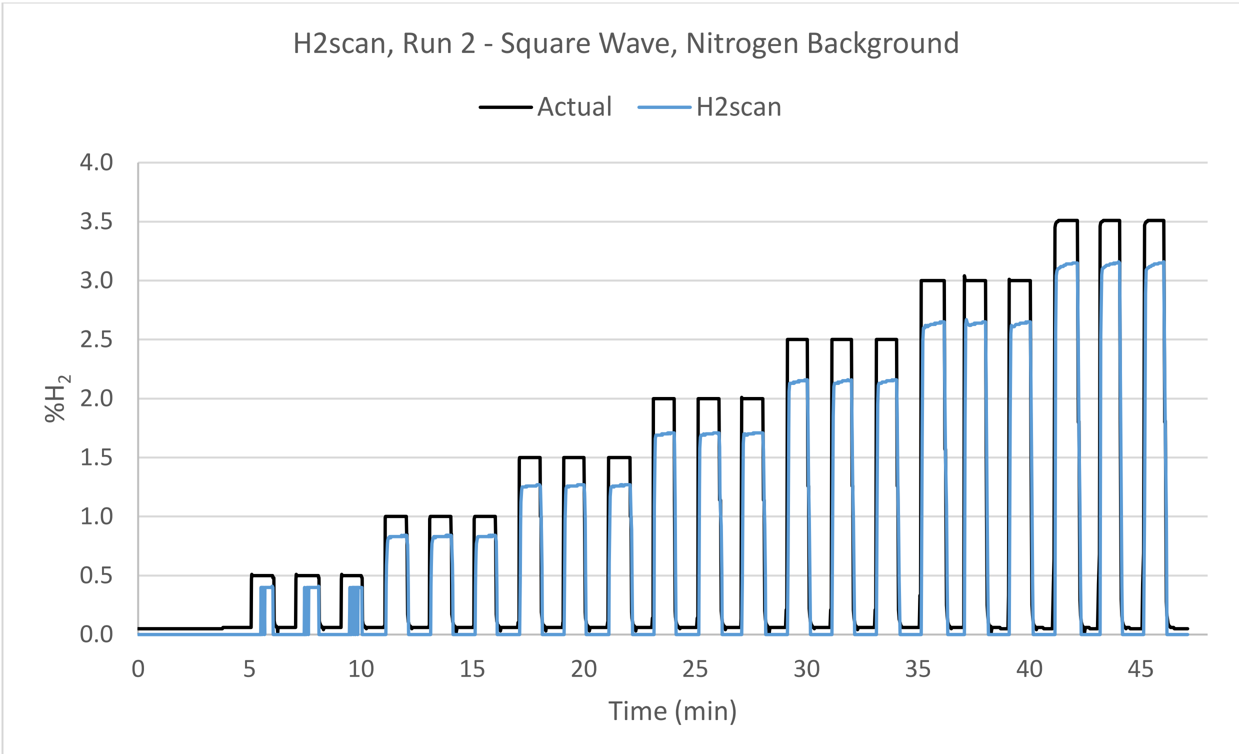

Figure 183. H2scan data for run 2 of the square wave test with a nitrogen background.

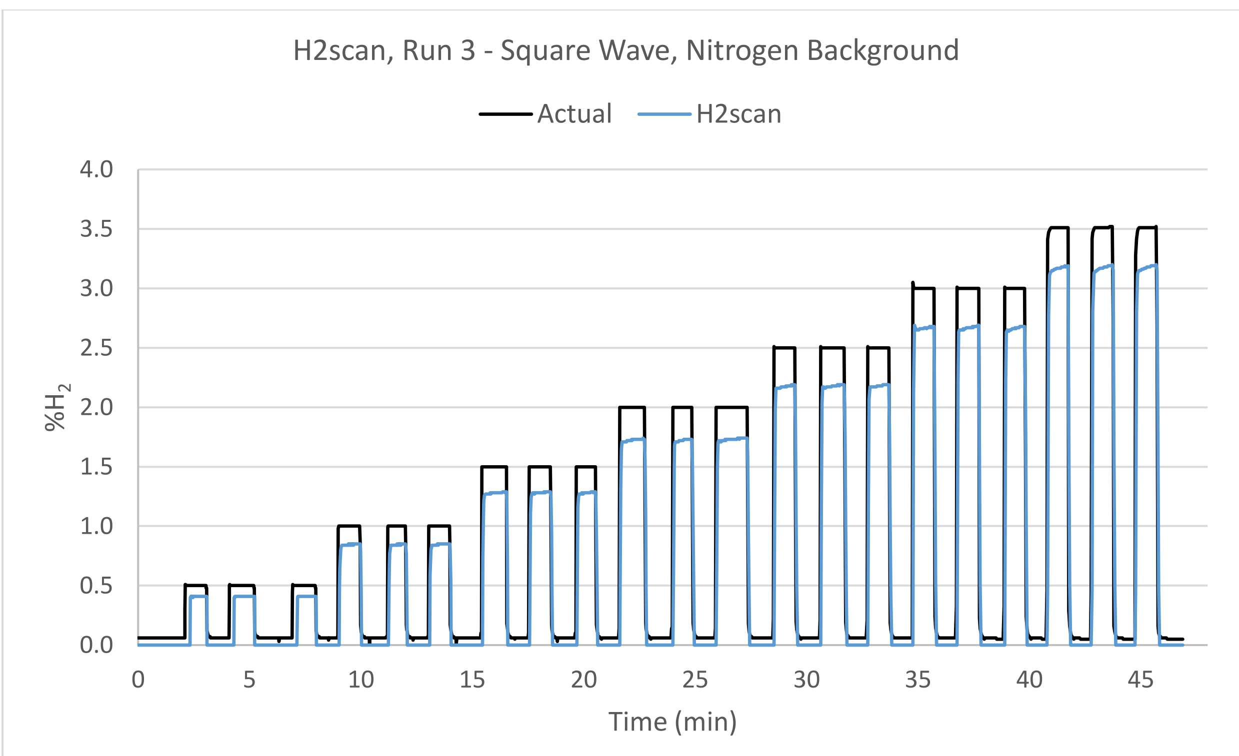

Figure 184. H2scan data for run 3 of the square wave test with a nitrogen background.

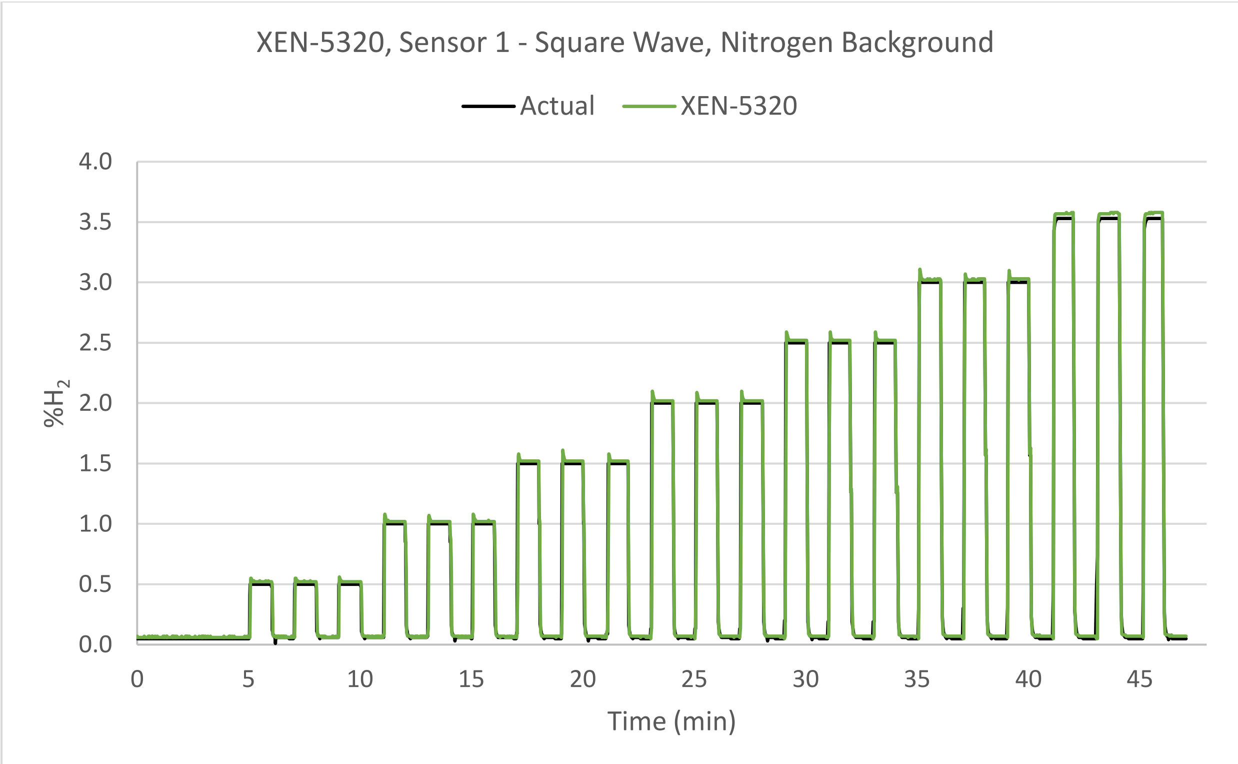

Figure 185. XEN-5320 data for sensor 1 in the square wave test with a nitrogen background.

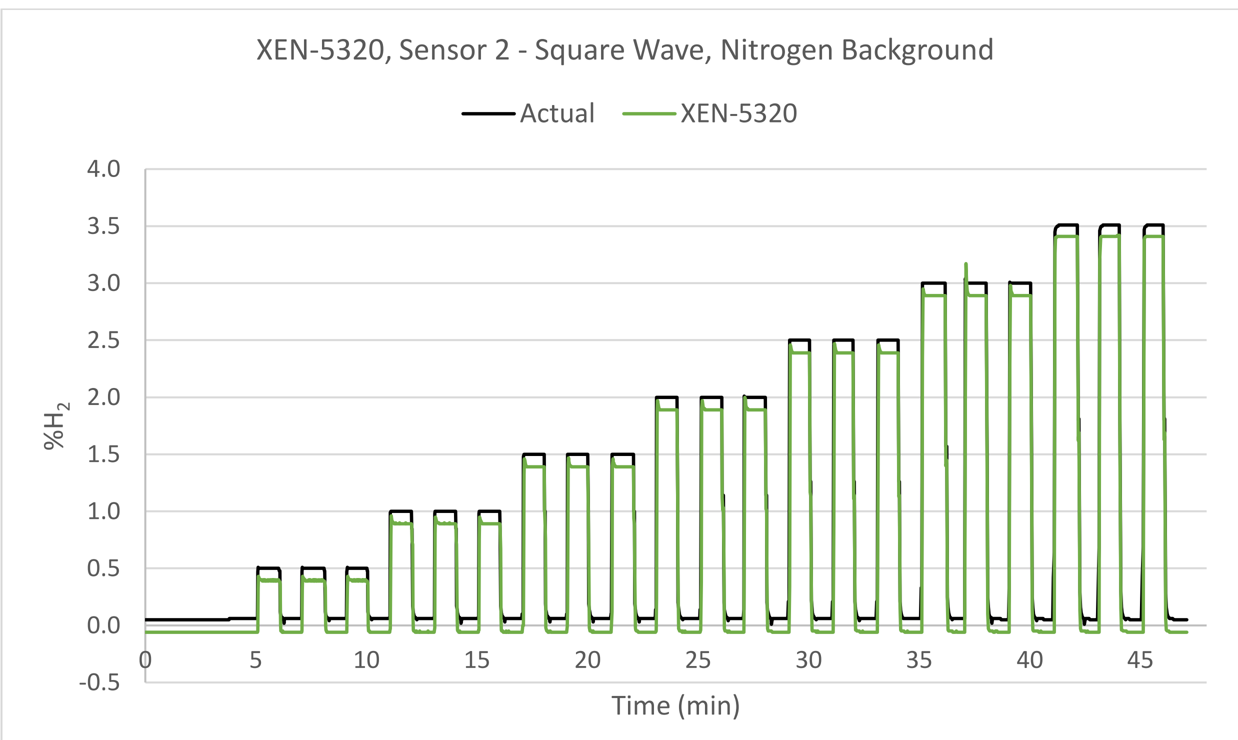

Figure 186. XEN-5320 data for sensor 2 in the square wave test with a nitrogen background.

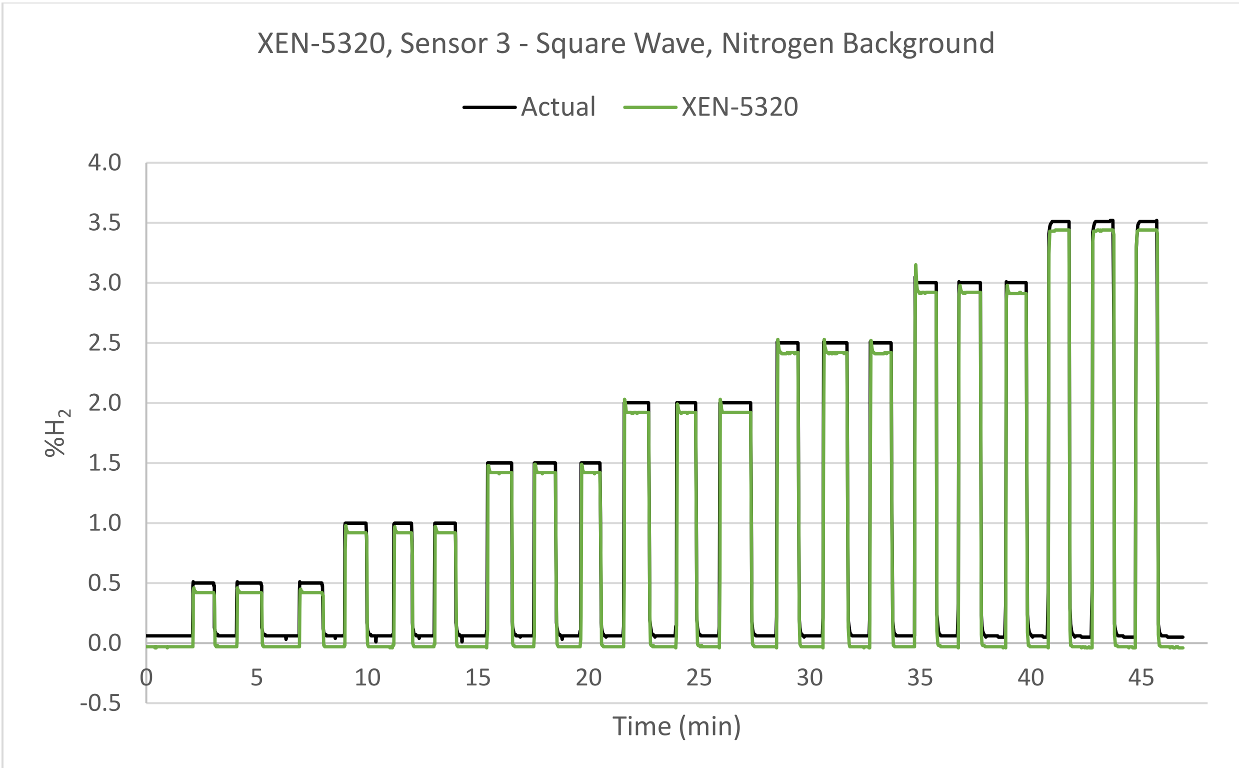

Figure 187. XEN-5320 data for sensor 3 in the square wave test with a nitrogen background.

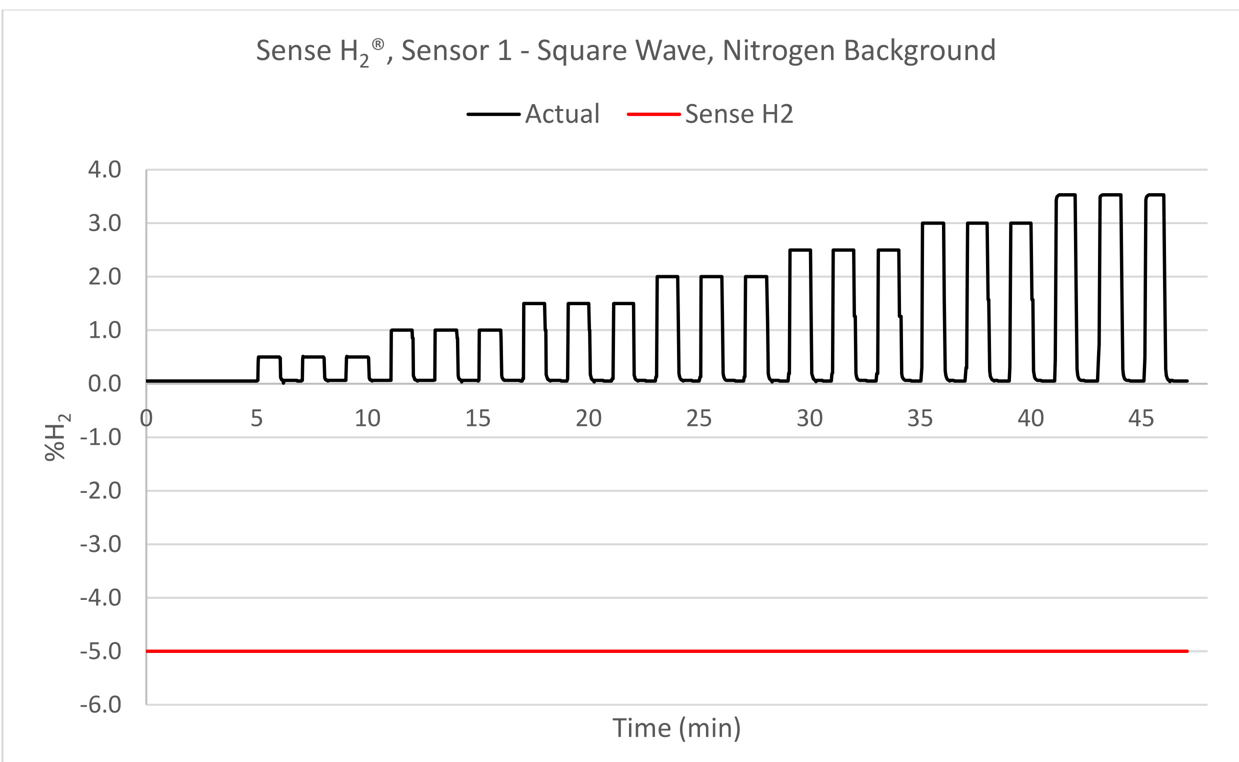

Figure 188. Sense H_2® data for sensor 1 in the square wave test with a nitrogen background.

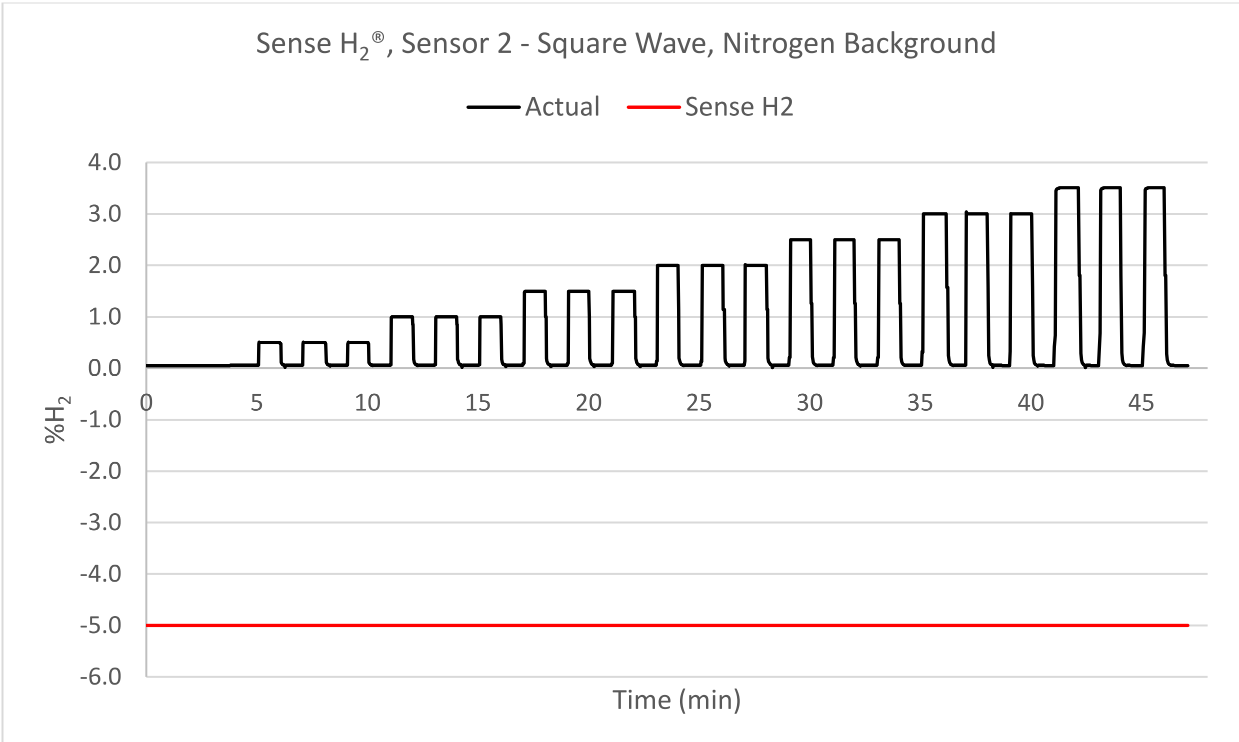

Figure 189. Sense H_2® data for sensor 2 in the square wave test with a nitrogen background.

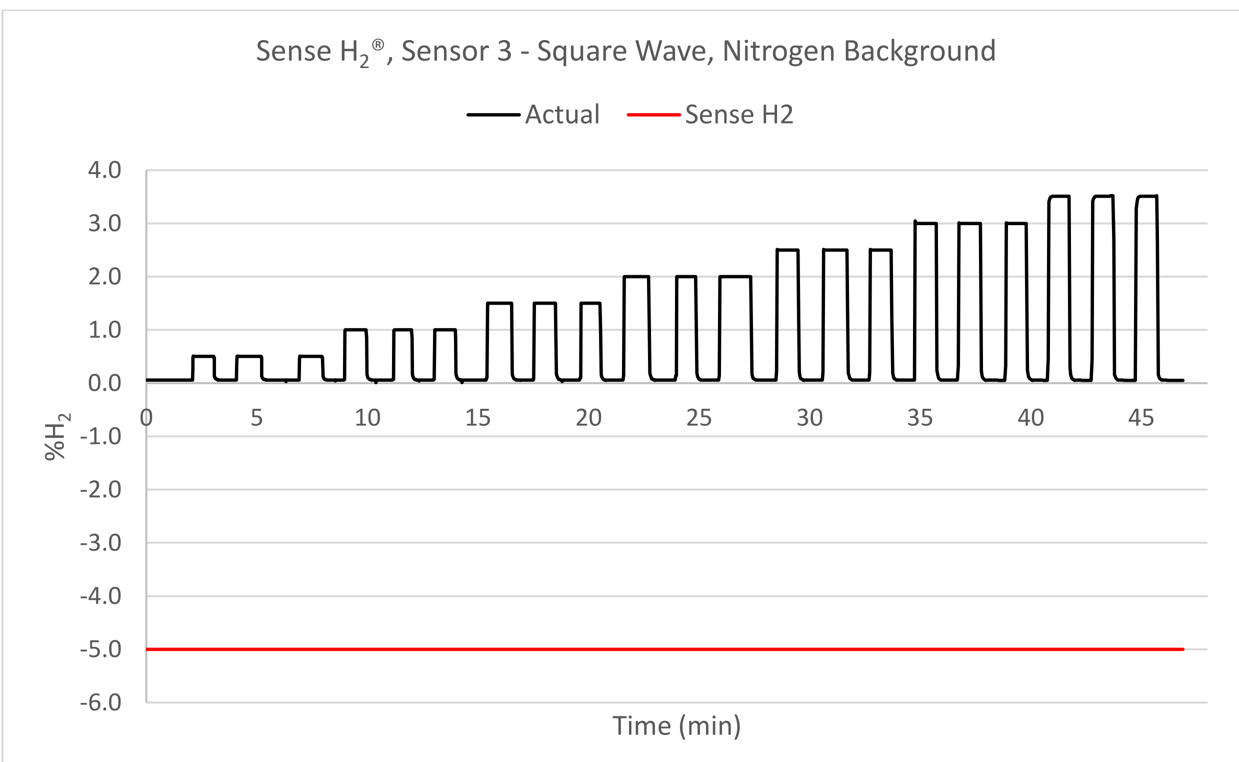

Figure 190. Sense H_2® data for sensor 3 in the square wave test with a nitrogen background.

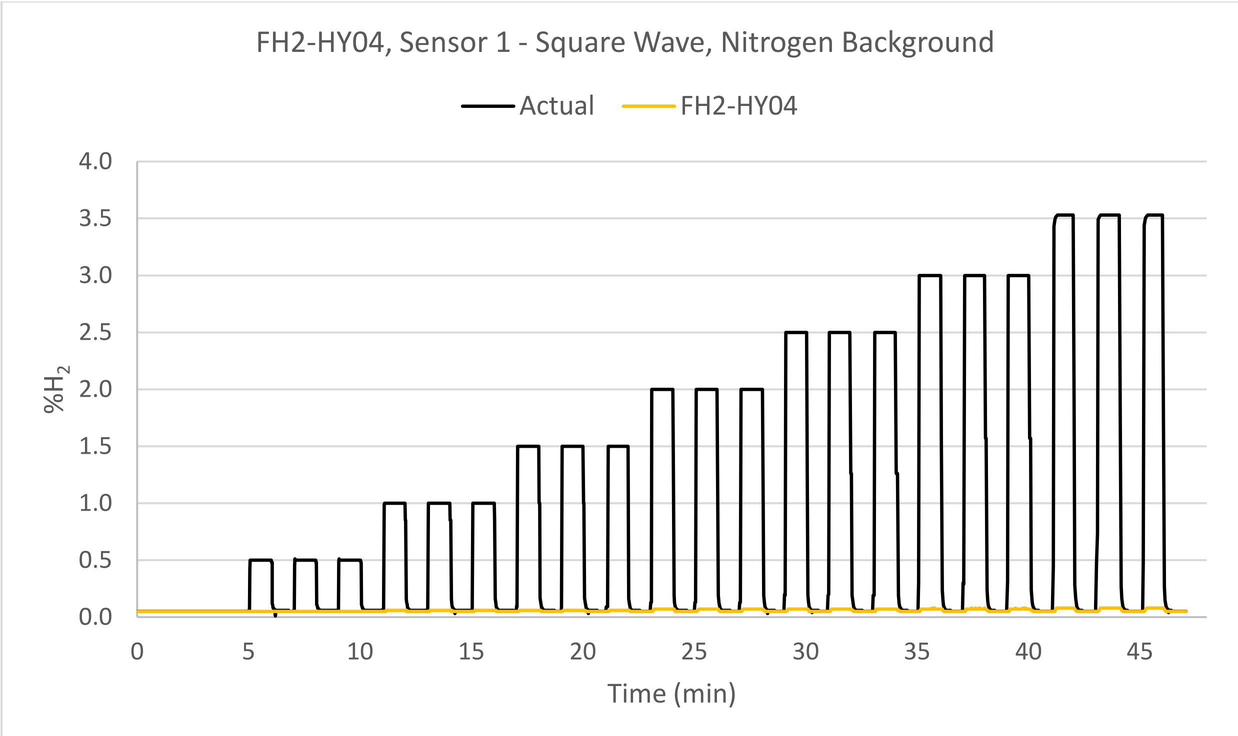

Figure 191. FH2-HY04 data for sensor 1 in the square wave test with a nitrogen background.

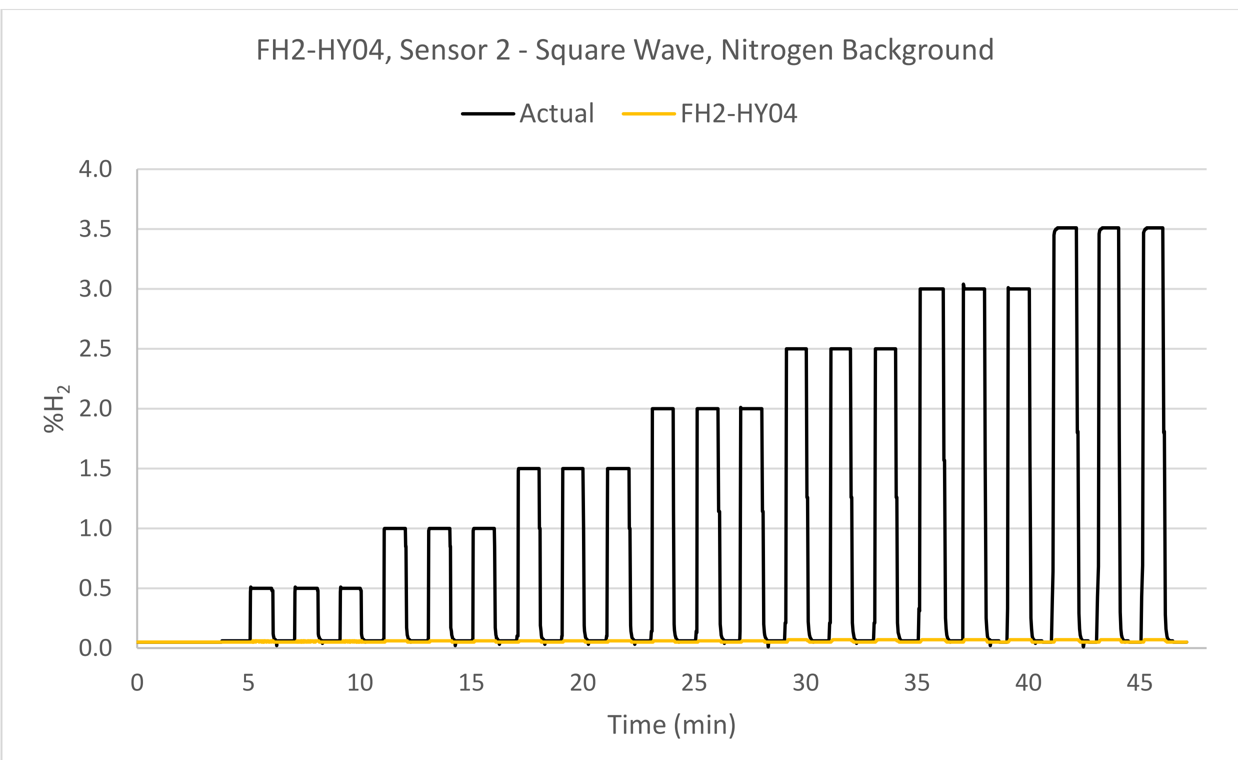

Figure 192. FH2-HY04 data for sensor 2 in the square wave test with a nitrogen background.

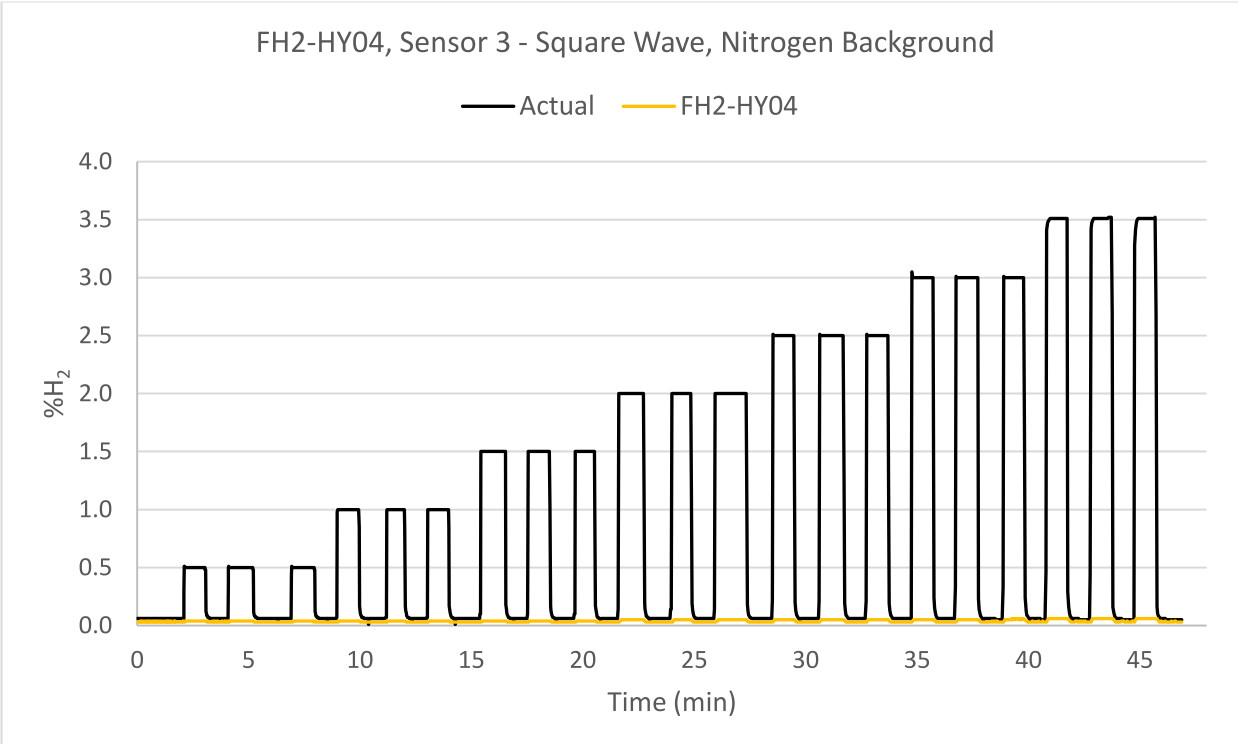

Figure 193. FH2-HY04 data for sensor 3 in the square wave test with a nitrogen background.

For each hydrogen concentration, the average value after a sensor had stabilized was calculated. Those values, as well as the repeatability (the difference between the maximum and minimum values for each hydrogen concentration) are given in Table 18. Because the Sense H_2® and FH2-HY04 were not functioning properly in a nitrogen background, they are omitted from the tables.

Table 18. Repeatability Results – Nitrogen Background

Sensor	Sensor/ Run	$\%H_2$	Value 1 ($\%H_2$)	Value 2 ($\%H_2$)	Value 3 ($\%H_2$)	Repeatability ($\%H_2$)	Average Repeatability
H2scan 720B	1	0.50%	0.39	0.37	0.38	0.02	0.00% H_2
		1.00%	0.84	0.84	0.84	0.00	
		1.50%	1.27	1.27	1.27	0.00	
		2.00%	1.71	1.71	1.71	0.00	
		2.50%	2.15	2.16	2.16	0.01	
		3.00%	2.66	2.66	2.66	0.00	
		3.53%	3.20	3.20	3.20	0.00	
	2	0.50%	0.36	0.39	0.34	0.05	0.01% H_2
		1.00%	0.83	0.83	0.83	0.00	
		1.50%	1.26	1.26	1.26	0.00	
		2.00%	1.70	1.70	1.70	0.00	
		2.50%	2.14	2.14	2.15	0.01	
		3.00%	2.63	2.64	2.64	0.01	
		3.51%	3.14	3.14	3.14	0.00	
	3	0.50%	0.41	0.41	0.41	0.00	0.01% H_2
		1.00%	0.84	0.84	0.85	0.01	
		1.50%	1.28	1.28	1.28	0.00	
		2.00%	1.72	1.72	1.73	0.01	
		2.50%	2.17	2.18	2.18	0.01	
		3.00%	2.67	2.67	2.66	0.01	
		3.51%	3.17	3.17	3.18	0.01	
XEN-5320	1	0.50%	0.52	0.52	0.52	0.00	0.00% H_2
		1.00%	1.02	1.02	1.02	0.00	
		1.50%	1.52	1.52	1.52	0.00	
		2.00%	2.02	2.02	2.02	0.00	
		2.50%	2.52	2.52	2.52	0.00	
		3.00%	3.02	3.02	3.03	0.01	
		3.53%	3.57	3.57	3.58	0.01	
	2	0.50%	0.40	0.39	0.39	0.01	0.00% H_2
		1.00%	0.89	0.89	0.89	0.00	
		1.50%	1.39	1.39	1.39	0.00	
		2.00%	1.89	1.89	1.89	0.00	
		2.50%	2.39	2.39	2.39	0.00	
		3.00%	2.89	2.89	2.89	0.00	
		3.51%	3.41	3.41	3.41	0.00	
	3	0.50%	0.42	0.42	0.42	0.00	0.00% H_2
		1.00%	0.92	0.92	0.92	0.00	
		1.50%	1.42	1.42	1.42	0.00	
		2.00%	1.92	1.92	1.92	0.00	
		2.50%	2.42	2.42	2.41	0.01	
		3.00%	2.92	2.92	2.91	0.01	
		3.51%	3.44	3.44	3.44	0.00	

Results – Helium Background

Figure 194 through Figure 197 show the data collected for the square wave test with a helium background.

The H2scan also had repeatable results for each concentration in a helium background.

As seen in previous tests, the XEN-5320 cannot detect hydrogen in a helium background, and the Sense H_2® and FH2-HY04 did not function anaerobically.

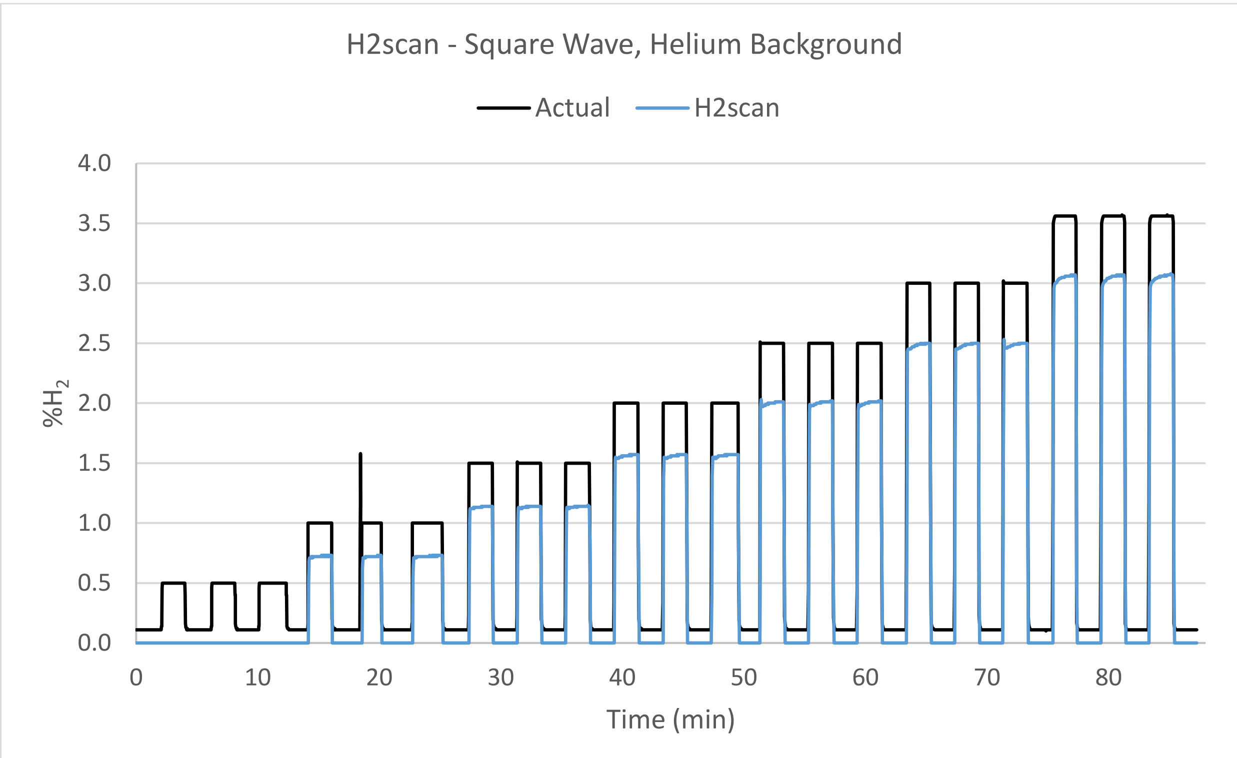

Figure 194. H2scan data for the square wave test with a helium background.

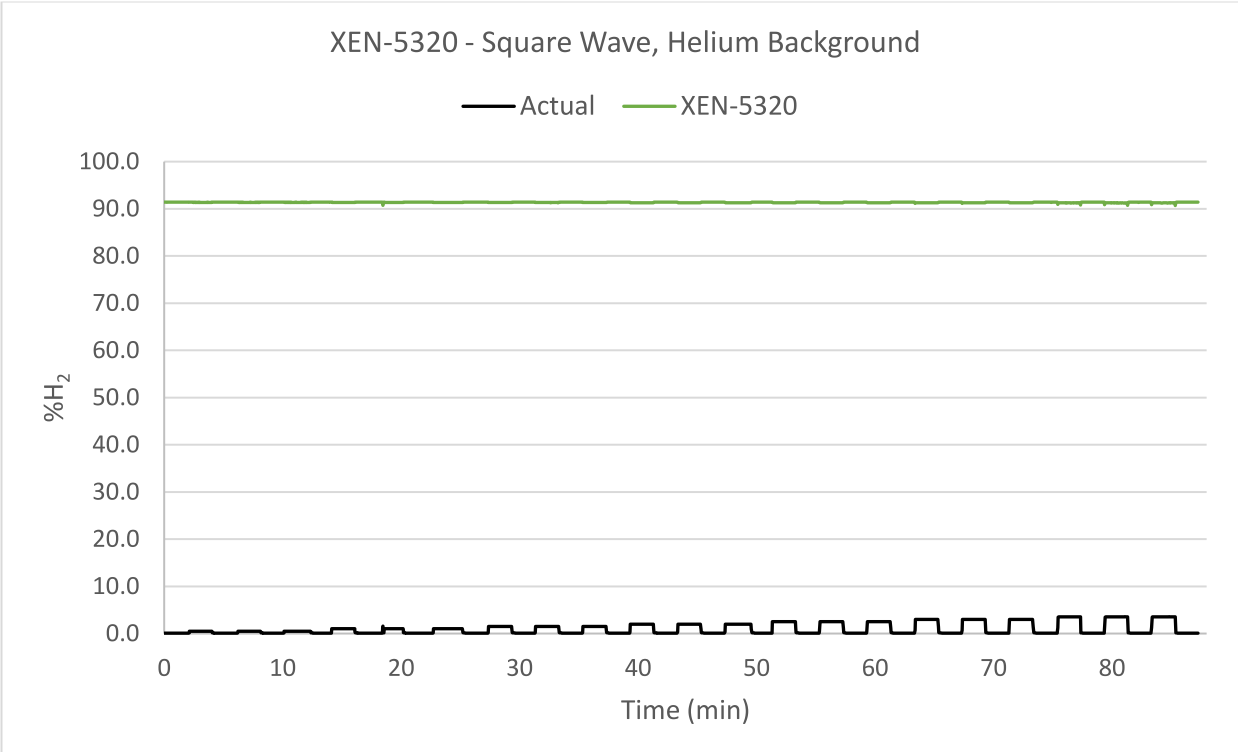

Figure 195. XEN-5320 data for the square wave test with a helium background.

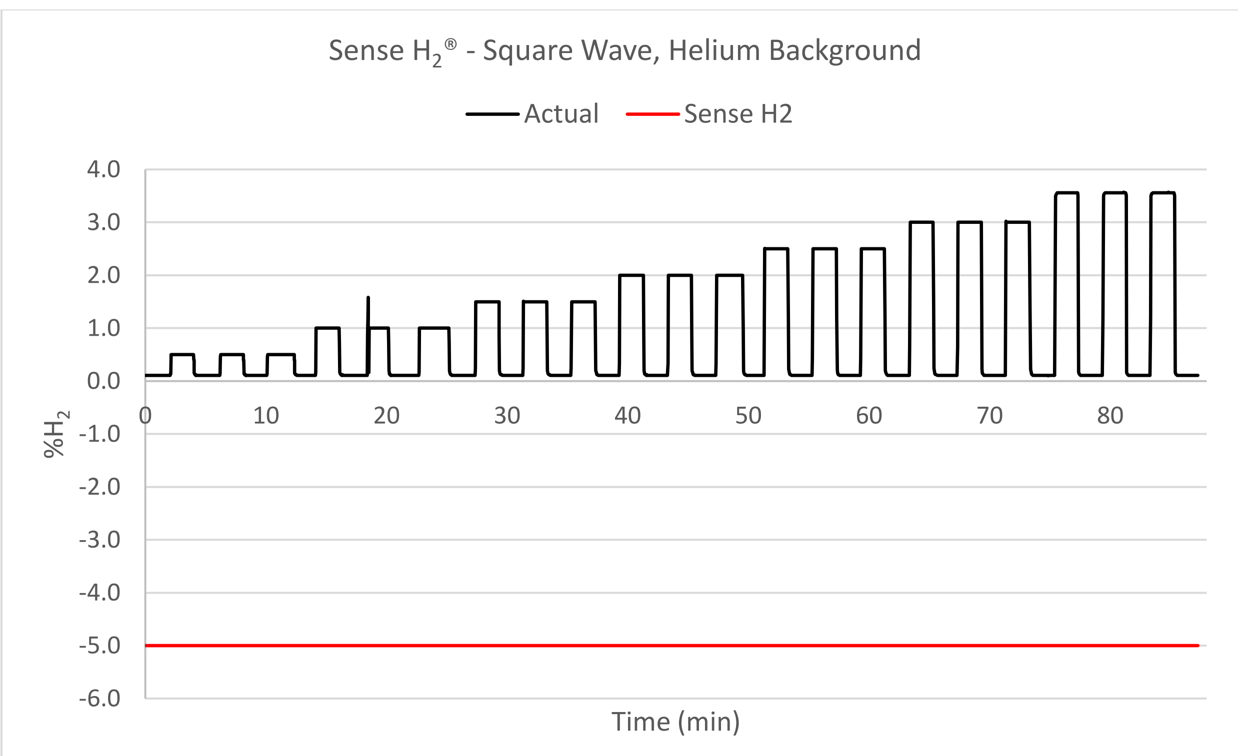

Figure 196. Sense H_2® data for the square wave test with a helium background.

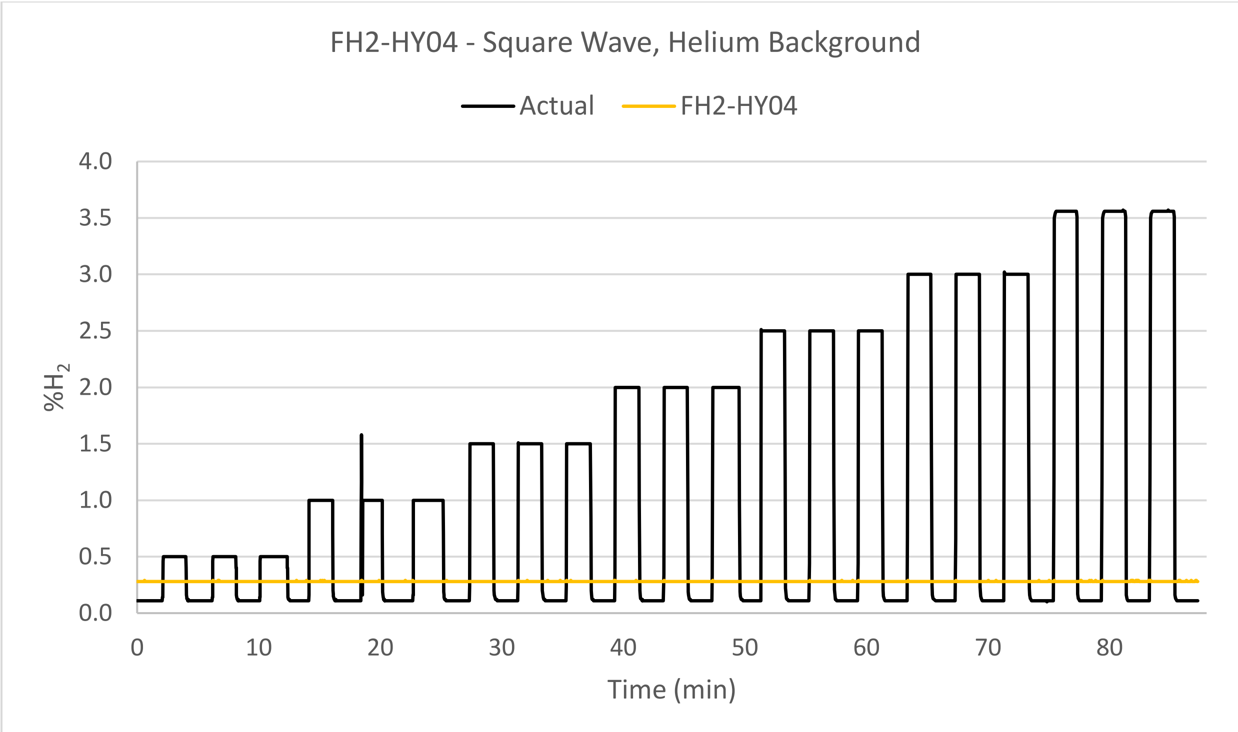

Figure 197. FH2-HY04 data for the square wave test with a helium background.

For each hydrogen concentration, the average value after a sensor had stabilized was calculated. Those values, as well as the repeatability (the difference between the maximum and minimum values for each hydrogen concentration) are given in Table 19. Because none of the other sensors were functioning properly in the helium background, only the H2scan data is given on the table.

Table 19. Repeatability Results – Helium Background

Sensor	**%H_2**	**Value 1 (%H_2)**	**Value 2 (%H_2)**	**Value 3 (%H_2)**	**Repeatability (%H_2)**	**Average Repeatability**
H2scan 720B	0.50%	0.00	0.00	0.00	0.00	0.00% H_2
	1.00%	0.72	0.72	0.72	0.00	
	1.50%	1.13	1.13	1.14	0.01	
	2.00%	1.56	1.56	1.56	0.00	
	2.50%	2.00	2.00	2.00	0.00	
	3.00%	2.48	2.48	2.49	0.01	
	3.56%	3.06	3.06	3.06	0.00	

Response Tests

This test was used to determine how quickly the sensors respond to the presence or absence of hydrogen. 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 hydrogen 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 hydrogen concentration.

Procedure

1. Connect hydrogen 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% hydrogen.
6. Allow outputs to stabilize.
7. Adjust gas flows for a hydrogen concentration of 1%.
8. Allow outputs to stabilize.
9. Adjust gas flows for a hydrogen 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 hydrogen 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 hydrogen concentration as follows.

For increasing gas concentrations:

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

where

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

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

For decreasing gas concentrations:

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

where

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

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

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 hydrogen 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 hydrogen concentration changed

Results – Air Background

Values for flow rates were chosen that required only the hydrogen MFC to be changed between the high (1%) and low (~0%) hydrogen 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 198 through Figure 213 show the data collected for this test.

In each test, the H2scan's output increased quickly following an increase in gas concentration, then rounded off and more gradually approached its final value. When the hydrogen concentration dropped to zero, the H2scan's output very quickly returned to zero as well.

The XEN-5320 responded almost immediately for both increasing and decreasing hydrogen concentrations. When the concentration increased, however, it very briefly overshot its final value slightly before dropping back down to it.

The Sense H_2® was less consistent from one test to another. In some cases, it increased and decreased in a stepwise fashion, in others it went directly to its final output. Two of the four tests showed the sensor output toggling between two of its 0.5% intervals – one test at the high concentration and one at the low concentration.

The FH2-HY04's output increased and decreased quickly as the hydrogen concentration changed.

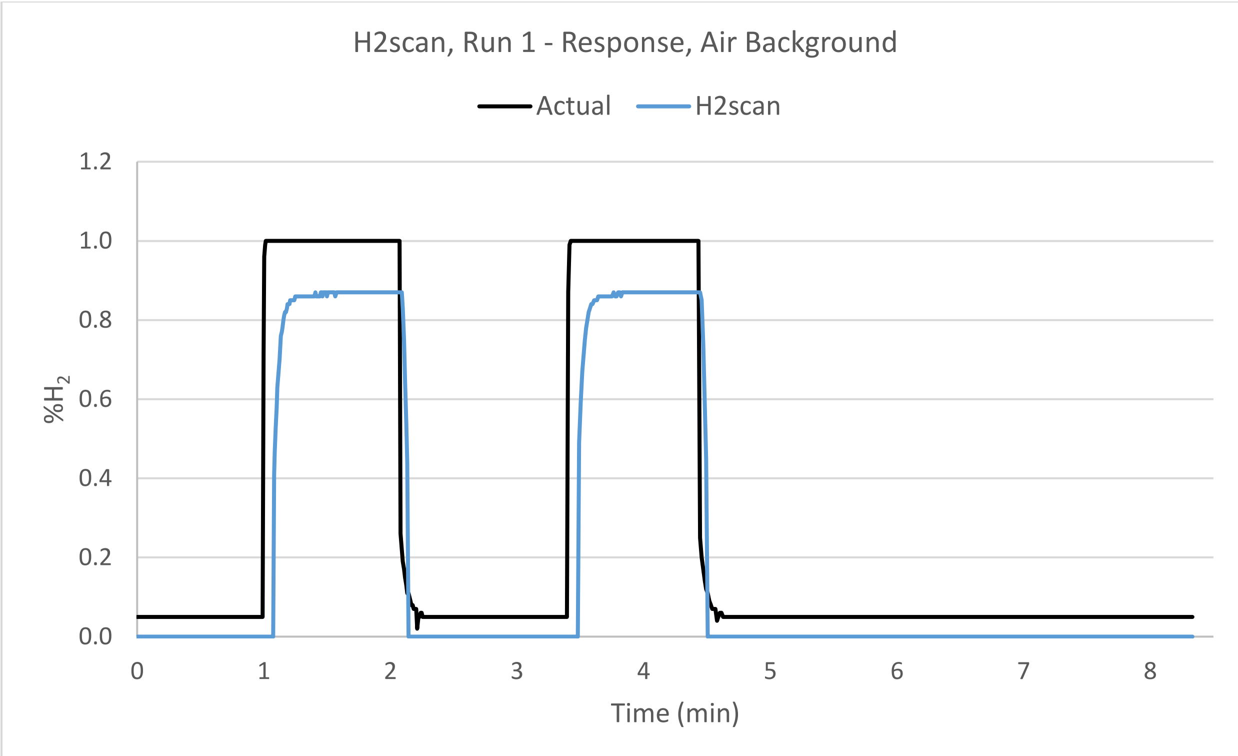

Figure 198. H2scan data for run 1 of the response test with an air background.

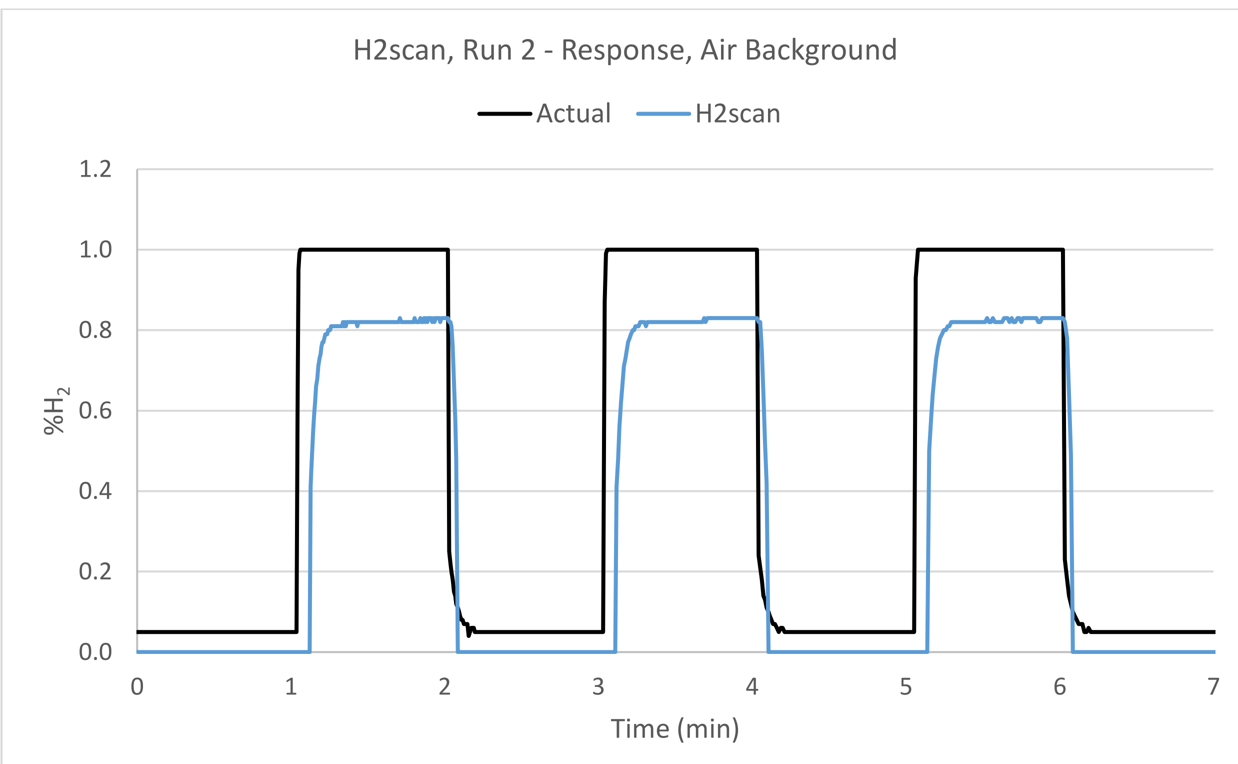

Figure 199. H2scan data for run 2 of the response test with an air background.

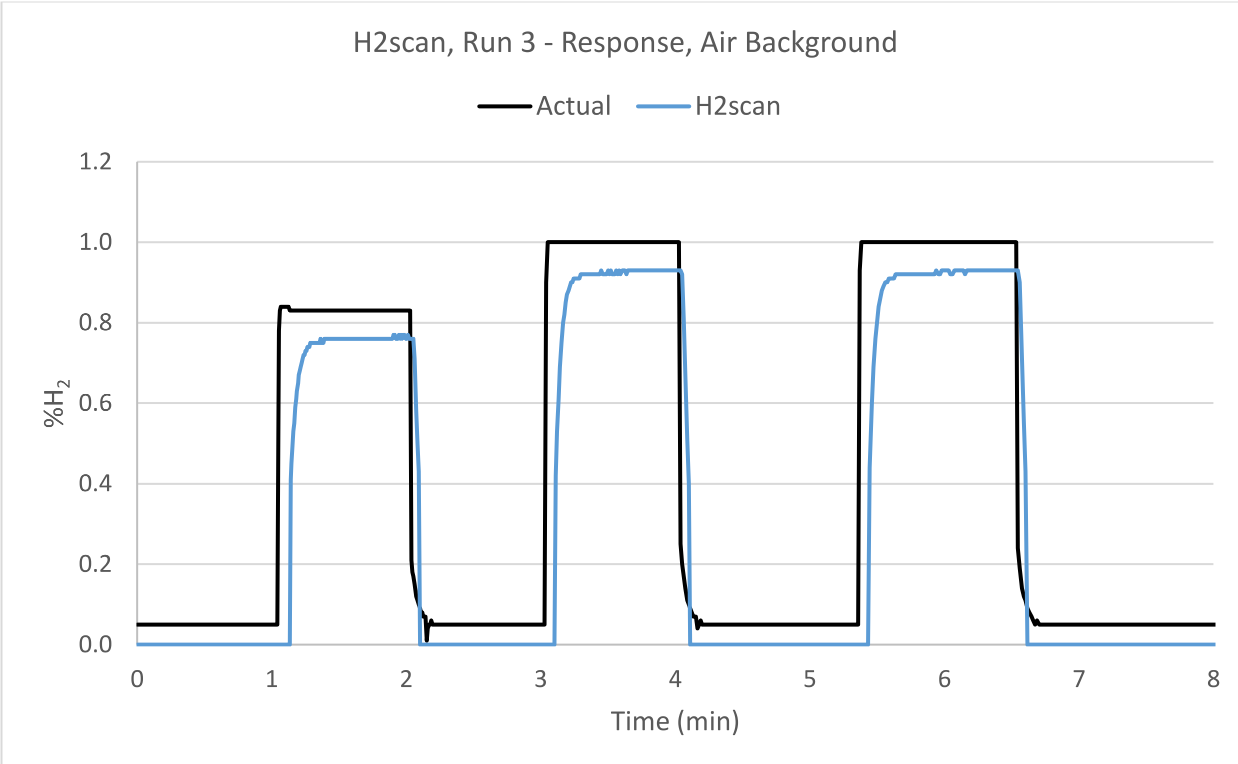

Figure 200. H2scan data for run 3 of the response test with an air background.

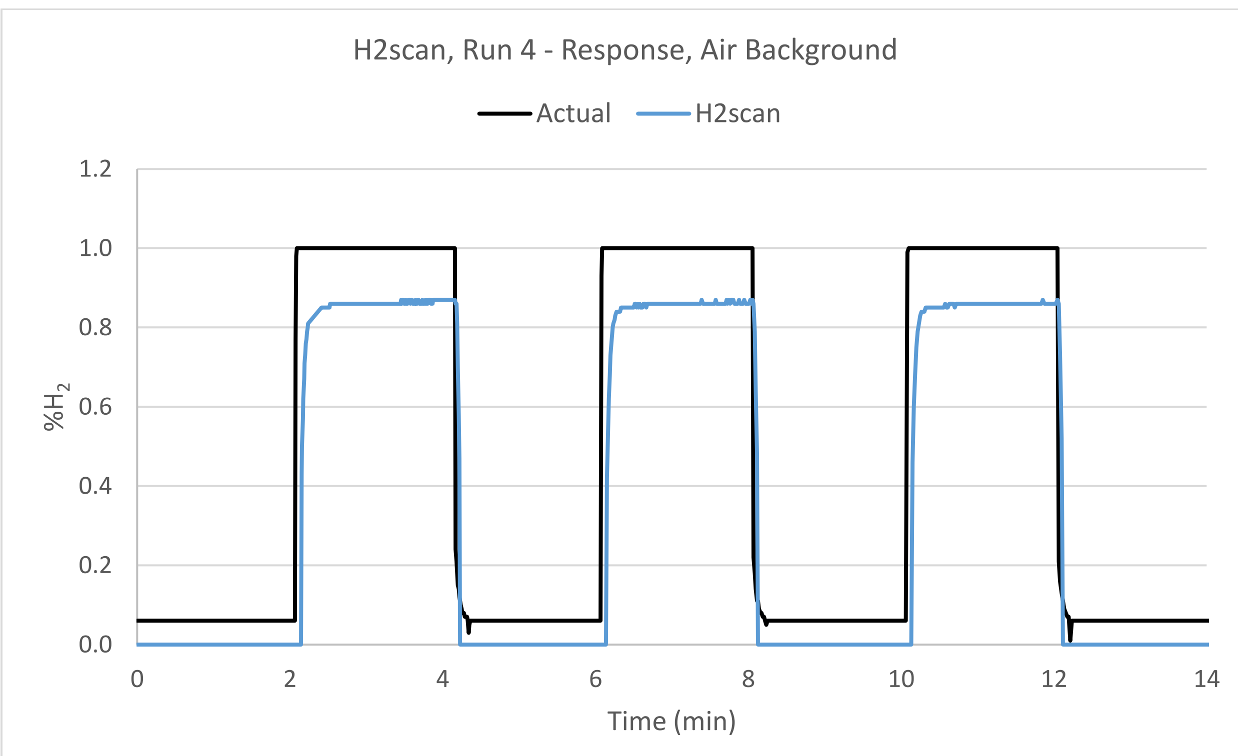

Figure 201. H2scan data for run 4 of the response test with an air background.

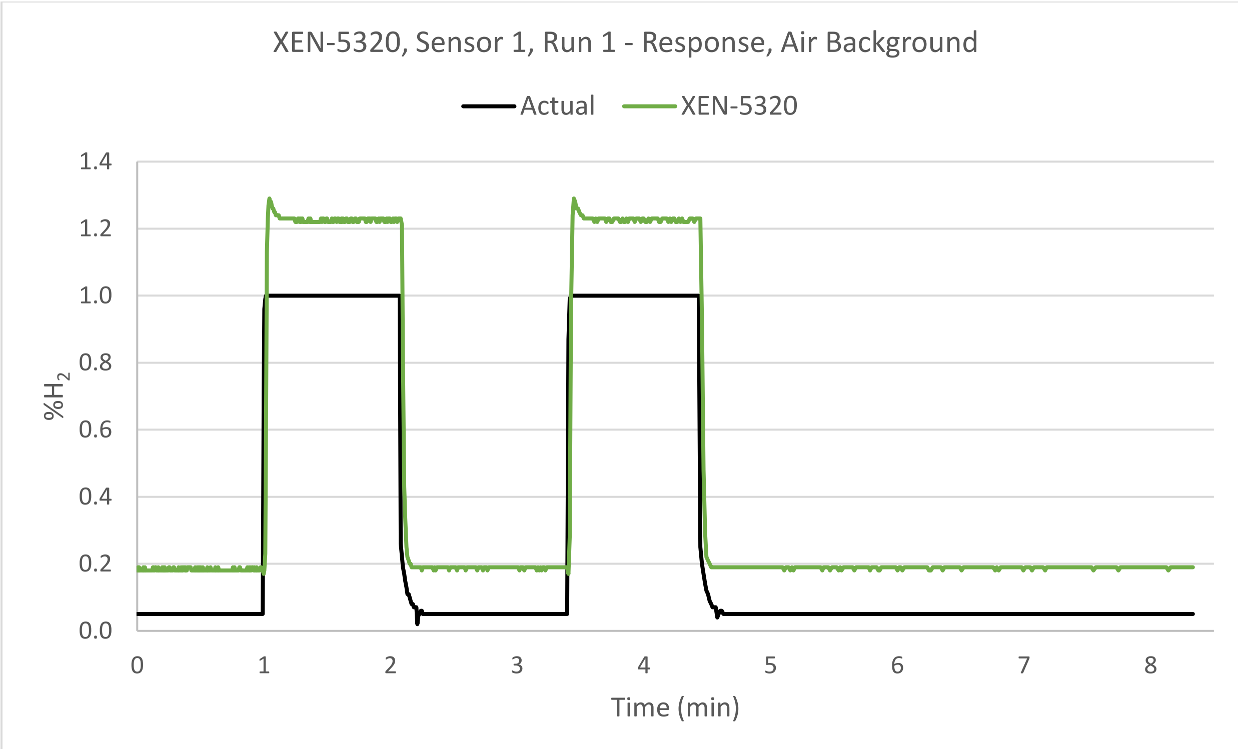

Figure 202. XEN-5320 data for sensor 1, run 1 of the response test with an air background.

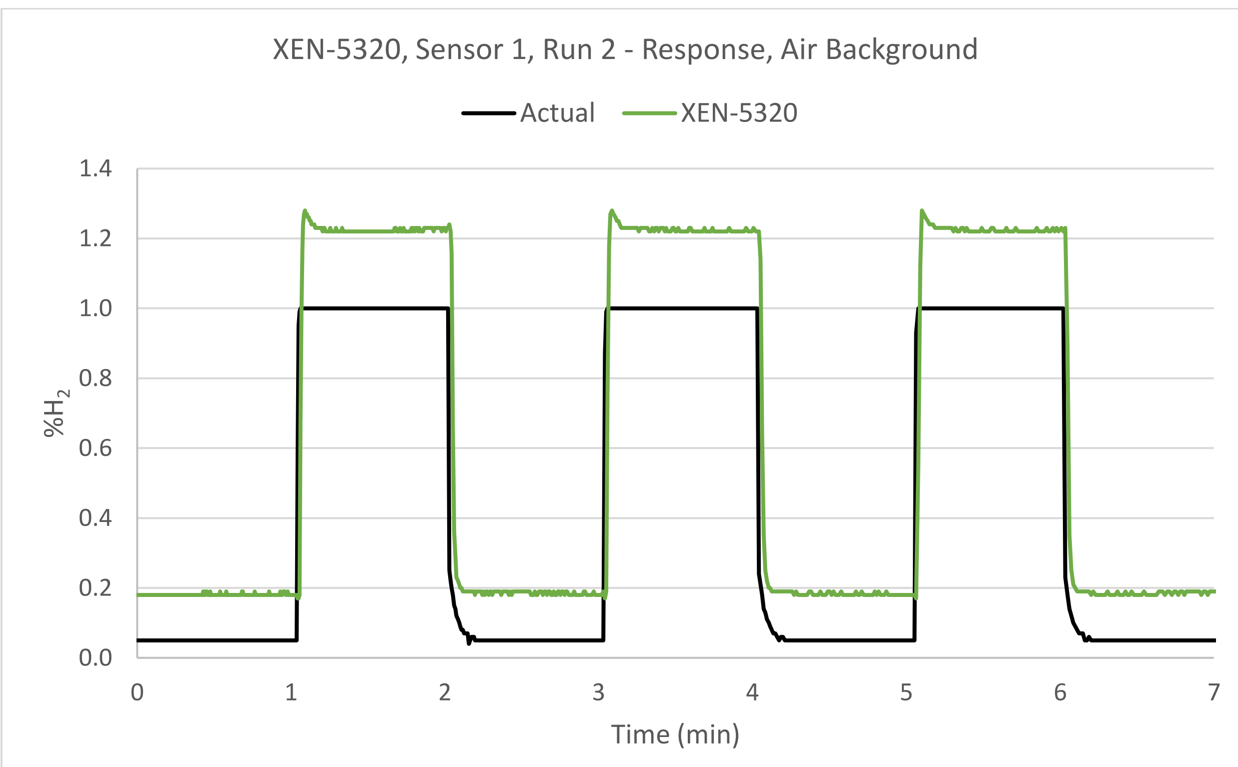

Figure 203. XEN-5320 data for sensor 1, run 2 of the response test with an air background.

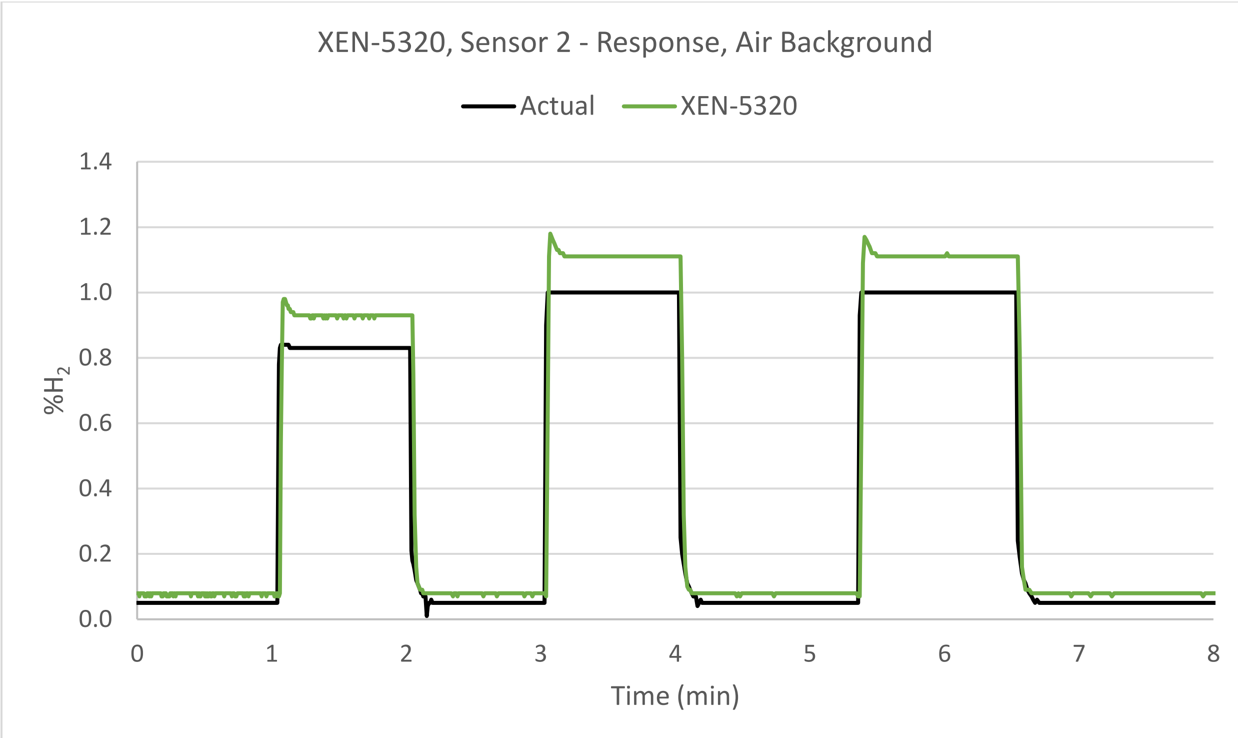

Figure 204. XEN-5320 data for sensor 2 in the response test with an air background.

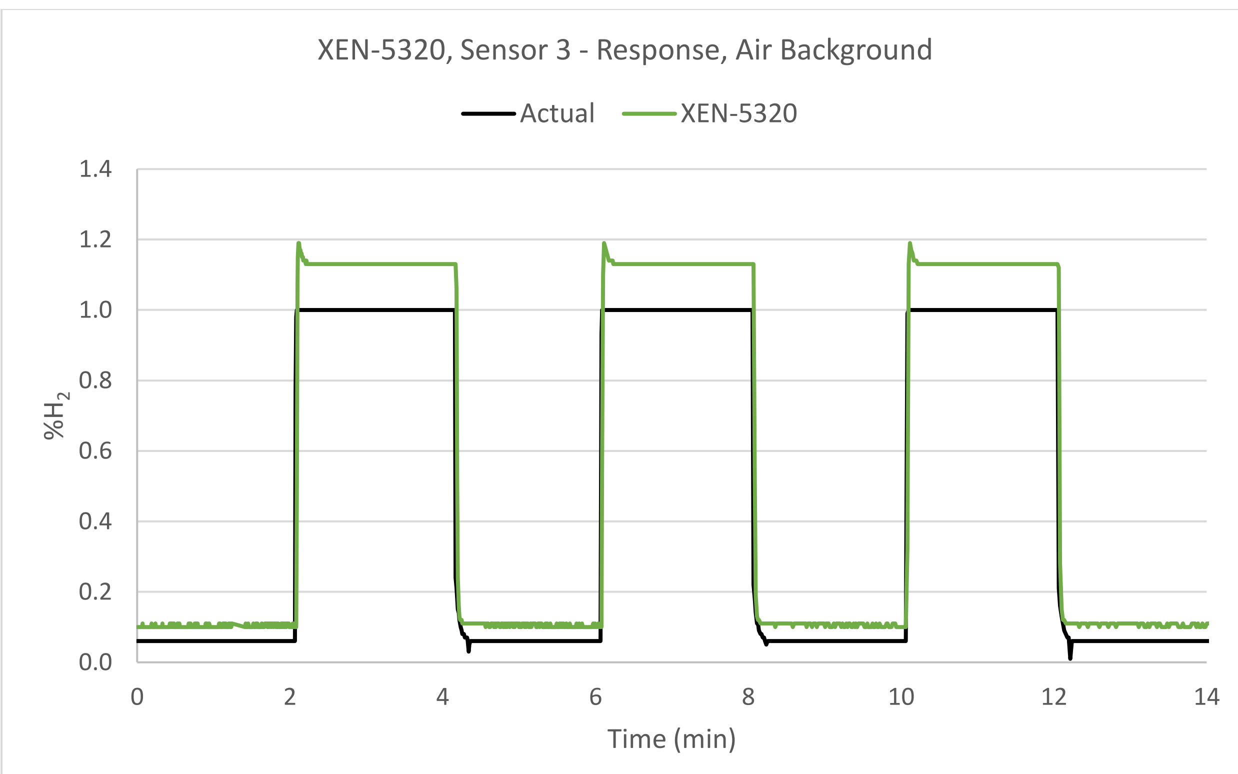

Figure 205. XEN-5320 data for sensor 3 in the response test with an air background.

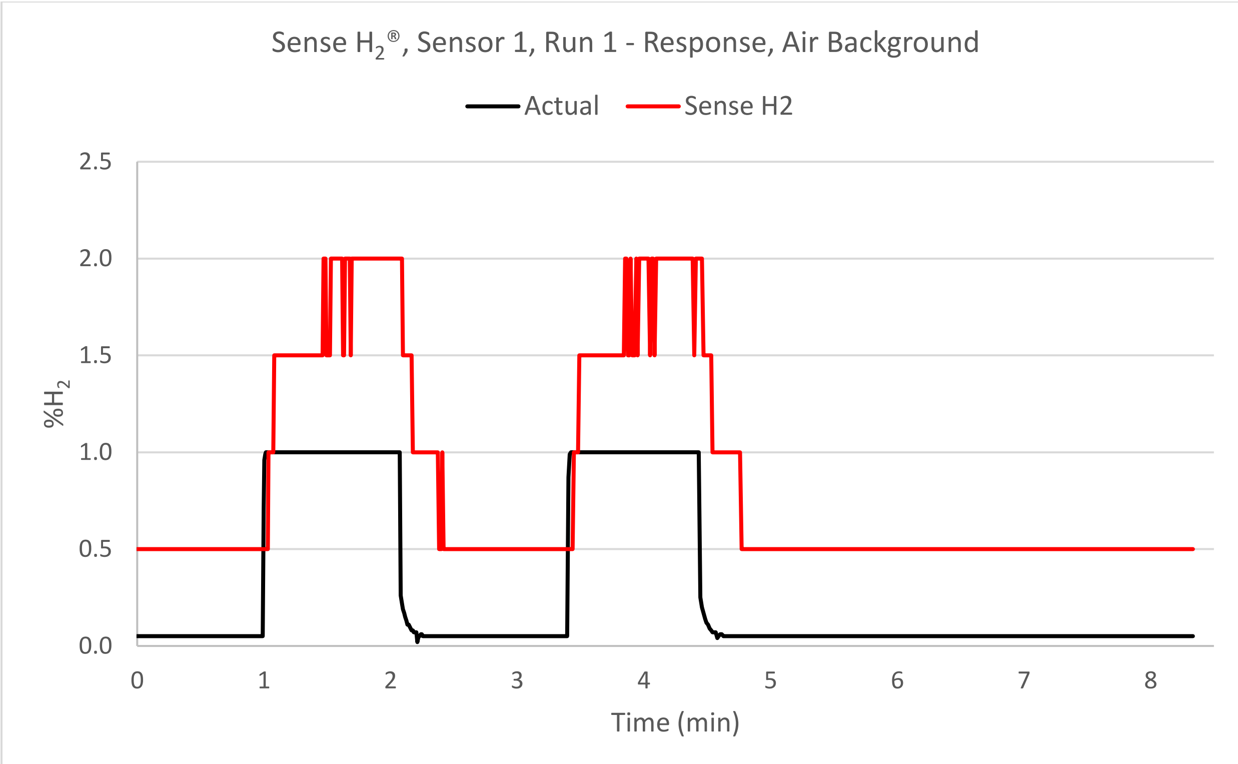

Figure 206. Sense H_2® data for sensor 1, run 1 of the response test with an air background.

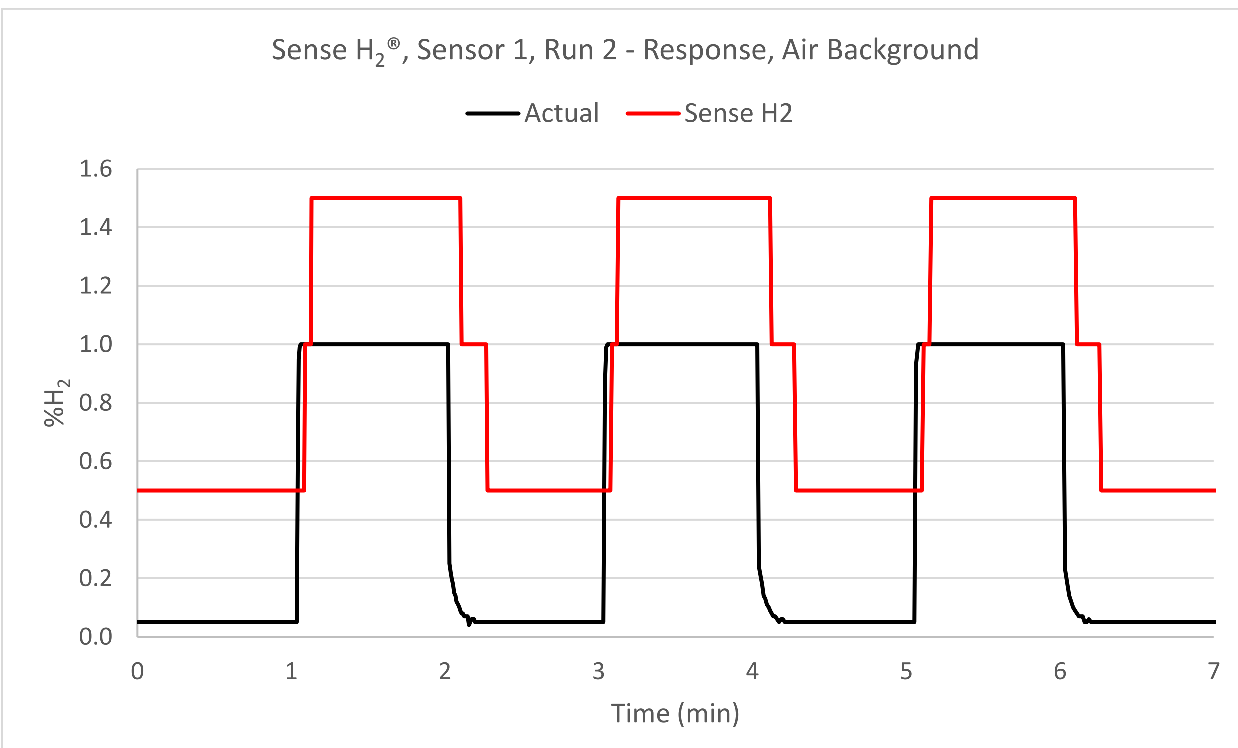

Figure 207. Sense H_2® data for sensor 1, run 2 of the response test with an air background.

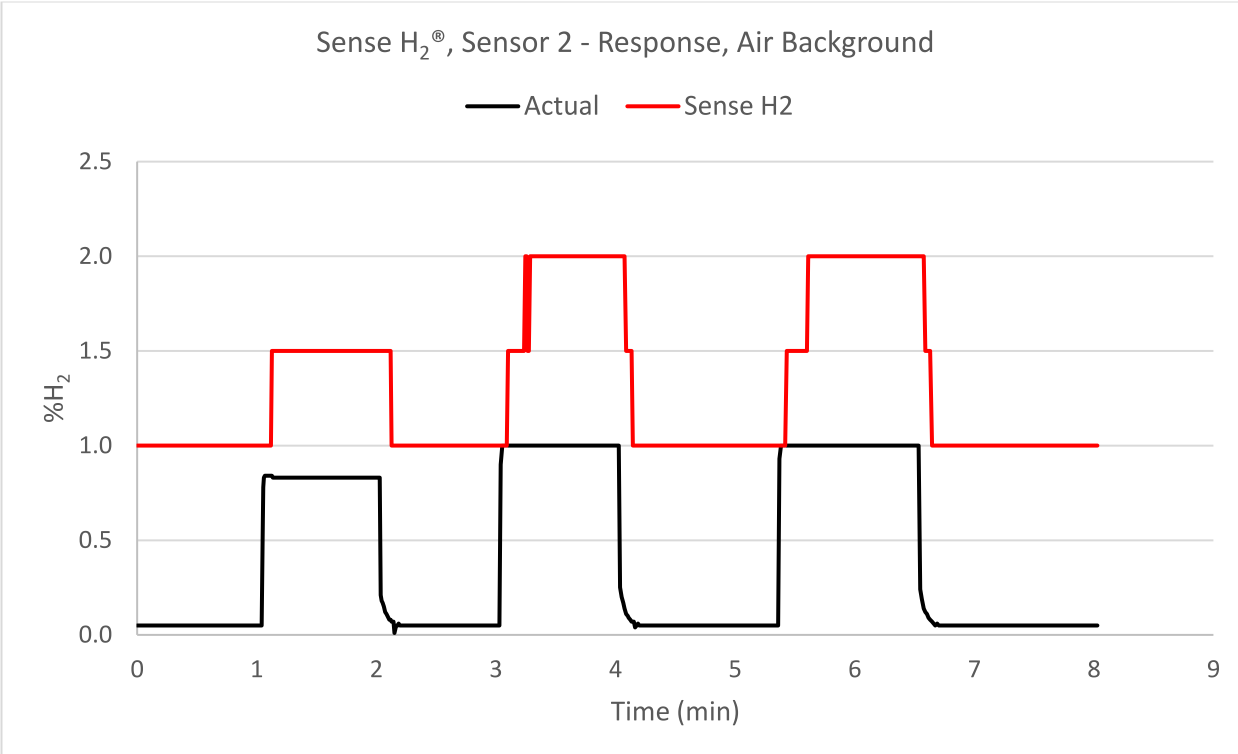

Figure 208. Sense H_2® data for sensor 2 in the response test with an air background.

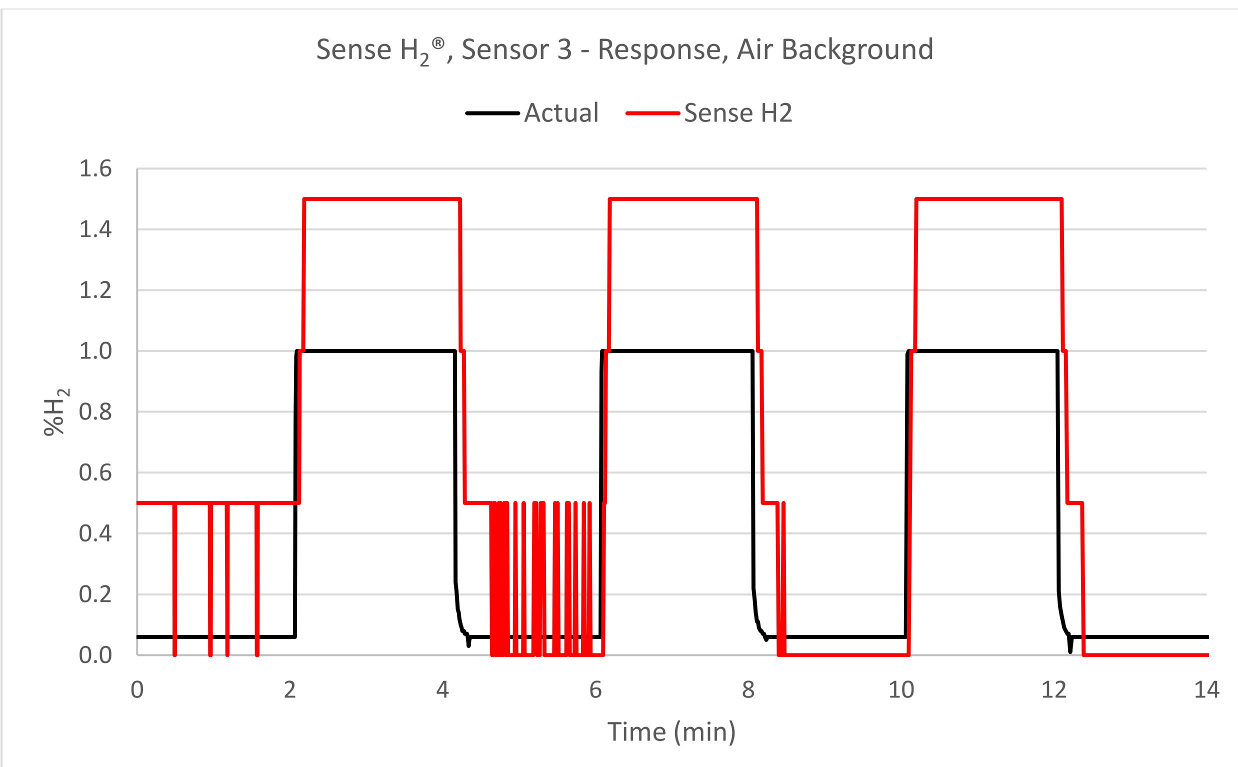

Figure 209. Sense H_2® data for sensor 3 in the response test with an air background.

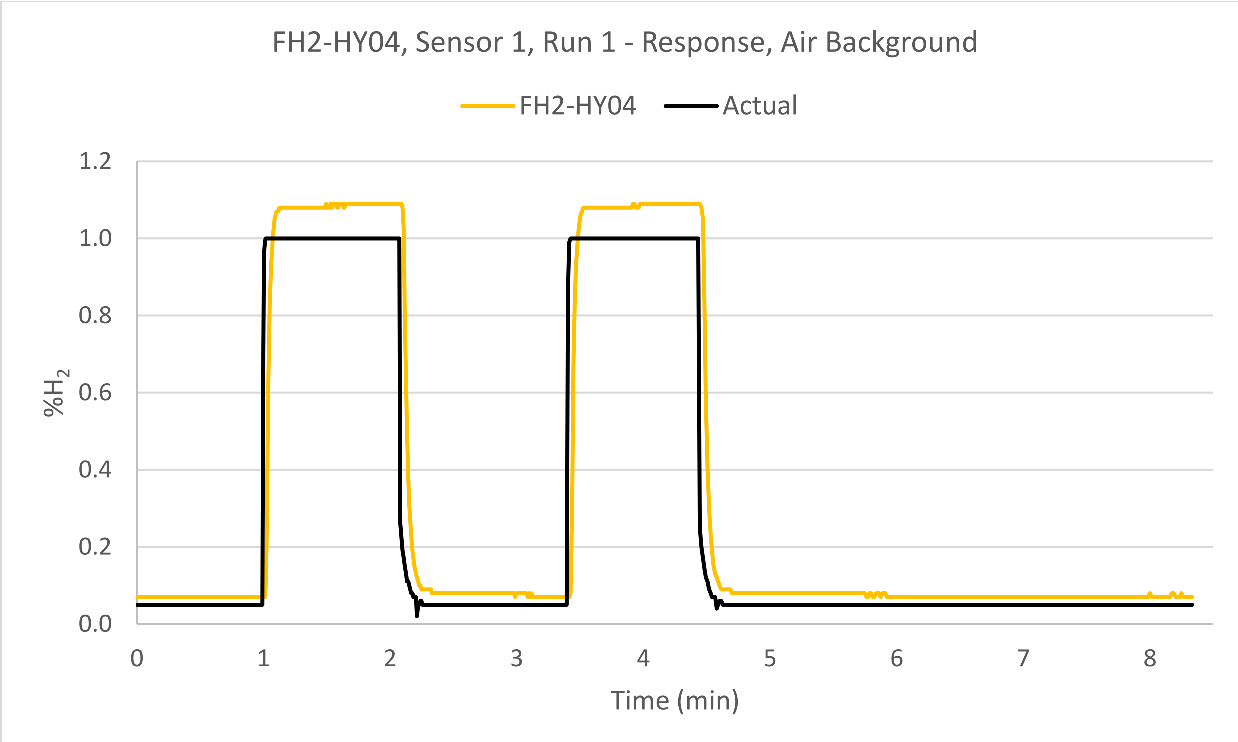

Figure 210. FH2-HY04 data for sensor 1, run 1 of the response test with an air background.

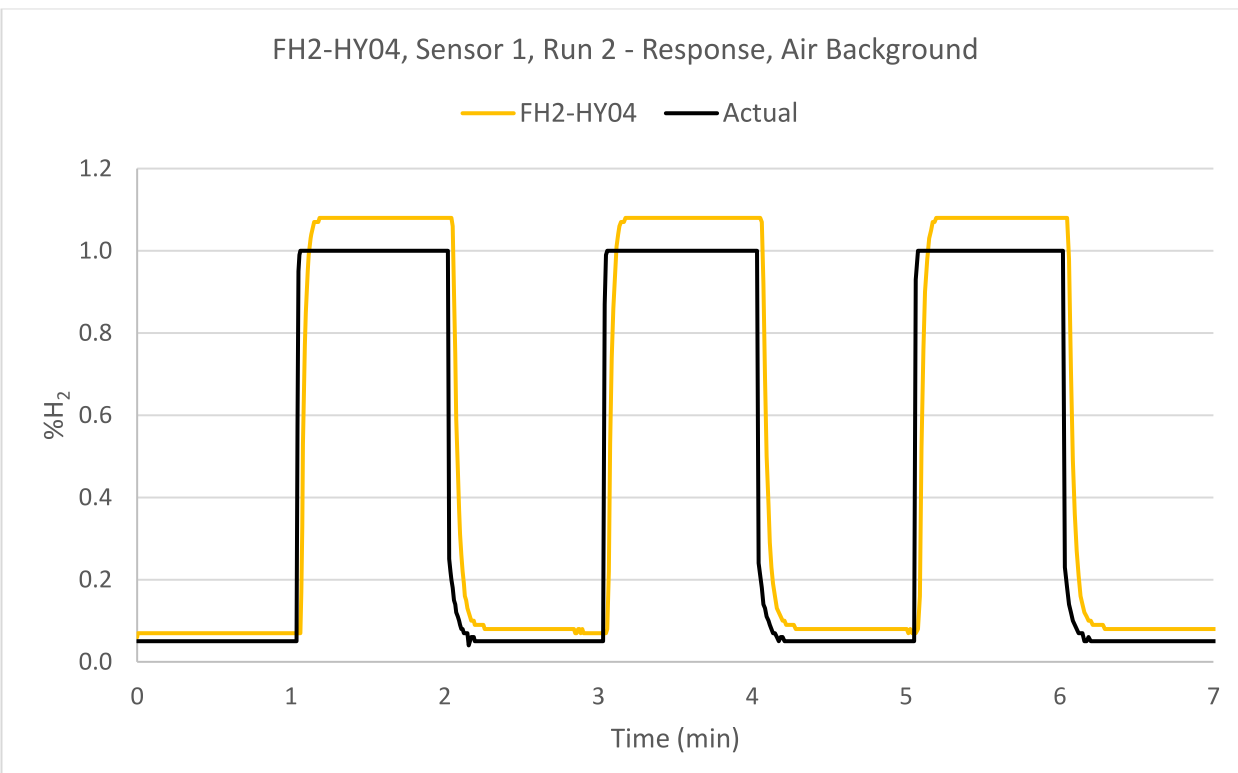

Figure 211. FH2-HY04 data for sensor 1, run 2 of the response test with an air background.

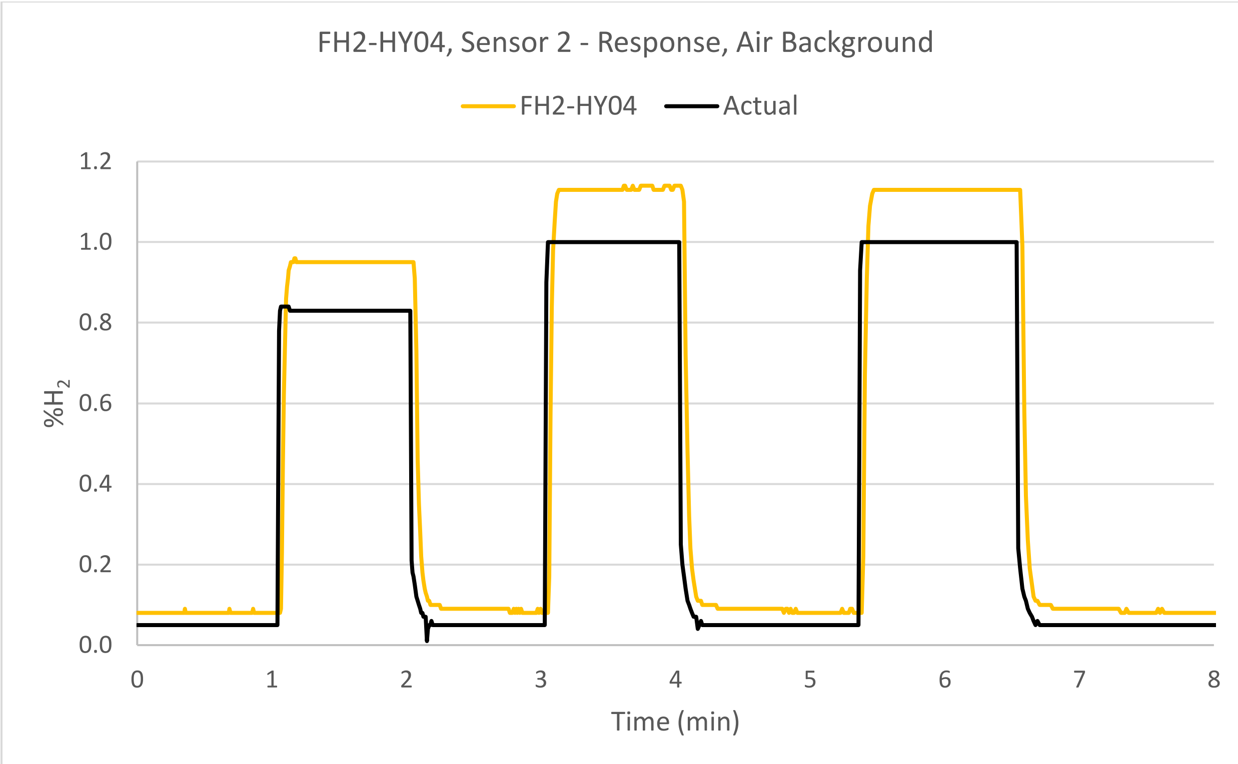

Figure 212. FH2-HY04 data for sensor 2 in the response test with an air background.

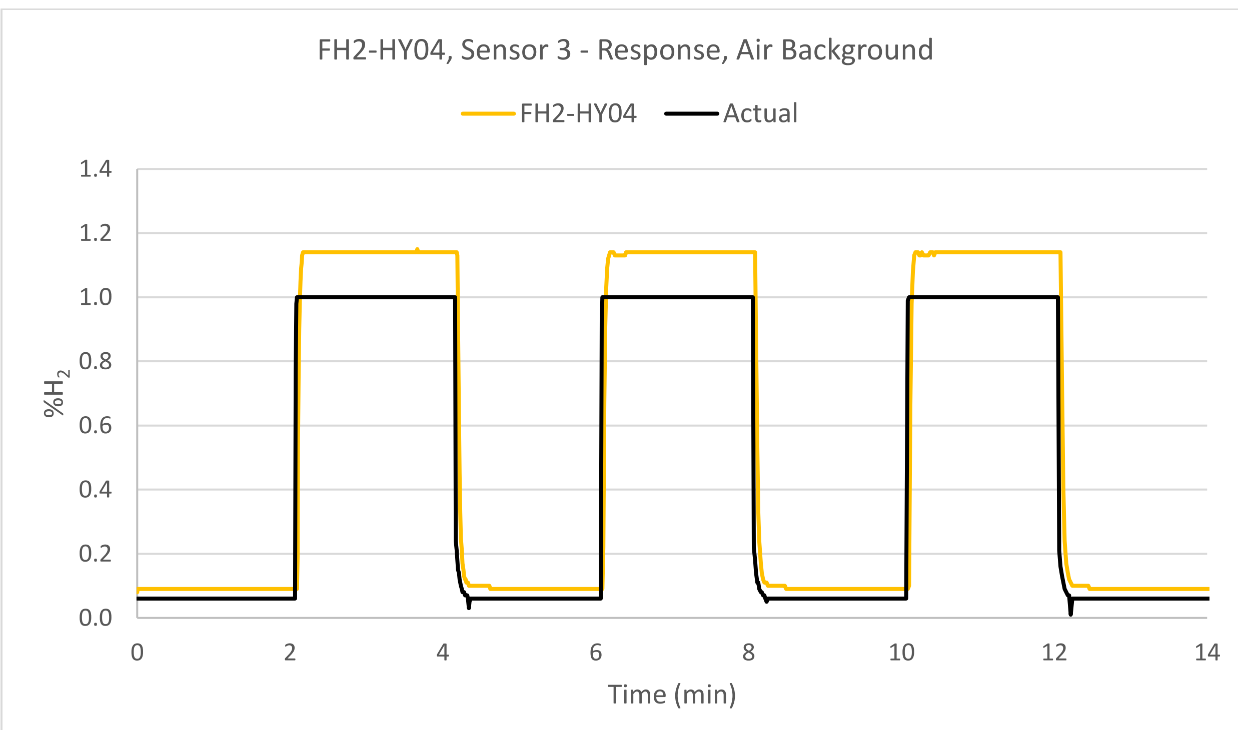

Figure 213. FH2-HY04 data for sensor 3 in the response test with an air background.

For each test, data was collected in three repetitions. Individual results are given in Table 20 and Table 21. Average values are given in Table 22.

The H2scan responded to a change in hydrogen concentration in about one second when the hydrogen concentration decreased and in under five seconds when it increased. It reached within 90% of its high values in under 10 seconds, while lowering to within 10% above its low values in under 5 seconds.

The XEN-5320 responded to a change in hydrogen concentration in about one second each time. It reached within 90% of its high values in 1-2 seconds, while lowering to within 10% above its low values in under 5 seconds.

The Sense H_2® responded to a change in hydrogen concentration in 3-4 seconds. It took 10-15 seconds for it to reach within 90% of its high values or within 10% above its low values.

The FH2-HY04 responded to a change in hydrogen concentration in 1-2 seconds. It reached within 90% of its high values in under 5 seconds and returned to within 10% of its low values in 10-15 seconds.

Table 20. Response Times – Air Background

Sensor	**Sensor/Run**	**Response Time – Low to High (s)**			**Response Time – High to Low (s)**		
H2scan 720B	Run 1	5.0	5.2	-	1.1	0.7	-
	Run 2	5.7	4.7	5.2	0.9	1.2	0.9
	Run 3	5.6	4.3	4.4	1.5	0.8	0.8
	Run 4	4.7	4.3	4.1	1.3	1.0	1.1
XEN-5320	Sensor 1/Run 1	0.8	0.6	-	0.6	0.7	-
	Sensor 1/Run 2	1.1	1.1	0.8	0.9	0.6	0.9
	Sensor 2	1.2	0.8	0.8	1.0	0.8	0.8
	Sensor 3	0.9	0.7	0.0	0.7	1.0	0.0
Sense H_2®	Sensor 1/Run 1	2.3	2.5	-	1.1	1.4	-
	Sensor 1/Run 2	2.9	2.8	2.9	4.8	5.0	4.6
	Sensor 2	4.7	3.8	3.7	5.4	3.0	2.6
	Sensor 3	3.3	2.2	2.0	4.2	3.5	3.2
FH2-HY04	Sensor 1/Run 1	1.1	1.2	-	1.1	0.7	-
	Sensor 1/Run 2	1.5	1.1	1.5	1.4	1.2	1.6
	Sensor 2	1.2	1.4	1.5	1.5	1.5	1.8
	Sensor 3	1.4	1.5	1.0	1.3	1.8	2.1

Table 21. T-90 and T-10 Times, Air Background

Sensor	Sensor/Run	T-90 Time (s)			T-10 Time (s)		
H2scan 720B	Run 1	9.0	8.5	-	3.7	3.6	-
	Run 2	9.0	8.7	8.7	3.4	3.8	3.1
	Run 3	9.6	8.7	8.4	3.9	4.4	4.2
	Run 4	8.5	8.1	7.0	3.6	3.5	3.2
XEN-5320	Sensor 1/Run 1	1.5	1.2	-	3.7	3.6	-
	Sensor 1/Run 2	1.8	1.7	1.5	4.3	3.8	3.9
	Sensor 2	2.0	1.4	1.5	3.9	3.7	3.4
	Sensor 3	1.4	1.5	1.0	3.6	3.5	3.2
Sense H_2®	Sensor 1/Run 1	28.4	26.8	-	18.1	19.5	-
	Sensor 1/Run 2	5.4	5.2	5.9	14.9	14.5	14.0
	Sensor 2	4.7	12.4	14.4	5.4	6.3	6.0
	Sensor 3	6.7	6.5	7.0	28.7	19.7	19.5
FH2-HY04	Sensor 1/Run 1	4.2	4.5	-	10.0	15.2	-
	Sensor 1/Run 2	4.4	4.7	4.5	10.0	10.8	10.9
	Sensor 2	3.5	3.8	3.7	8.4	9.6	15.3
	Sensor 3	3.7	3.6	4.1	10.2	10.9	10.2

Table 22. Average Response, T-90, and T-10 Times – Air Background

Sensor	Sensor/Run	Average Response Time Low to High (s)	Average Response Time High to Low (s)	Average T-90 Time (s)	Average T-10 Time (s)
H2scan 720B	Run 1	5.1	0.9	8.8	3.7
	Run 2	5.2	1.0	8.8	3.4
	Run 3	4.8	1.0	8.9	4.2
	Run 4	4.4	1.1	7.9	3.4
	Overall Avg.	4.9	1.0	8.6	3.7
XEN-5320	Sensor 1, Run 1	0.7	0.7	1.4	3.7
	Sensor 1, Run 2	1.0	0.8	1.7	4.0
	Sensor 2	0.9	0.9	1.6	3.7
	Sensor 3	0.5	0.6	1.3	3.4
	Overall Avg.	0.8	0.7	1.5	3.7
Sense H_2®	Sensor 1, Run 1	2.4	1.3	27.6	18.8
	Sensor 1, Run 2	2.9	4.8	5.5	14.5
	Sensor 2	4.1	3.7	10.5	5.9
	Sensor 3	2.5	3.6	6.7	22.6
	Overall Avg.	3.0	3.3	12.6	15.5
FH2-HY04	Sensor 1, Run 1	1.2	0.9	4.4	12.6
	Sensor 1, Run 2	1.4	1.4	4.5	10.6
	Sensor 2	1.4	1.6	3.7	11.1
	Sensor 3	1.2	0.9	3.8	10.4
	Overall Avg.	1.3	1.4	4.1	11.2

Results – Nitrogen Background

Values for flow rates were chosen that required only the hydrogen MFC to be changed between the high (1%) and low (~0%) hydrogen 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 214 through Figure 225 show the data collected for this test.

The H2scan and XEN-5320 performed similarly to their responses in air. The H2scan responded quickly to an increase in hydrogen concentration, then more gradually settled at its final value and dropped very quickly to 0% when the hydrogen concentration was decreased. The XEN-5320 responded very quickly in both directions, briefly overshooting its final value when hydrogen concentrations increased.

As with previous tests, the Sense H_2® and FH2-HY04 did not function anaerobically.

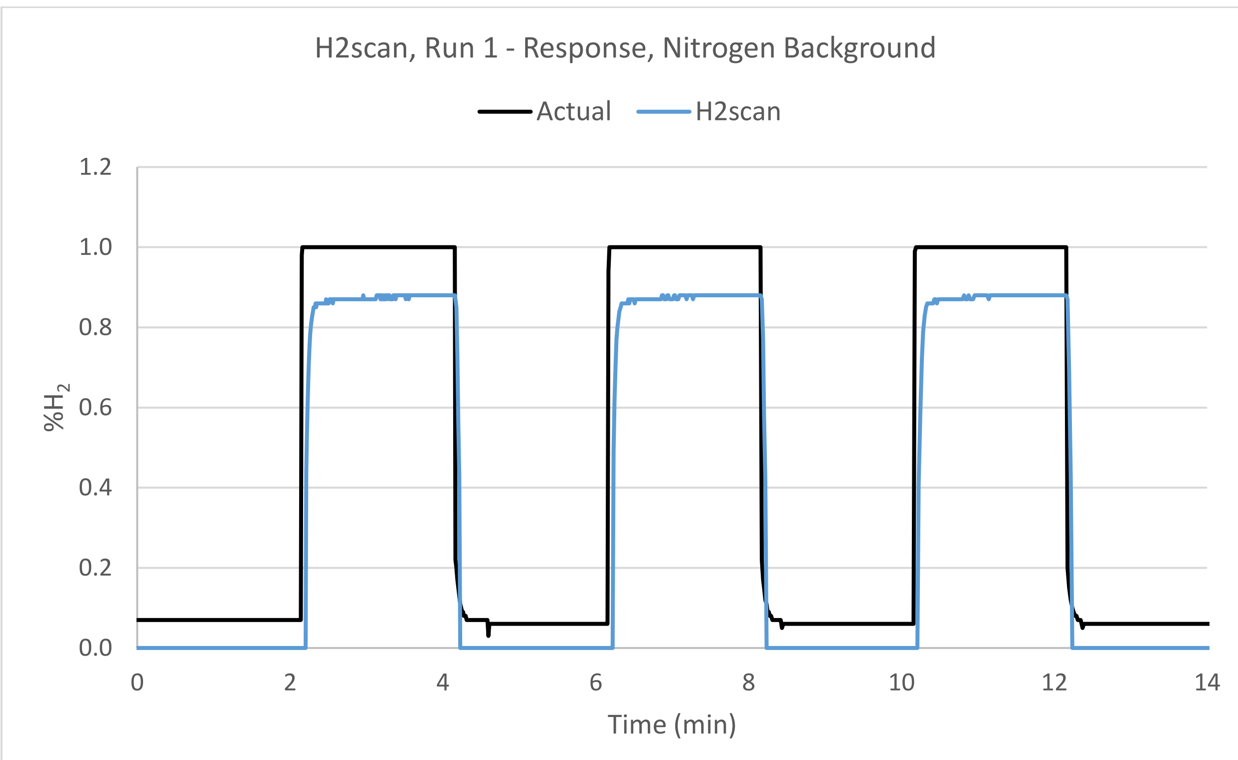

Figure 214. H2scan data for run 1 of the response test with a nitrogen background.

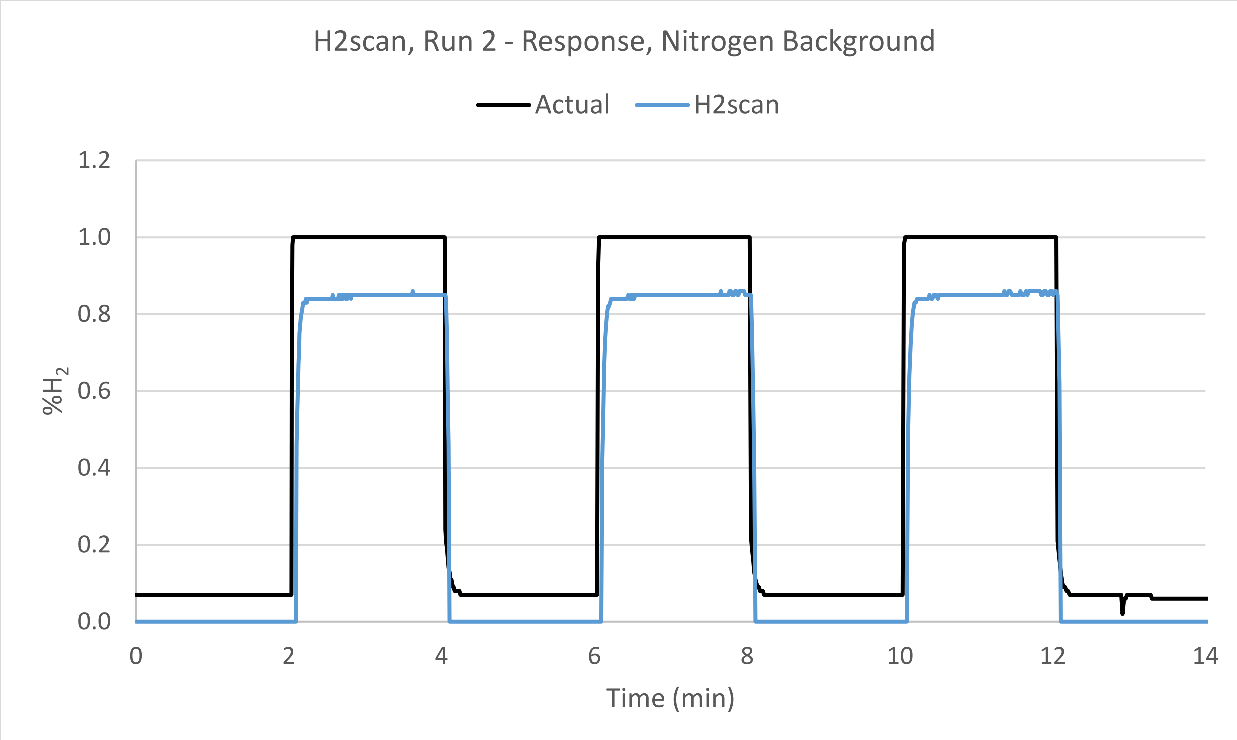

Figure 215. H2scan data for run 2 of the response test with a nitrogen background.

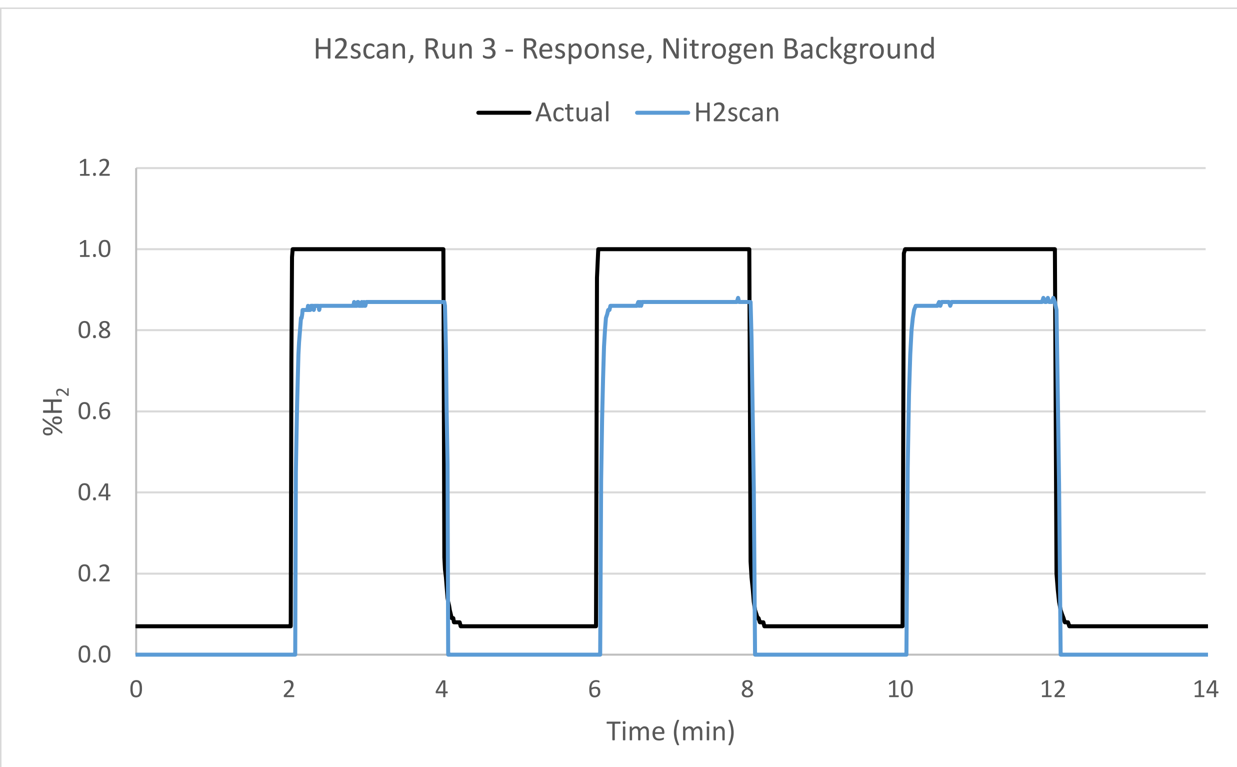

Figure 216. H2scan data for run 3 of the response test with a nitrogen background.

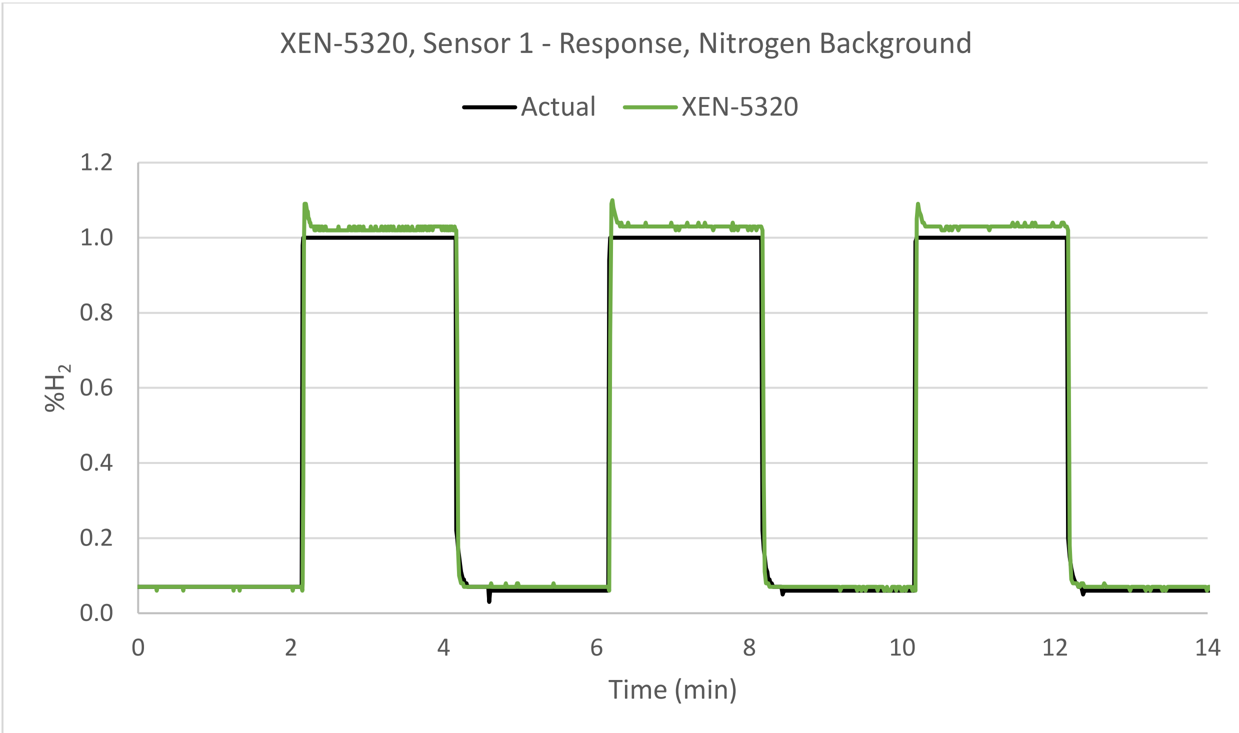

Figure 217. XEN-5320 data for sensor 1 in the response test with a nitrogen background.

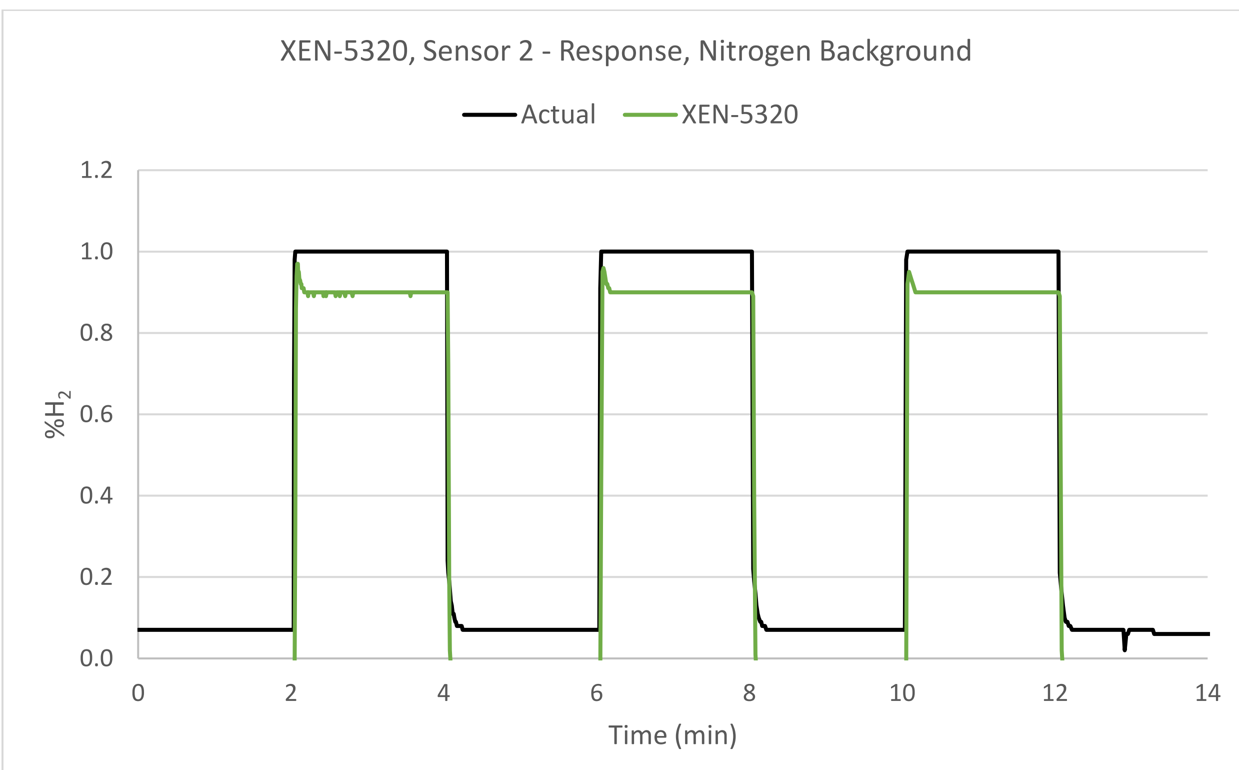

Figure 218. XEN-5320 data for sensor 2 in the response test with a nitrogen background.

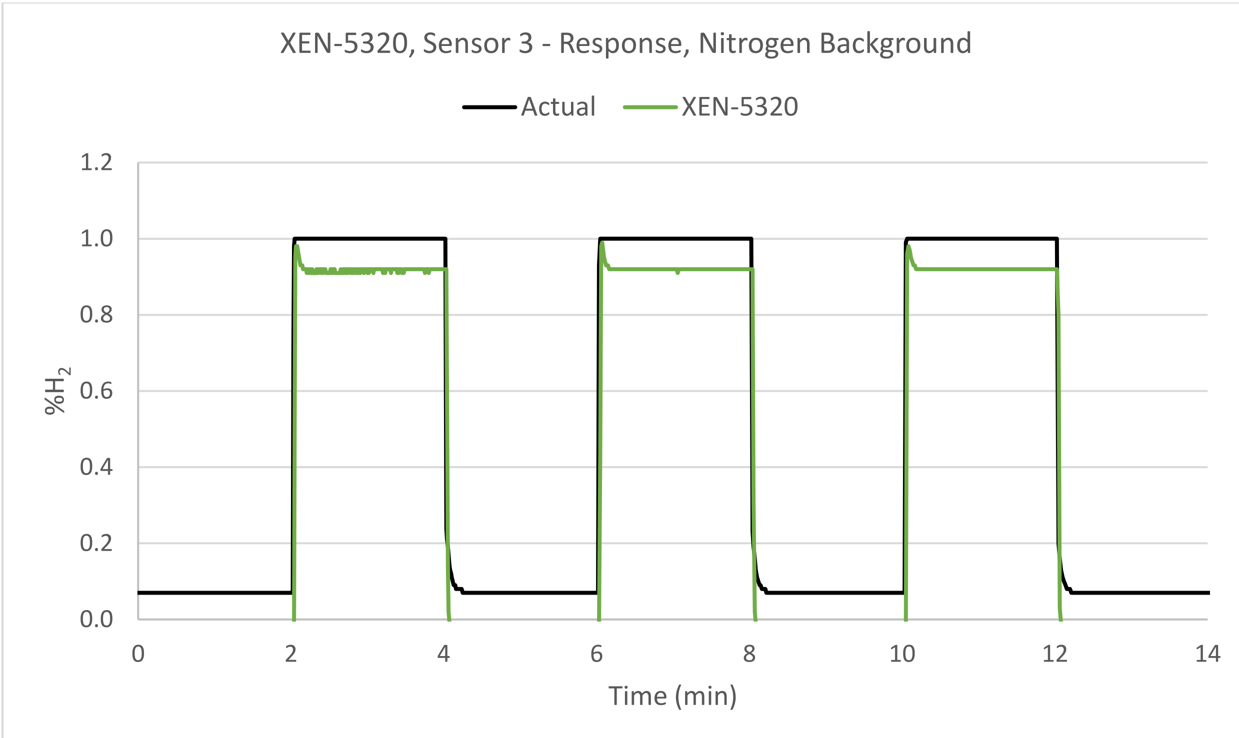

Figure 219. XEN-5320 data for sensor 3 in the response test with a nitrogen background.

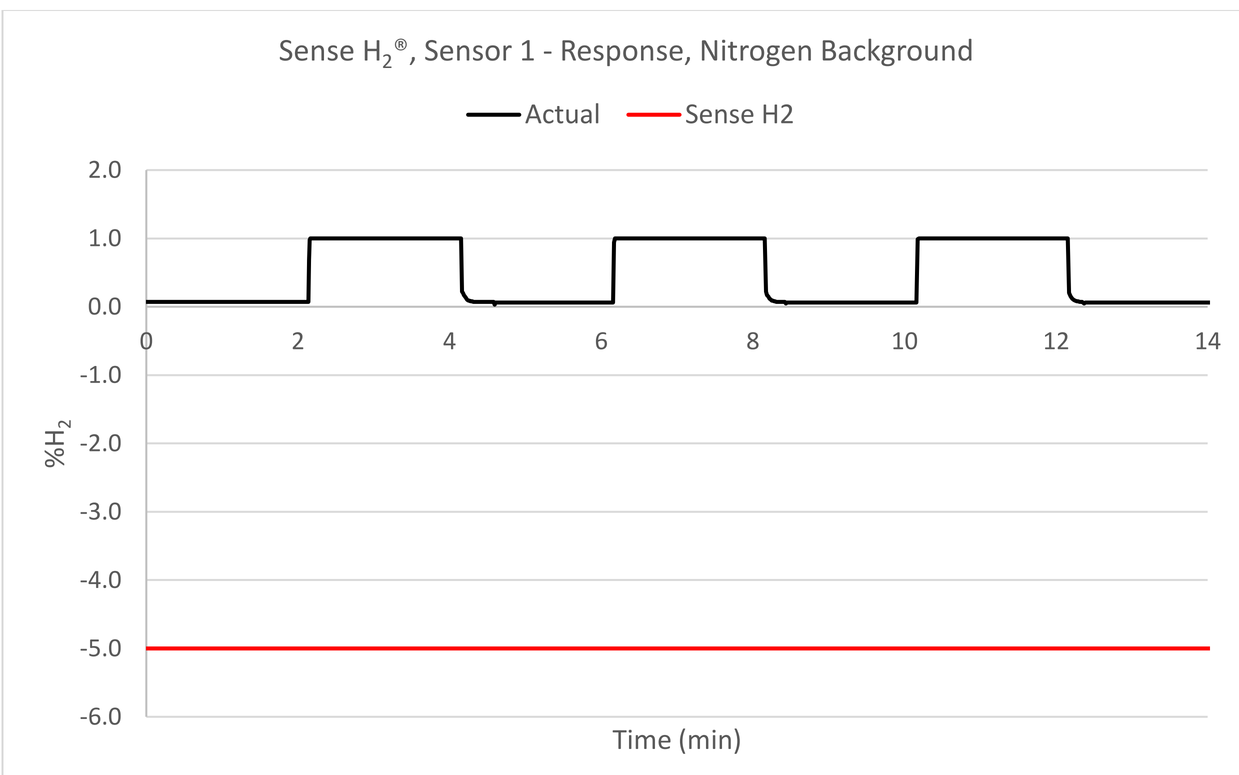

Figure 220. Sense H_2® data for sensor 1 in the response test with a nitrogen background.

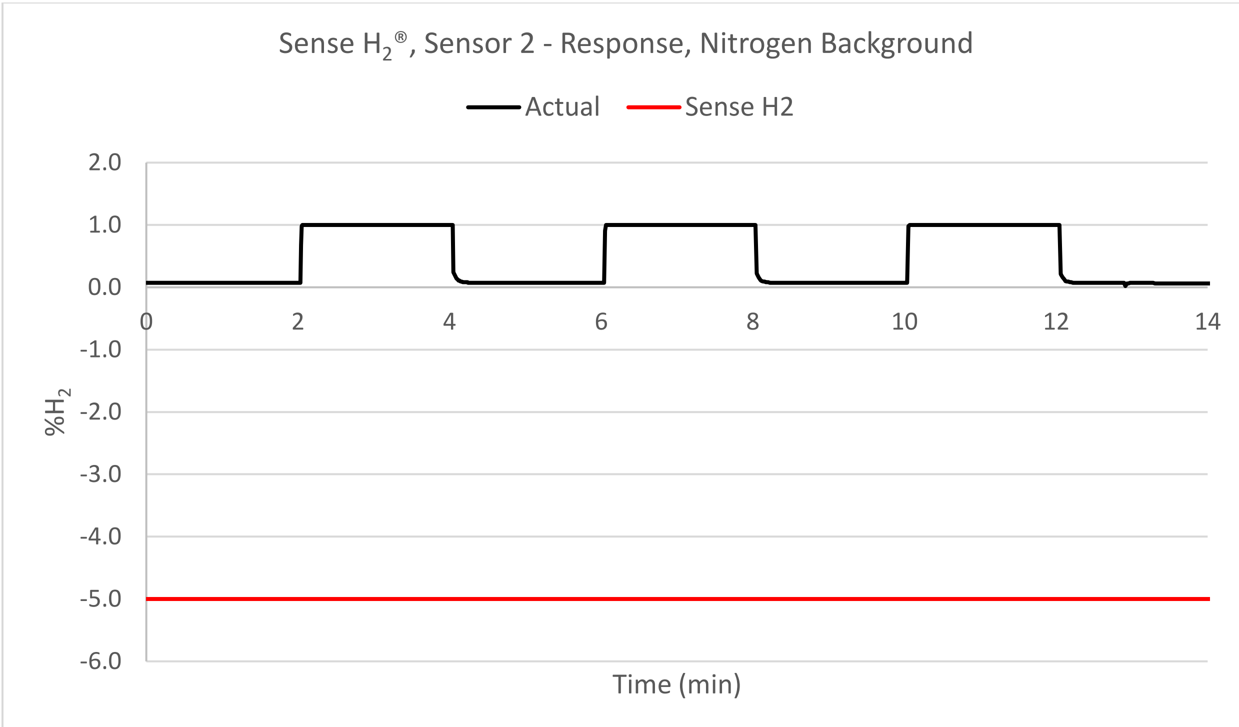

Figure 221. Sense H_2® data for sensor 2 in the response test with a nitrogen background.

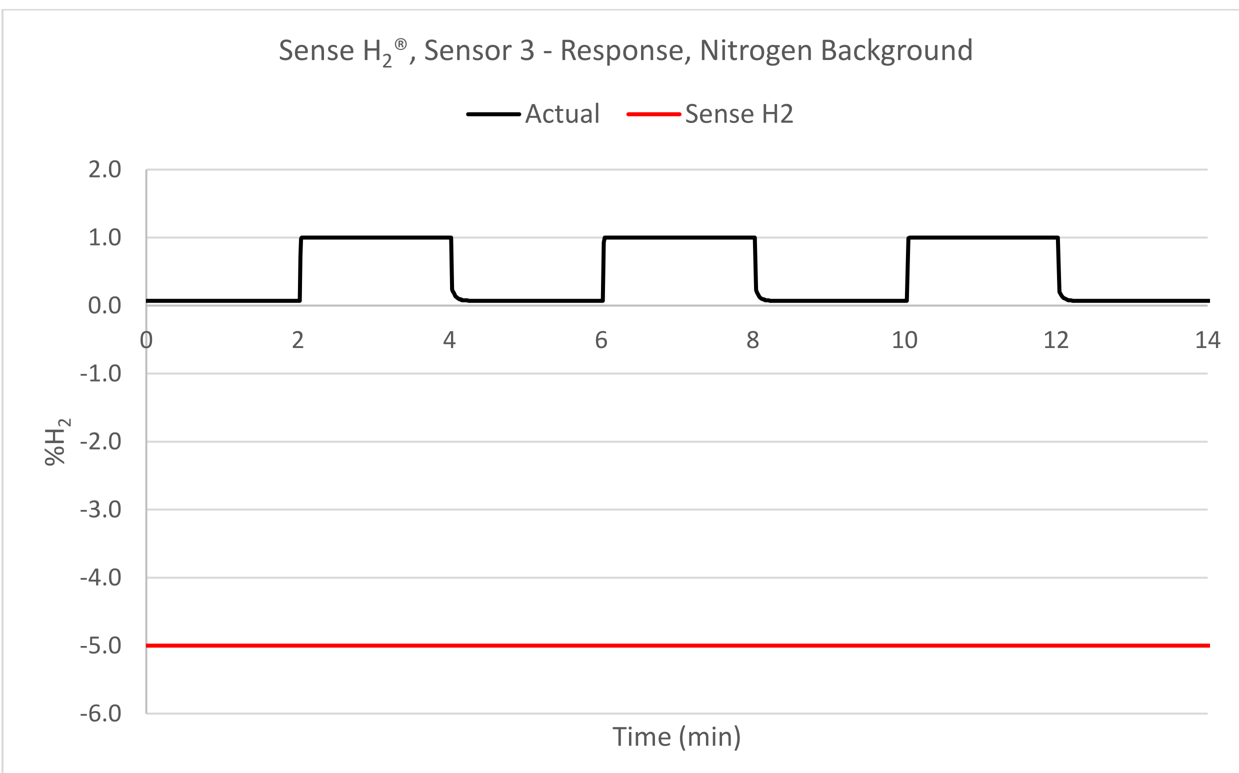

Figure 222. Sense H_2® data for sensor 3 in the response test with a nitrogen background.

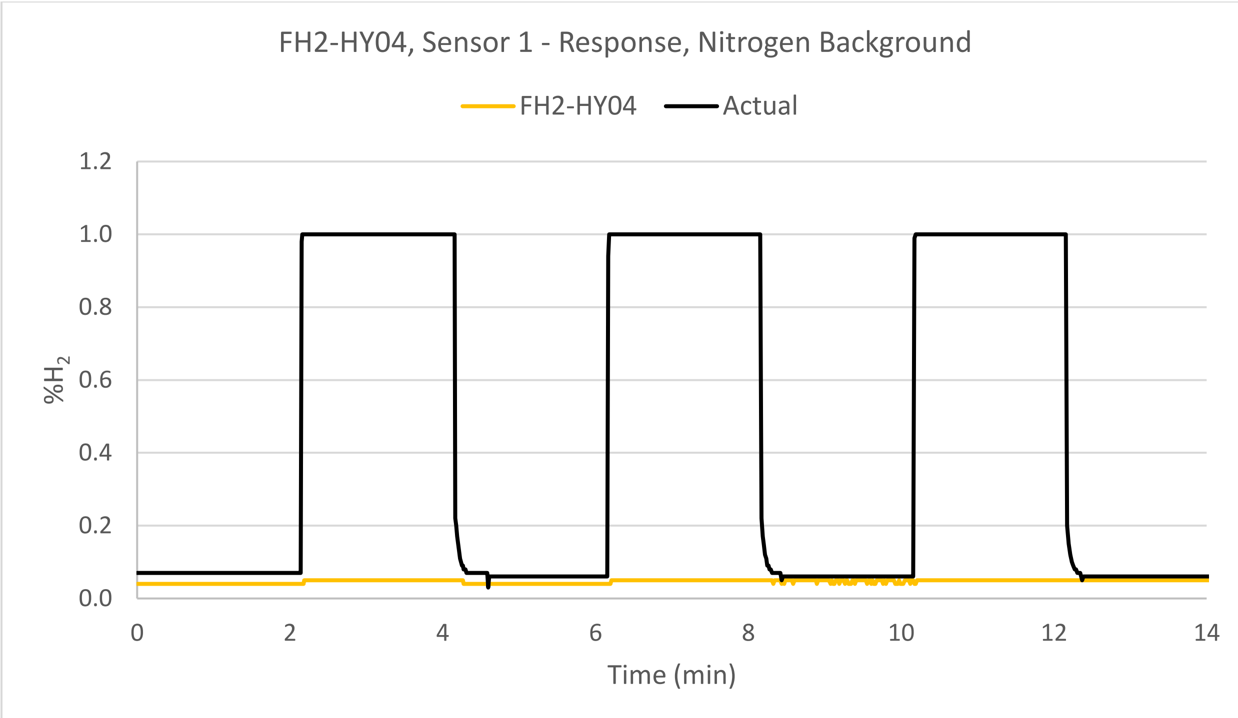

Figure 223. FH2-HY04 data for sensor 1 in the response test with a nitrogen background.

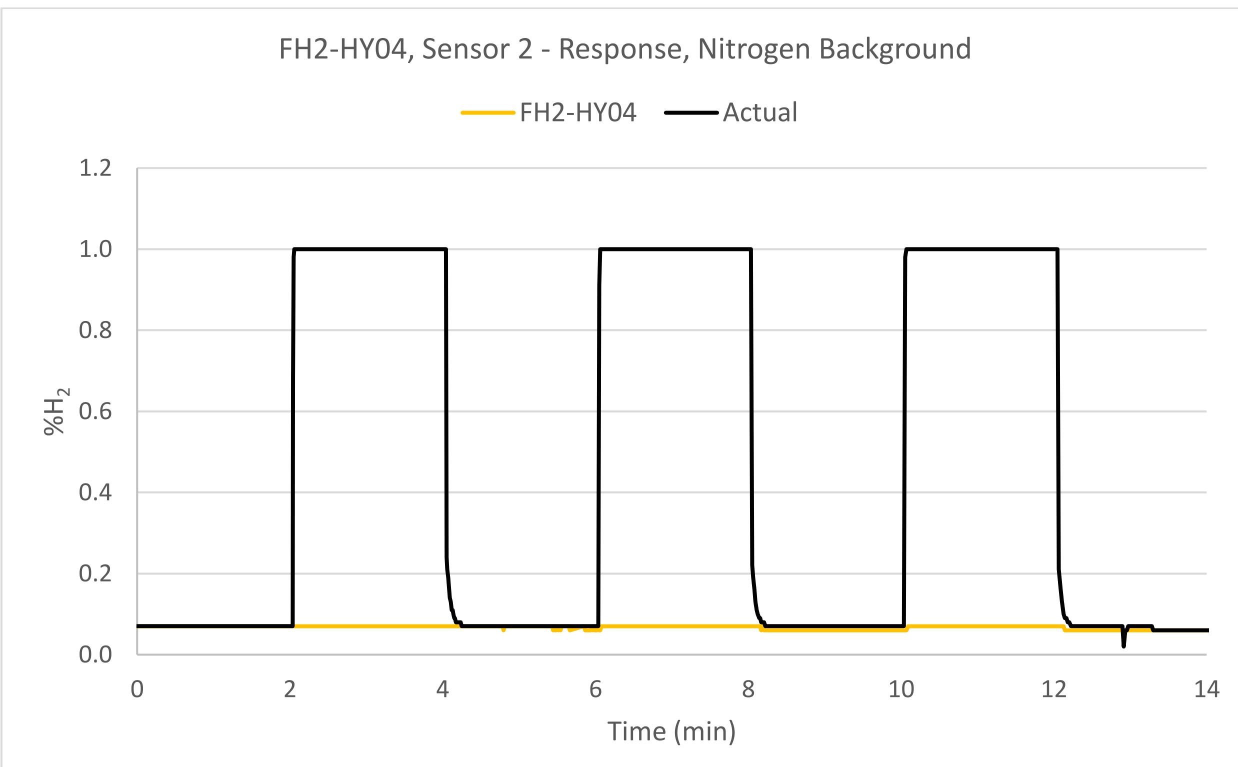

Figure 224. FH2-HY04 data for sensor 2 in the response test with a nitrogen background.

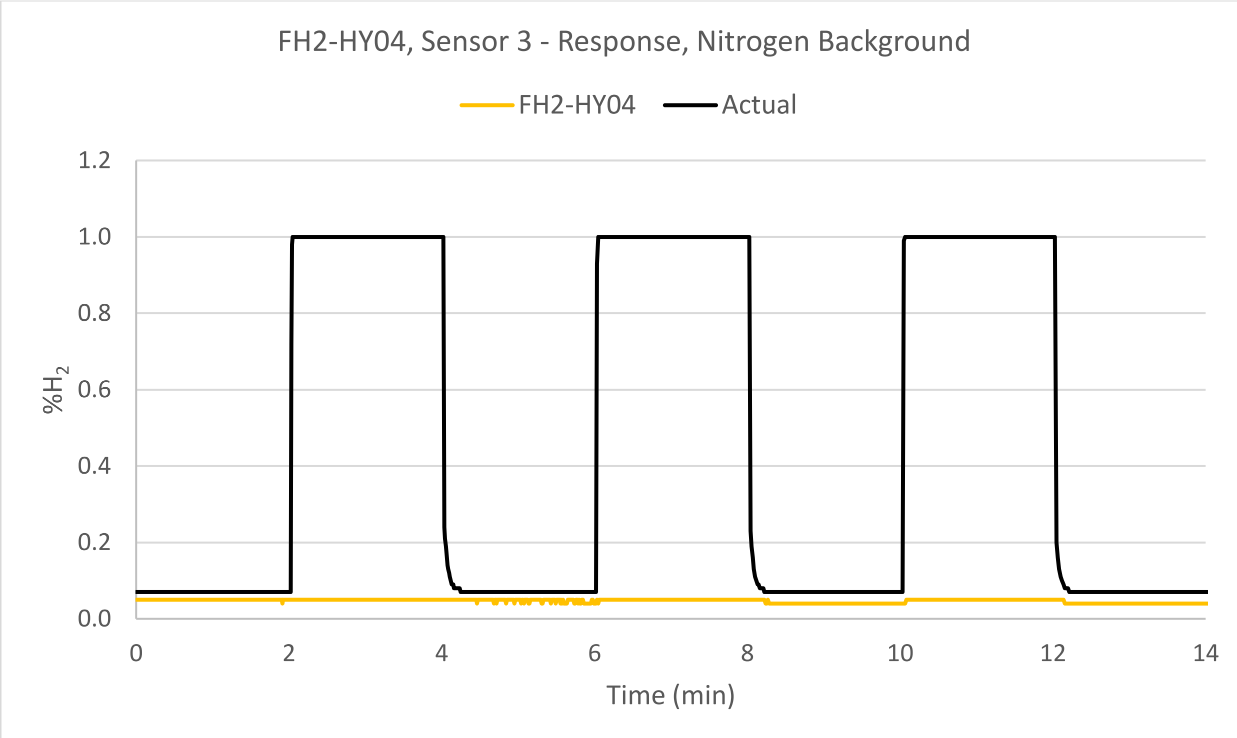

Figure 225. FH2-HY04 data for sensor 3 in the response test with a nitrogen background.

For each test, data was collected in three repetitions. Individual results are given in Table 23 and Table 24. Average values per sensor are given in Table 25. Because the Sense H_2® and FH2-HY04 were not functioning properly in a nitrogen background, they are omitted from the tables.

The H2scan responded to a change in hydrogen concentration in about one second when the hydrogen concentration decreased and in under five seconds when it increased. It reached within 90% of its high values in under 10 seconds, and decreased to within 10% above its low values in under 5 seconds.

The XEN-5320 responded to a change in hydrogen concentration in about one second or less each time. It reached within 90% of its high values in 1-2 seconds, and decreased to within 10% above its low values in under 5 seconds.

Table 23. Response Times – Nitrogen Background

Sensor	**Sensor/Run**	**Response Time Low to High (s)**			**Response Time High to Low (s)**		
H2scan 720B	1	3.9	4.0	3.2	0.7	0.9	1.2
	2	3.7	3.3	3.3	0.6	0.9	1.5
	3	3.5	3.1	3.0	0.6	0.9	0.0
XEN-5320	1	0.5	0.8	1.0	0.7	0.9	0.0
	2	0.5	0.7	1.1	0.6	0.0	0.0
	3	1.0	0.8	1.0	0.6	0.9	0.0

Table 24. T-90 and T-10 Times – Nitrogen Background

Sensor	Sensor/Run	T-90 Time (s)			T-10 Time (s)		
H2scan 720B	1	7.4	7.0	6.5	2.9	3.6	3.6
	2	6.5	6.3	6.2	3.3	3.5	2.6
	3	6.4	6.3	6.0	3.1	3.6	3.3
XEN-5320	1	1.4	1.6	1.0	3.7	2.7	2.6
	2	1.5	1.7	1.1	3.3	3.5	3.8
	3	1.5	1.6	1.0	3.8	3.6	4.4

Table 25. Average Response, T-90, and T-10 Times – Nitrogen Background

Sensor	Sensor/Run	Average Response Time Low to High (s)	Average Response Time High to Low (s)	Average T-90 Time (s)	Average T-10 Time (s)
H2scan 720B	1	3.7	0.9	7.0	3.4
	2	3.4	1.0	6.3	3.1
	3	3.2	0.5	6.2	3.3
	Overall Avg.	3.4	0.8	6.5	3.3
XEN-5320	1	0.8	0.5	1.3	3.0
	2	0.8	0.2	1.4	3.5
	3	0.9	0.5	1.4	3.9
	Overall Avg.	0.8	0.4	1.4	3.5

Results – Helium Background

Values for flow rates were chosen that required only the hydrogen MFC to be changed between the high (1%) and low (~0%) hydrogen 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 226 through Figure 229 show the data collected for this test.

The H2scan responded similarly to its performance in other background gases. It responded very quickly to a change in hydrogen concentration for both increasing and decreasing concentrations. When the hydrogen concentration increased, it gradually settled on its final value after a rapid initial increase.

As seen in previous tests, the XEN-5320 cannot detect hydrogen in a helium background, and the Sense H_2® and FH2-HY04 did not function anaerobically.

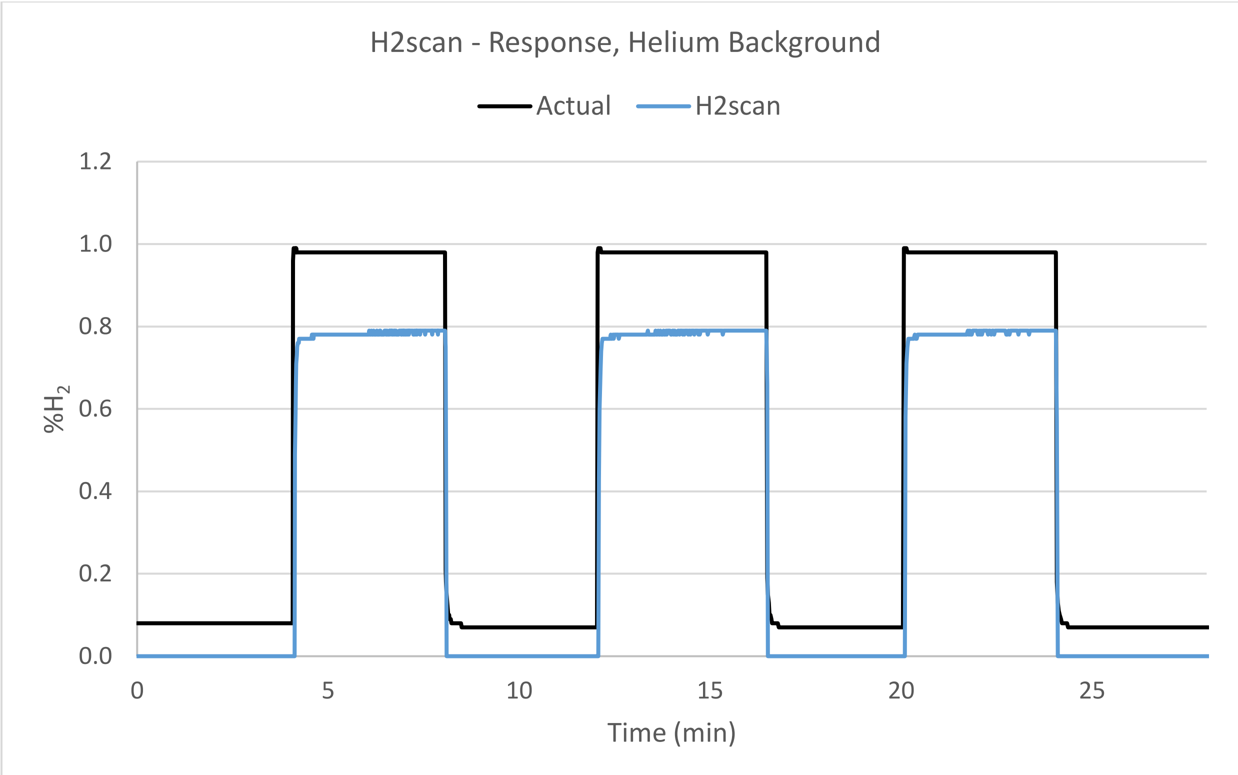

Figure 226. H2scan data for the response test with a helium background.

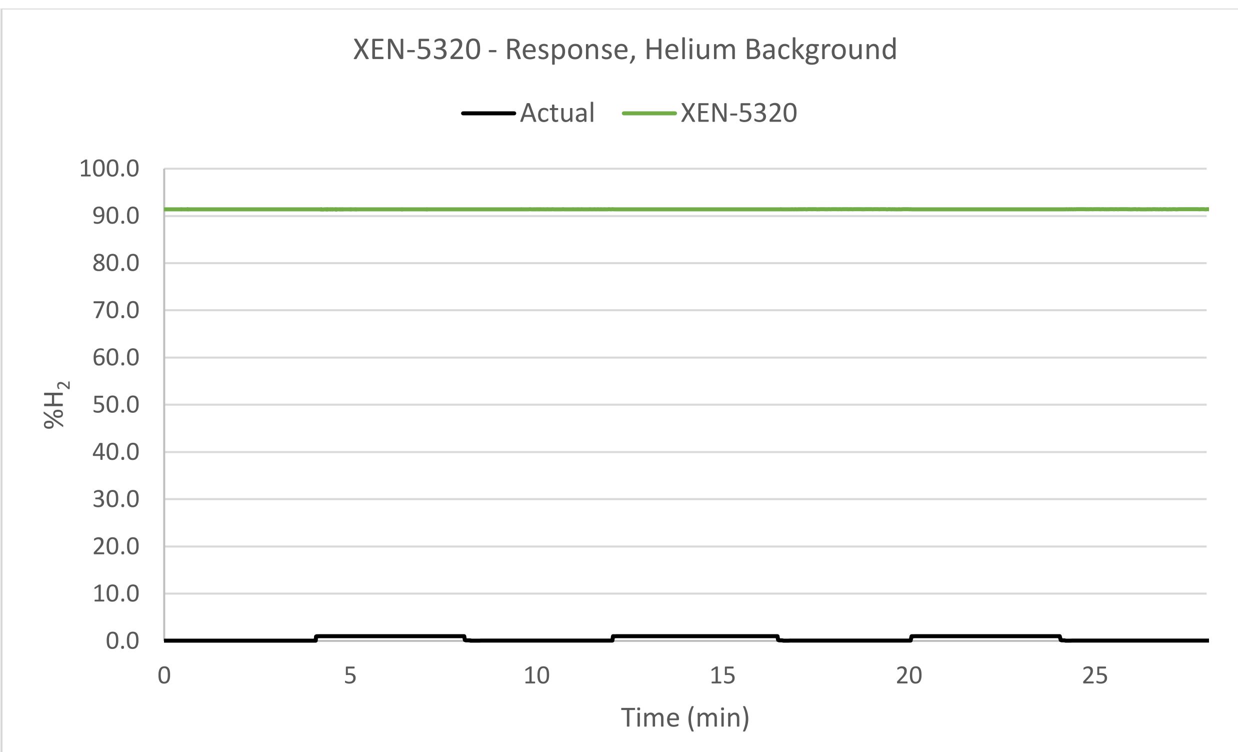

Figure 227. XEN-5320 data for the response test with a helium background.

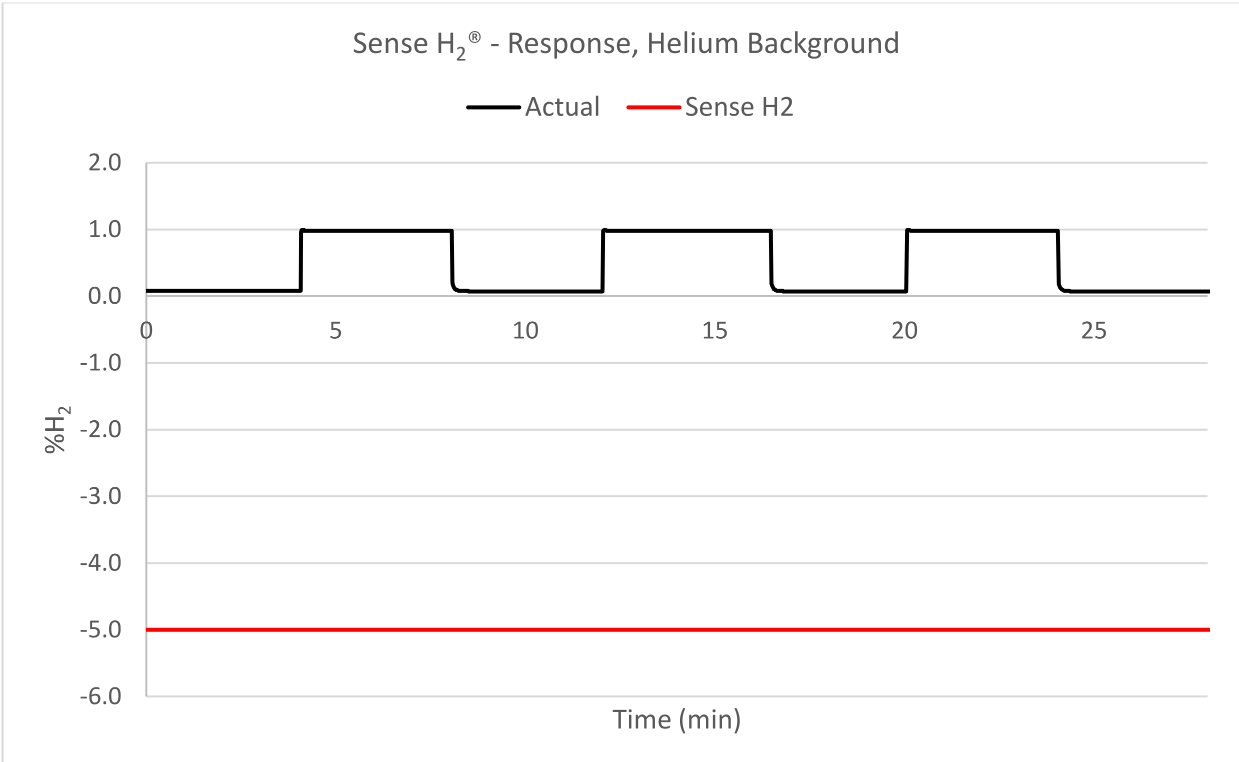

Figure 228. Sense H_2® data for the response test with a helium background.

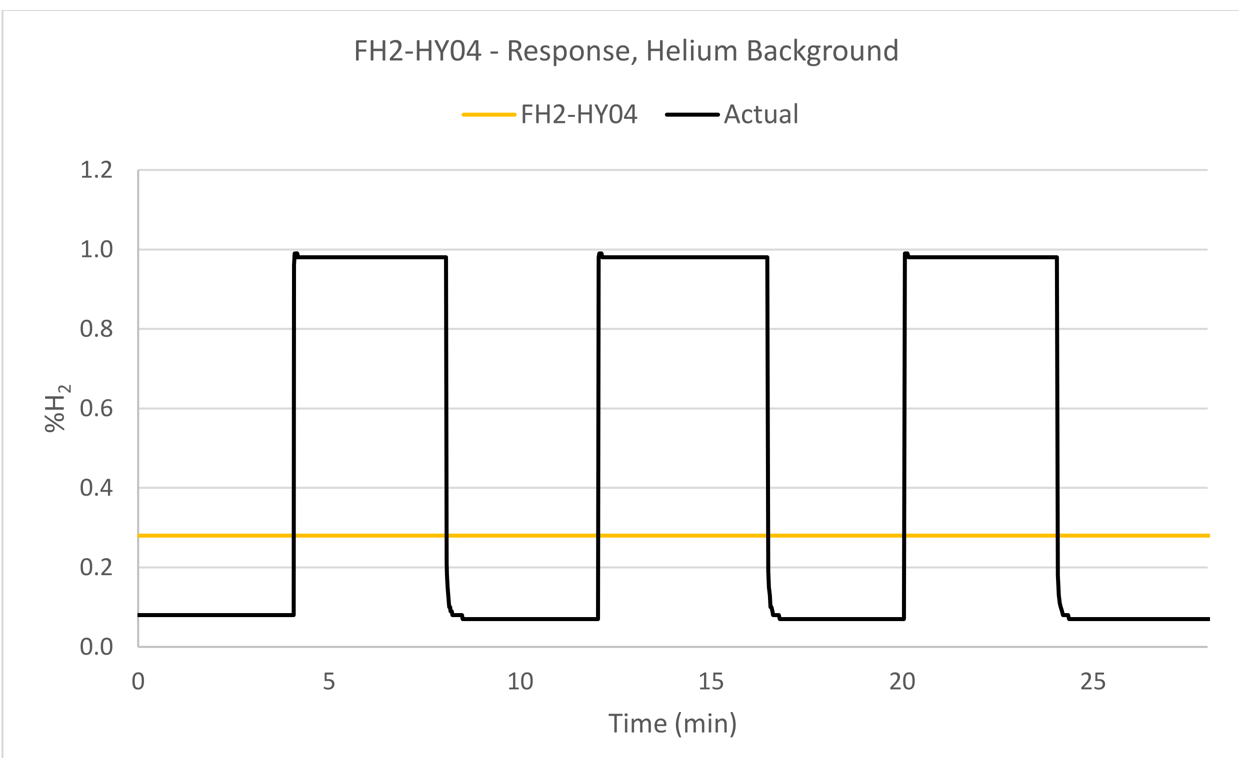

Figure 229. FH2-HY04 data for the response test with a helium background.

For each test, data was collected in three repetitions. Individual results are given in The H2scan responded to a change in hydrogen concentration immediately when the hydrogen concentration decreased and in 2-3 seconds when it increased. It reached within 90% of its high values in just over 5 seconds, and decreased to within 10% above its low values in 1-2 seconds.

Table 26. Average values per sensor are given in Table 27. Because none of the other sensors were functioning properly in the helium background, only the H2scan data is given on the table.

The H2scan responded to a change in hydrogen concentration immediately when the hydrogen concentration decreased and in 2-3 seconds when it increased. It reached within 90% of its high values in just over 5 seconds, and decreased to within 10% above its low values in 1-2 seconds.

Table 26. Average Response, T-90, and T-10 Times – Helium Background

Sensor	**Response Time Low to High (s)**			**Response Time High to Low (s)**			**T-90 Time (s)**			**T-10 Time (s)**		
H2scan 720B	2.9	2.2	2.9	0.0	0.0	0.0	5.1	5.5	4.3	1.8	1.3	1.6

Table 27. Average Response, T-90, and T-10 Times – Helium Background

Sensor	**Average Response Time Low to High (s)**	**Average Response Time High to Low (s)**	**Average T-90 Time (s)**	**Average T-10 Time (s)**
H2scan 720B	2.7	0.0	5.0	1.6

Effects of Power Cycling Sensors

In an air background, two replications of each test were performed with the same set of sensors. This allows examination of the repeatability of the sensors following a power cycling and cool down period, in this case data were collected five days apart.

To quantify any shift, a percent difference was calculated between the average sensor outputs on both days as follows:

$$\%\,Difference = \frac{Run\ 2\ Output - Run\ 1\ Output}{Average\ of\ Run\ 1\ and\ Run\ 2\ Outputs} \times 100\%$$

Table 28 lists the results. Missing values are the result of a divide by zero error, but in those cases, the sensor had identical outputs on the two tests. The XEN-5320 and FH2-HY04 both had minimal changes. The H2scan's percent difference was also less than 10%. The Sense H_2®'s outputs were up to 56% different between runs.

Table 28. Percent Difference Calculated between Outputs of Identical Runs on the Same Sensors.

% H_2	**H2scan**	**XEN-5320**	**Sense H_2®**	**FH2-HY04**
0.05	-	0%	-56%	0%
0.50	-	0%	-38%	-2%
1.00	-7%	0%	-29%	-1%
1.50	-6%	1%	-18%	-1%
2.00	-5%	0%	-15%	0%
2.40	-4%	0%	0%	0%

Figure 230 through Figure 233 show the two sets of data for each sensor. In these, the time has been stretched on one of the data sets so that the changes in hydrogen concentration are aligned between the two units for ease of comparison. The H2scan has a small shift between the two data sets. The XEN-5320 and FH2-HY04 align very closely. The outputs of the Sense H_2® differ for most of the hydrogen concentrations.

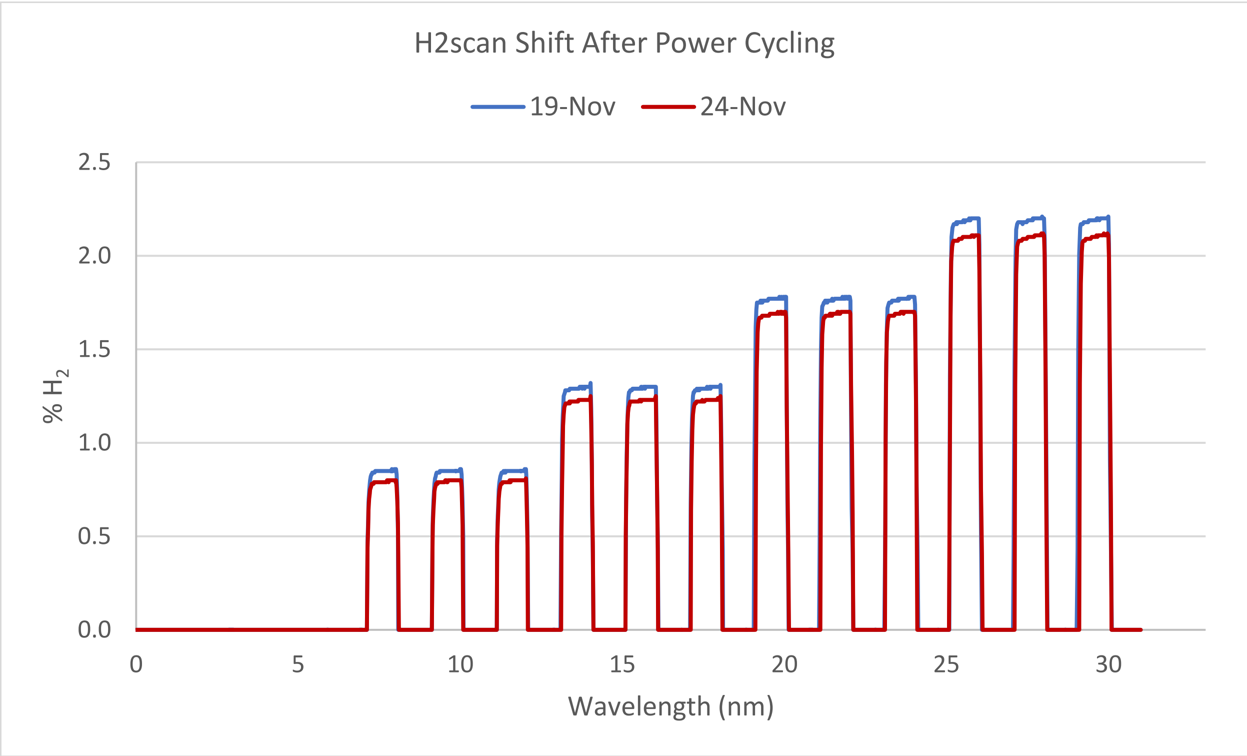

Figure 230. A comparison of the outputs of the H2scan after power cycling the unit.

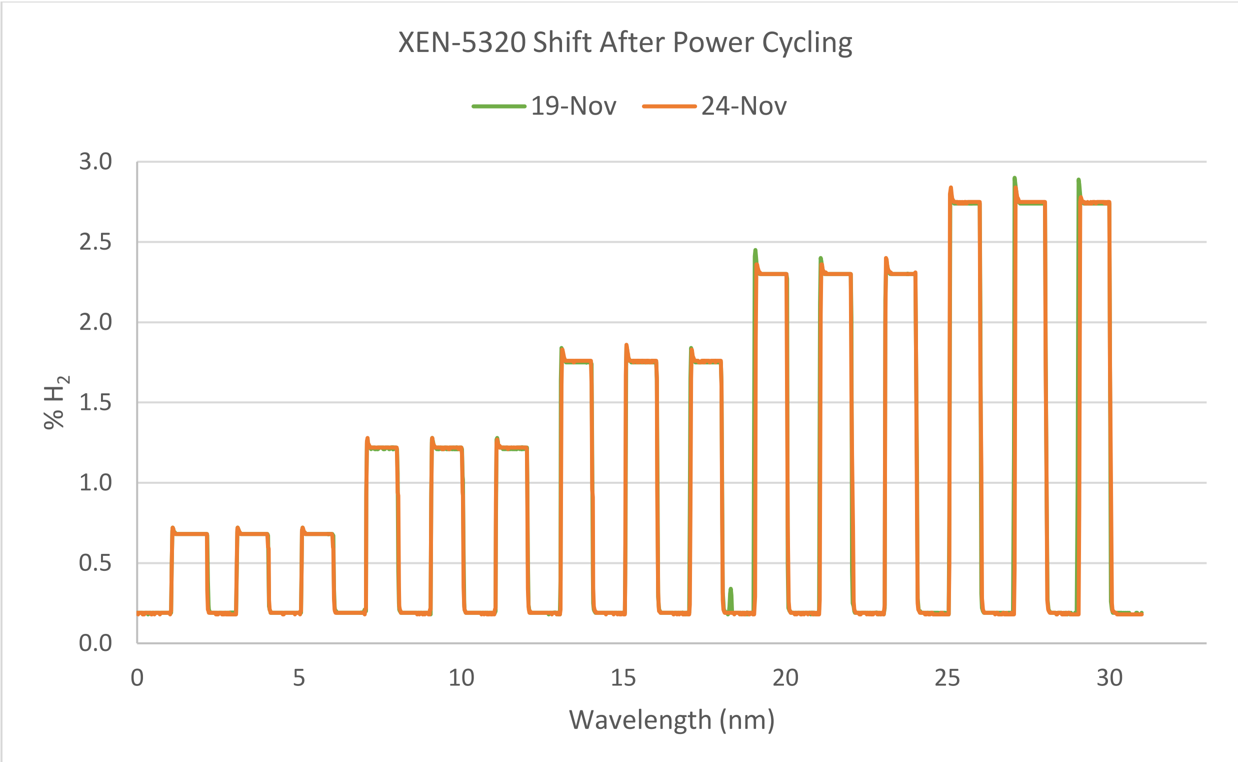

Figure 231. A comparison of the outputs of the XEN-5320 after power cycling the unit.

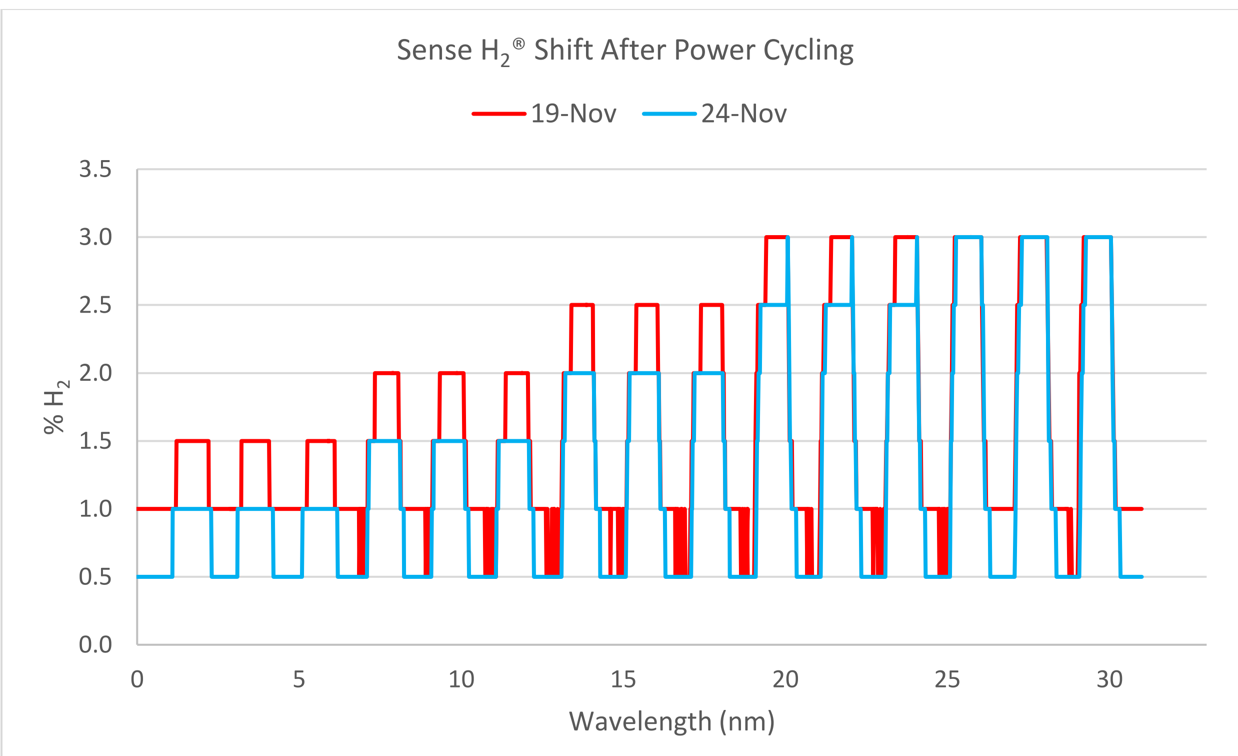

Figure 232. A comparison of the outputs of the Sense H_2® after power cycling the unit.

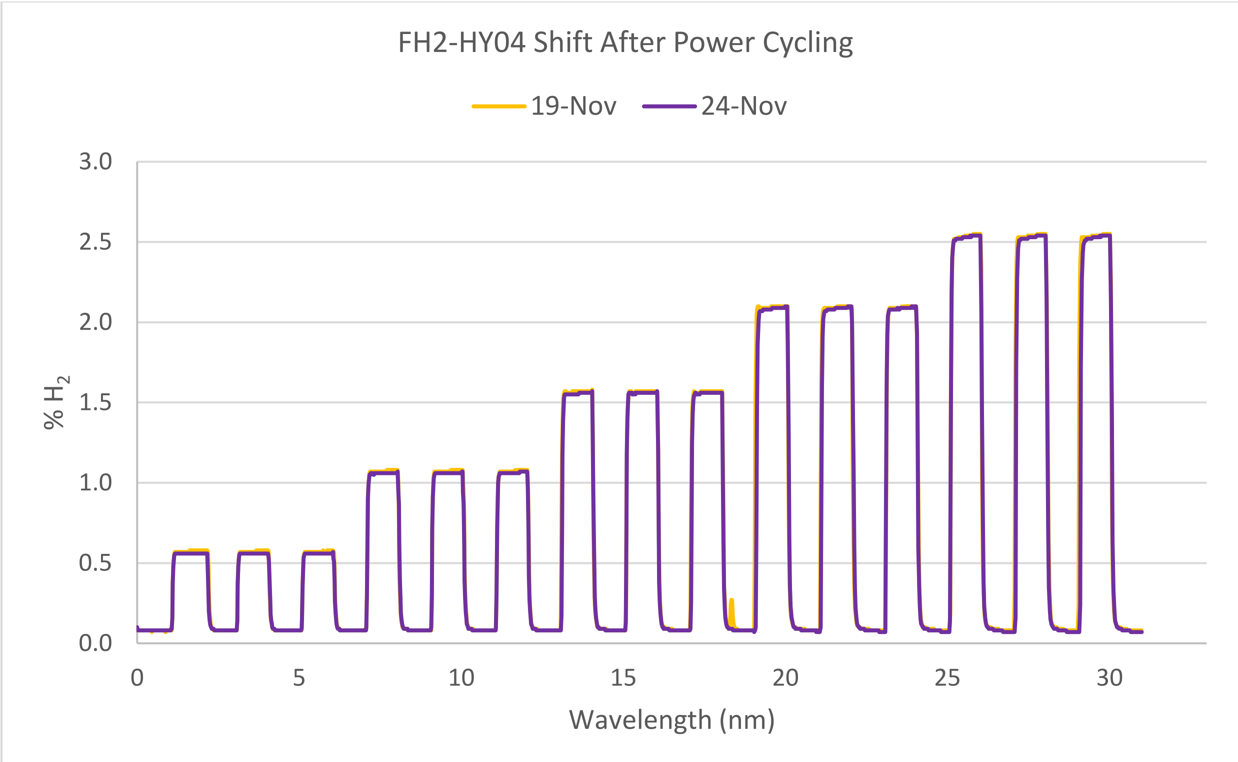

Figure 233. A comparison of the outputs of the FH2-HY04 after power cycling the unit

Summary of Results

Table 29 through Table 32 include a summary of the results of each test, grouped by sensor.

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 hydrogen concentration occurs at the sensors.
- Gas concentration changes are not instantaneous. The hydrogen gas flow is changed separately from the dilution gas flow.
- MFCs are 10k sccm units, with their lowest calibration point at 1000 sccm. In the LDL tests, gas flow rates below 1000 sccm were used.
- Most of these sensors have pressure requirements that limit allowable gas flows and prevent pressure testing per PVS.
- The hydrogen 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.

Further evaluation with these sensors is possible in the future.

HY-OPTIMA™ H2scan 720B

All tests were conducted using a single H2scan sensor. Table 29 gives the average values over repeat tests using this sensor as an overall summary. This sensor was tested as received, but does have options for user calibration that would likely improve its accuracy and precision.

This sensor performed in backgrounds of air, nitrogen, and helium.

Table 29. H2scan 720B Test Results Summary

Test	**Background Gas**	**Average Result**
0% Drift	Air	0.00% H_2
	Nitrogen	0.00% H_2
	Helium	0.00% H_2
2% Drift	Air	0.01% H_2
	Nitrogen	0.03% H_2
	Helium	0.00% H_2
LDL – Increasing %H_2	Air	0.51% H_2
	Nitrogen	0.50% H_2
	Helium	0.56% H_2
LDL – Decreasing %H_2	Air	0.52% H_2
	Nitrogen	0.50% H_2
	Helium	0.56% H_2
Accuracy	Air	-14%
	Nitrogen	-13%
	Helium	-31%
Precision	Air	1%
	Nitrogen	0%
	Helium	0%
Repeatability	Air	0.00% H_2
	Nitrogen	0.01% H_2
	Helium	0.00% H_2
Response Time – Low to High	Air	4.9 s
	Nitrogen	3.4 s
	Helium	2.7 s
Response Time – High to Low	Air	1.0 s
	Nitrogen	0.8 s
	Helium	0.0 s
T-90 Time	Air	8.6 s
	Nitrogen	6.5 s
	Helium	5.0 s
T-10 Time	Air	3.7 s
	Nitrogen	3.3 s
	Helium	1.6 s

Xensor XEN-5320

Three XEN-5320 sensors were used throughout this evaluation, one for each set of tests. Table 30 gives the average values of their results as an overall summary. This sensor was tested as received, but does have options for user calibration.

Table 30. XEN-5320 Test Results Summary

Test	Background Gas	Average Result
0% Drift	Air	0.01% H_2
	Nitrogen	-0.01% H_2
2% Drift	Air	0.00% H_2
	Nitrogen	0.01% H_2
LDL – Increasing %H_2	Air	< 0.10% H_2
	Nitrogen	< 0.10% H_2
LDL – Decreasing %H_2	Air	< 0.10% H_2
	Nitrogen	< 0.10% H_2
Accuracy	Air	16%
	Nitrogen	-4%
Precision	Air	1%
	Nitrogen	0%
Repeatability	Air	0.00% H_2
	Nitrogen	0.00% H_2
Response Time - Low to High	Air	0.8 s
	Nitrogen	0.8 s
Response Time - High to Low	Air	0.7 s
	Nitrogen	0.4 s
T-90 Time	Air	1.5 s
	Nitrogen	1.4 s
T-10 Time	Air	3.7 s
	Nitrogen	3.5 s

NMT Sensors Sense H_2®

Three Sense H_2® sensors were used throughout this evaluation, one for each set of tests. Table 31 gives the average values of their results as an overall summary. This sensor was tested as received, but does have options for user calibration.

Table 31. Sense H_2® Test Results Summary

Test	Background Gas	Average Result
0% Drift	Air	-0.2% H_2
2% Drift	Air	0.1% H_2
LDL – Increasing %H_2	Air	0.25% H_2
LDL – Decreasing %H_2	Air	0.13% H_2
Accuracy	Air	74%
Precision	Air	2%
Repeatability	Air	0.01% H_2
Response Time - Low to High	Air	3.0 s
Response Time - High to Low	Air	3.3 s
T-90 Time	Air	12.6 s
T-10 Time	Air	15.5 s

Nissha FIS FH2_HY04

Three FH2-HY04 sensors were used throughout this evaluation, one for each set of tests. Table 32 gives the average values of their results as an overall summary. This sensor was tested as received, but does have options for user calibration.

Table 32. FH2-HY04 Test Results Summary

Test	Background Gas	Average Result
0% Drift	Air	0.01% H_2
2% Drift	Air	0.01% H_2
LDL – Increasing %H_2	Air	< 0.10% H_2
LDL – Decreasing %H_2	Air	< 0.10% H_2
Accuracy	Air	10%
Precision	Air	1%
Repeatability	Air	0.00% H_2
Response Time - Low to High	Air	1.3 s
Response Time – High to Low	Air	1.4 s
T-90 Time	Air	4.1
T-10 Time	Air	11.2

Acknowledgements

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

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Dr. Mark Nurge
Curtis Ihlefeld
James Captain
Robert Cox
Dr. Richard Arkin
Guy Naylor
Teresa Lawhorn
Nick Spangler

Hardware and Equipment Support

Hazardous Gas Laboratory
Applied Physics Laboratory
Applied Chemistry Laboratory

Appendix A: Materials and Equipment

Mass Flow Controllers (MFCs)

1. H2 Gas MFC
    - MKS Model 1179B-31039, 10000 sccm
    - SN G502741G20
    - Metrology number M9111, calibrated 22-Jan-20, calibration due 22-Jan-21
2. Dilution Gas MFC
    - MKS Model 1179B-31039, 10000 sccm
    - SN G502799G20
    - Metrology number M9173, calibrated 30-Mar-20, calibration due 30-Mar-21

Pressure Transducer

- MKS Baratron® Model 626A13TBD
- SN 010609505
- Calibrated 06-Nov-2019, due 06-Nov-2020
- KSC Metrology # ZC1008

Hydrogen Blend Gas K-Bottles

1. Hydrogen in Air
    - Boggs Gas
    - Certified standard, 2.92% H_2
    - Lot 219sci20dp1
2. Hydrogen in Nitrogen
    - Boggs Gas
    - Certified standard, 3.62% H_2
    - Lot 071sci10DP1
3. Hydrogen in Helium
    - Boggs Gas
    - Certified standard, 3.57% H_2
    - Lot 071sci20DP1

Appendix B: Manufacturer's Specifications for Sensors

The following information has been taken from the manufacturer's user's manuals and spec sheets for the sensors.

HY-OPTIMA™ H2scan 720B

MODEL	Hydrogen Range		Hydrogen MUST be present	CO Limit	H2S Limit	Calibration Background Gas	Max Pressure
	Min	Max					
710B	0.1%	10%	Yes	<100 ppm	<20 ppm	N2	2 atm
730B	0.5%	100%	Yes	<100 ppm	<1000 ppm	N2	2 atm
740B	0.5%	100%	Yes	20%	3%	N2	2 atm
720B	0.4%	5%	No[1]	0	0	O2, N2	2 atm

1.2.2 Model 720B

The HY-OPTIMA™ 720B Process Hydrogen Analyzer has been specifically manufactured to operate in an air or inert background.

- Operation in background streams in which H2 is not typically present
- Calibration Background Gas: Air or Inert
- Hydrogen Sensitivity Range:
  - 0.4% to 5% hydrogen by volume at 1.0 atm
  - 10% to 125% hydrogen lower flammability limit

Note:

Please disregard all warnings and statements to avoid operation in air or oxygen background; these warnings and statements do not apply to the HY-OPTIMA™ 720B In-Line Process Hydrogen Analyzers which have been manufactured for implementation in background gas streams with air.

HY-OPTIMA™ 720B Process Hydrogen Analyzers operating in air do not require the conditioning procedure.

H2scan recommends the hydrogen gas concentrations for both the Field Verification and Field Calibration gases to be 1% and 2% hydrogen in a balance of air.

1.3.1 Performance Specifications

MODEL	Hydrogen Range		Hydrogen MUST be present	CO Limit	H2S Limit	T90 Response Time (sec)	Accuracy		Drift/Week		Repeatability		Linearity	
	Min	Max					Min to 10% H2	10 to Max% H2	Min to 10% H2	10 to Max% H2	Min to 10% H2	10 to Max% H2	Min to 10% H2	10 to Max% H2
710B	0.1%	10%	Yes	<100 ppm	<20 ppm	< 90	0.15%	N/A	0.15%	N/A	0.15%	N/A	0.15%	N/A
730B	0.5%	100%	Yes	<100 ppm	<1000 ppm	< 60	0.3%	1.0%	0.2%	0.4%	0.2%	0.4%	0.2%	0.4%
740B	0.5%	100%	Yes	20%	3%	< 90	0.3%	1.0%	0.2%	0.4%	0.2%	0.4%	0.2%	0.4%
720B	0.4%	5%	No[1]	0	0	< 60	0.3%	N/A	0.3%	N/A	0.3%	N/A	0.3%	N/A

Note: Sensor performance specifications are absolute and assume a dry process stream, an ambient temperature of 25°C, pressure compensation, and are in addition to any errors in the calibration gases used. The accuracy is specified for the serial port and digital display output only.

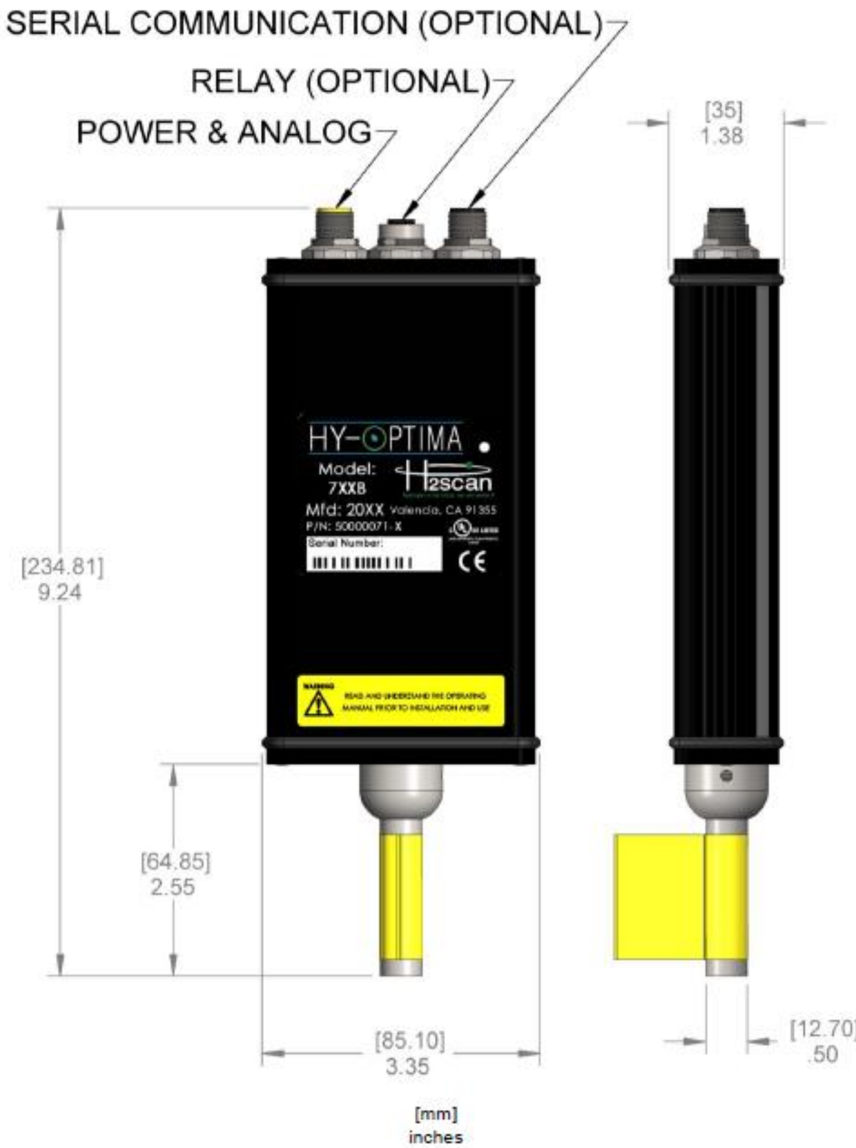
1. 720B models operated in background streams in which H2 is not typically present and may be operated in an Air, O2, or N2 background.

1.3.2 Operating Specifications

Sample Gas Flow Rate	0.1 to 10 slpm (1.0 slpm is recommended)
Pressure	Recommended Operating Pressure at Analyzer: 0.95 – 1.1 atm (14.0-16.1 psia) Maximum: 2 atm absolute (29.4 psia)*
Temperature	Gas Stream: -20°C to +60°C Operating: -20°C to +55°C Storage: -40°C to +80°C
Input Power	10 – 26VDC, 10W
Analog Output	**Current** 4 – 20mA - OR - **Voltage** 0 – 5VDC Maximum load impedance: 650Ω
Environmental	Indoor/Outdoor Use** Altitude up to 2000 meters Pollution degree 2 environment
Ingress Protection	IP64 capable**
Relay Contacts	Two programmable relays with both normally open (N.O.) and normally closed (N.C.) contacts. One relay with normally closed (N.C.) contacts. 1A @ 30VDC SPDT
Serial Communication	RS232 or RS422 19200 bps, no parity, 8 bit data, 1 stop bit, no handshaking
Weight	0.37kg (0.82lbs)

* Analyzers are factory calibrated at 1 atm

**UL did not test Outdoor Use or IP64 during 61010-1 evaluation.


SERIAL COMMUNICATION (OPTIONAL)
RELAY (OPTIONAL)
POWER & ANALOG
[35]
1.38
HY-OPTIMA
Model:
7XXB
H2scan
Mfd: 20XX Valencia, CA 91355
P/N: 50000071-X
Serial Number:
READ AND UNDERSTAND THE OPERATING MANUAL PRIOR TO INSTALLATION AND USE
[234.81]
9.24
[64.85]
2.55
[85.10]
3.35
[12.70]
.50
[mm]
inches

Xensor XEN-5320

Features

- Thermal conductivity and binary gas mixtures measurement
- Temperature (T) and Humidity (RH) compensated
- T and RH measurement inside sensor head
- Digital communication via USB, CAN bus or WIFI
- Analog output for USB PCB model without housing, voltage output 0.5 V – 2.5 V.
- Signal output
  - Hydrogen 0-100%
  - Helium 0-100%
  - General output
  - Vacuum reading
  - Custom 23-point look-up table (examples available)
- Measurement speed
  - Standard: All data 3 Hz
  - Fast: Limited data ≈ 40 Hz,
  - Burst: only output, 500 Hz, CAN only
  - Tau: burst with heater on/off, CAN only
- Temperature range -20 °C to +85 °C
- Humidity range 0-95% non-condensing
- Start-up time: <1 second
- Standard data refresh time: 0.3 second
- T_{90} sensing and T_{10} recovery time: down to 0.6 s
  Optional ultrafast sensing element: <0.05 s
- Power via CAN, USB; WIFI via Li-ion battery

Comes with LabView read-out software.

3 Specifications

Preliminary Specifications (at 23 °C, 101 kPa, 50 %RH)

Item	*Typical*	*Unit*	*Remarks*
General			
Sensitivity for traces of H_2	-2.0	%/%	Signal change for concentration in air
Sensitivity for traces of He	-1.1	%/%	Signal change for concentration in air
Sensitivity for traces of CO_2	+0.3	%/%	Signal change for concentration in air
Sensitivity for vacuum	-4.7	%/Pa	For low pressures
Inaccuracy H_2 and He	1 to 3	%FS	Built in curves
Inaccuracy vacuum	10	%	Between 1 Pa and 10 kPa
Noise	0.04	%	Of signal in air
Offset drift	0.2	%/yr	Of signal in air
Operating limits			
Temperature operating range	-20 to + 55	ºC	For best accuracy
Temperature operating range	-20 to + 85	ºC	Reduced accuracy
Temperature operating range	-20 to + 55	ºC	For WIFI version
Temperature operating range	-20 to + 30	ºC	For WIFI version during charging
Temperature changes	<1	ºC/min	Maximum rate of change
Humidity operating range	0-95	%RH	Non-condensing
Humidity	45-85	%RH	Non-condensing for WIFI version
Humidity changes	<1	%RH/min	Maximum rate of change
Pressure range	800-1200	mbar	Best accuracy
	200-800	mbar	Reduced accuracy
Operation speed			
System start up time	«1	Second	
T_{90} response time	«1	Second	For 0% to 2% hydrogen in air.
T_{10} recovery time	«1	Second	For 2% to 0% hydrogen in air.
T_{63} response time RH sensor	8	Seconds	
Data update rate	3.3	Hz	All versions
Accelerated Data update rate	40	Hz	CAN + USB version, limited data
Maximum Output voltage update rate	500	Hz	CAN version, output voltage only
Electrical			
Current consumption	21	mA	CAN version
Current consumption	33	mA	USB version
Average current consumption	65	mA	WIFI version
Battery charge current	500	mA	
Battery life	15	hrs	950 mAh, when new
Analog output	0.5-2.5	V	For 0-100% output signal (or custom)
Storage			
Temperature storage limits	10-40	ºC	
Humidity storage limits	20-70	%RH	

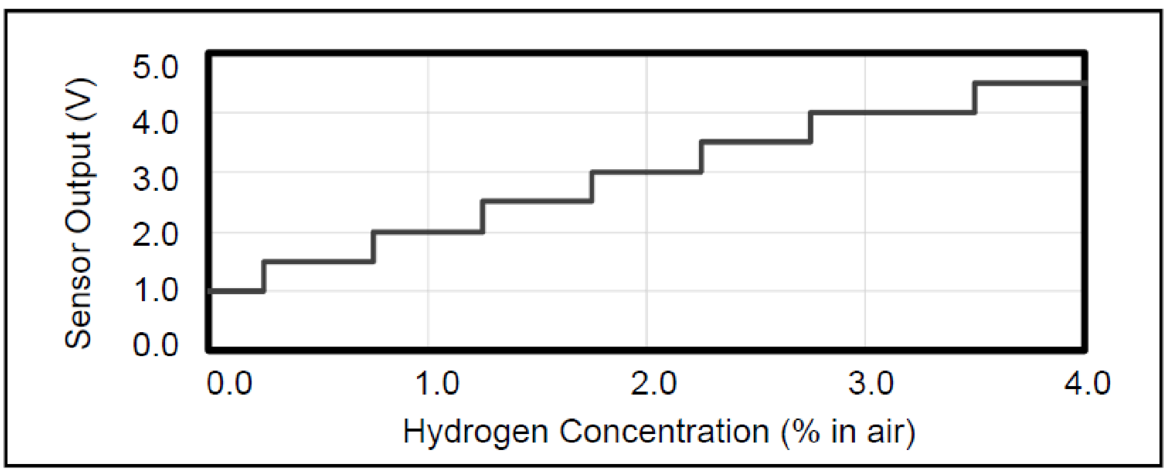
Dimensions			
CAN-HP	110 x M27	mm^3	High Pressure housing
USB version	40×20×10	mm^3	no housing, PCB version.
WIFI/battery version	63×51×24	mm^3	
Weight	≈ 6	g	XEN-5320-USB without cable
Weight	≈13	g	XEN-5320-USB-ABS without cable
Weight	≈135	g	XEN-5320-CAN-HP without cable

NMT Sensors Sense H_2®

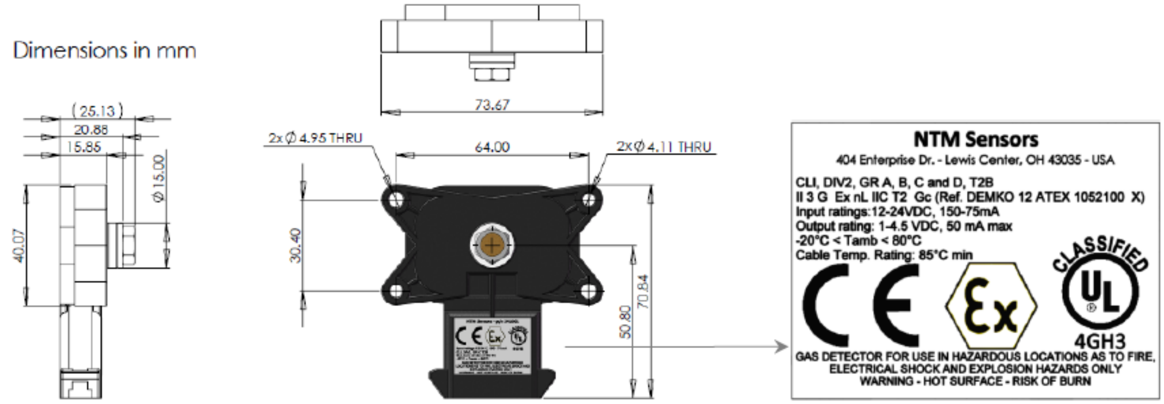
Table of Typical Characteristics:

Metric	Min	Max	Units
Characteristics:			
H_2 range (in air)	0.25	4.0	%
Voltage input	12	24	Vdc
Output (sensing range)	1.0	4.5	Vdc
Error state (output signal)	0.50	0.50	Vdc
Error state (output signal)	4.75	4.75	Vdc
Power consumption (25°C)	0.10	0.15	A
Response time (T90)	—	5	Sec.
Recovery time (T10)	—	5	Sec.
Environmental Conditions:			
Ambient temperature	-20	80	°C
Relative humidity	5	95	%R.H.
Linear flow rate	0.02	5.00	m/s
Hazardous Location Approvals:	UL Class I, Div 2, GR A-D, T2B ATEX Class I, Zone 2 Ex nL IIC T2 Gc		

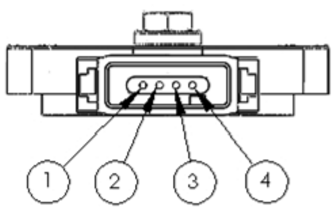
Typical Calibration:



Sensor Dimensions:



Wire Pin-Out:

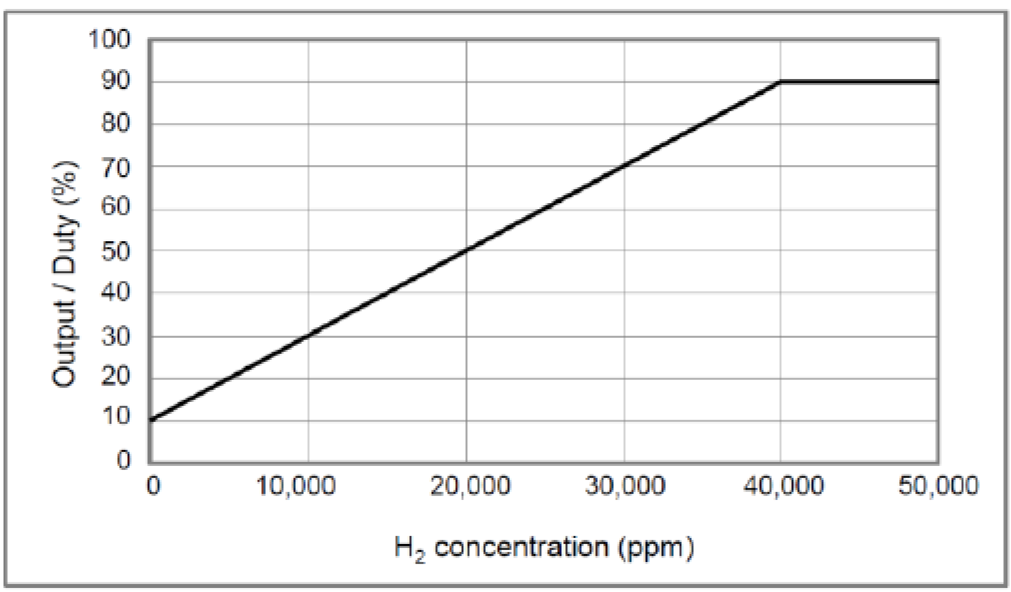


Wire Pin Out

Pin	Symbol	Function	Wire color
1	SIG+	Output Signal (+)	Blue
2	SIG-	Output Signal Ground	Black
3	PWR-	Input Power Ground	Black
4	PWR+	Input Power (+)	Red

Electrical Ratings:
Input: 12-24 VDC, 0.15 A maximum
Output: 1-4.5 VDC, 50 mA maximum

Nissha FH2-HY04



H_2 concentration (ppm) = 500 x (Duty% - 10)

Specifications: FH2-HY04

Item	Contents
Detection gas	Hydrogen
Concentration range	0 to 4 vol.% in air
Initial accuracy	± 10%
Speed of response (T80)	< 2 seconds
Start-up time	< 1 second
Supply voltage	12V (9 to 16 V) DC
Power consumption	About 1.0W
Output signal	PWM (10 to 90% duty); negative logic
Operating temperature range	-35℃ to 85℃
Storage temperature range	-40℃ to 105℃
Humidity	< 95%RH (no condensation)
Dimensions (without the attaching part)	62 (W) × 49 (D) × 22.5 (H) mm
Weight	Approx. 58g

Performance of the FH2-HY04 (FIS specifications)

1) Detection range: Hydrogen: 0 to 4.0vol% in air (LEL0% to LEL100%)
(recommended alarm level: 10,000ppm or 20,000ppm)

2) Accuracy: +/-10% (initial)

3) Response speed (T80): < 2 seconds

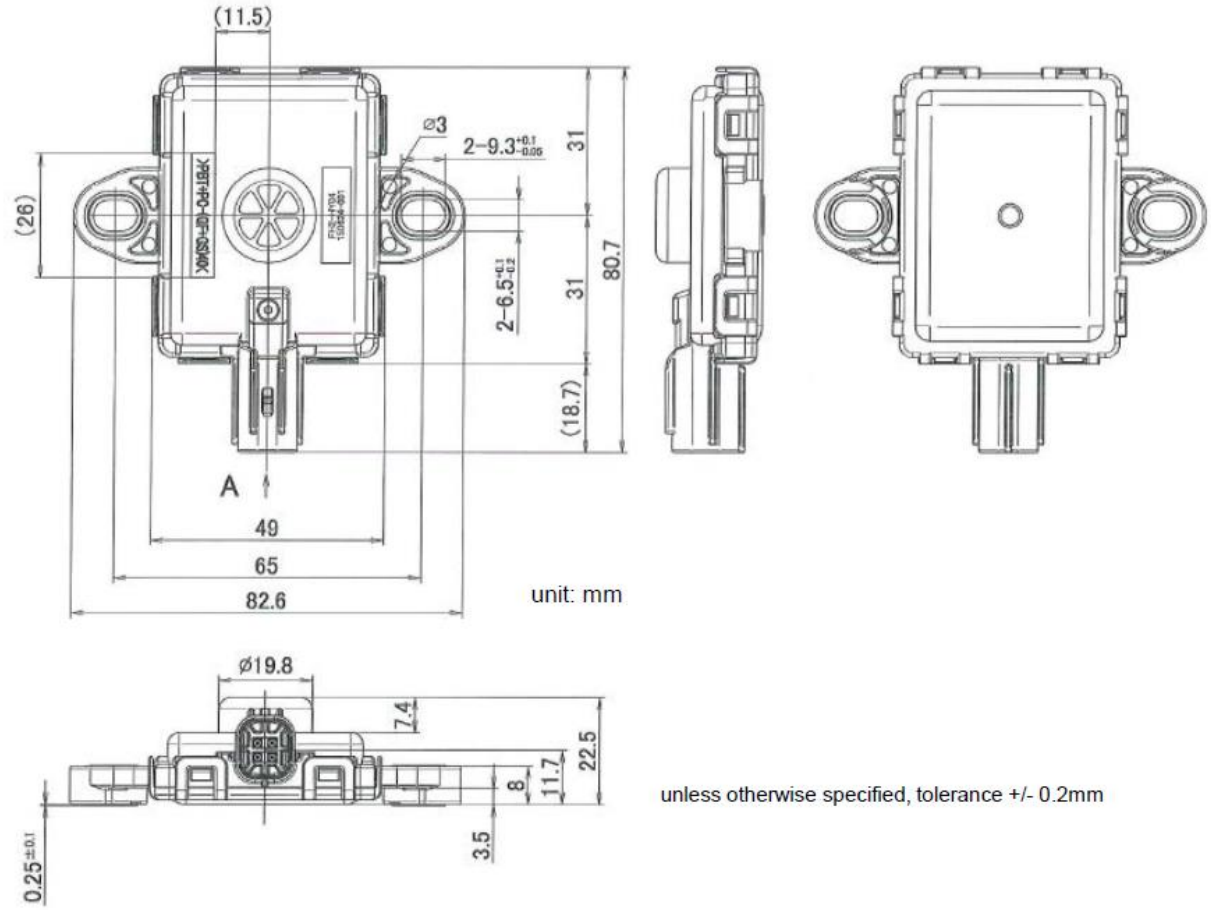
4) Cross sensitivity: No effect from 5,000ppm level of HC, CO, Dimethyl ether or alcohol

5) Start up time: < 1 second

6) Poisoning resistance: < +/-20%: sensitivity drift after exposure to 100ppm HMDSO/D5 (in air) for more than 10,000 hours

7) Expected life: Operation time > 20,000hrs
(accuracy: < +/-20% in normal environment)

2. Dimensions



unit: mm

unless otherwise specified, tolerance +/- 0.2mm