# Laboratory Evaluation: Sensirion SGP40



South Coast AQMD

AQ-SPEC

Air Quality Sensor Performance Evaluation Center

# Background

Three **Sensirion SGP40** sensors (units IDs: d72, 302, c70) were evaluated in the South Coast AQMD Chemistry Laboratory under controlled Volatile Organic Compound (VOC) and interferent gas concentrations, temperature, and relative humidity. The sensor measurements were compared with two reference instruments (Thermo Fisher Scientific, Model 55i; hereinafter **Thermo 55i** and Agilent gas chromatograph with flame ionization detection, Model 6890N Network; hereinafter **GC-FID**) measuring the same pollutant.

**<u>Sensirion SGP40 (*3 units tested*)</u>:**

- VOC Sensor – Metal Oxide (Sensirion SGP40, non-FEM)
  - Sensor outputs index or raw signal values, not ppm
  - VOC operable range: 0.3-30 ppm (ethanol in clean air)
  - Limit of detection: <0.05 ppm for Ethanol
  - Measurement interval: 1-min
  - Indoor air quality monitoring
- Measures: VOC (Index, raw signal; not in ppm)
- Unit cost: ~$80
- Units IDs: d72, 302, c70

Sensirion SGP40

Thermo 55i

GC-FID

***<u>Reference Instruments</u>*:**

- **<u>Thermo Fisher 55i</u>**
  - Measures: methane ($CH_4$) and non-methane hydrocarbon (NMHC)
  - Unit cost: ~$27,000
  - Specifications:
  - Measurement ranges: 0-50 ppm
  - Limit of Detection (LOD): 50 ppb
  - Analysis time: ~70 seconds
  - Accuracy: ±1% of range
  - Repeatability: ±2% of measured value or 50 ppb (whichever is larger)
  - Drift: ±2% of span over 24 hours
  - Ambient operating temperature: 15-35 °C
  - Sample temperature: ambient to 35 °C
- **Agilent Gas Chromatograph**
  - Flame Ionization Detection
  - Time Resolution: 22-min
  - Unit cost: ~ $100,000
  - Limit of Detection (LOD): dependent on the species, typically <1 ppb

# Outline

1. Reference instruments comparison
2. VOC blend results (Phase 1 through Phase 6)
3. Benzene-only results (Phase 2 and Phase 6)
4. Discussion

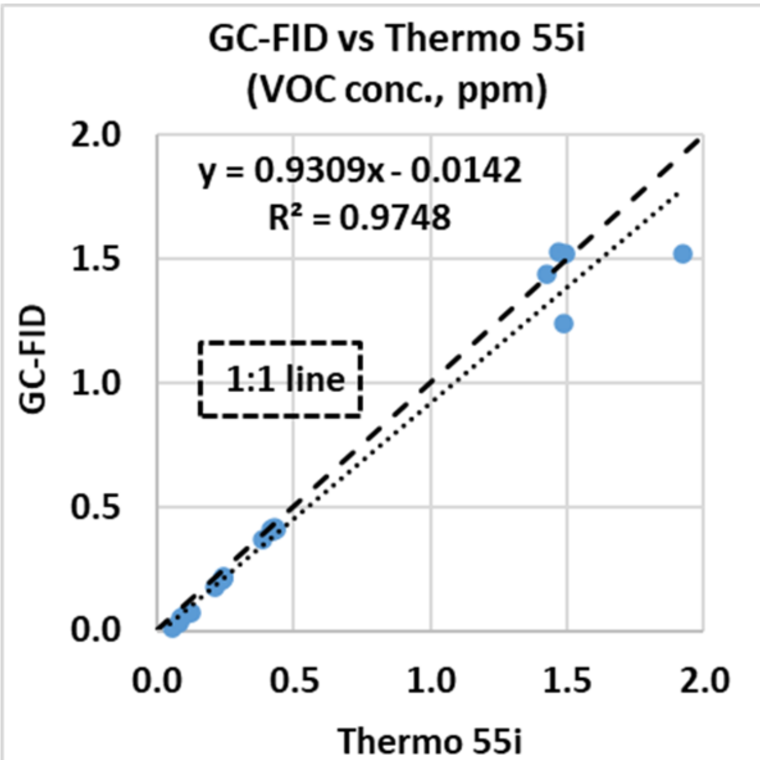
# About Sensirion SGP40 and Data Handling

- The Sensirion SGP40 was incorporated to a development board as an evaluation kit that allows for data visualization and retrieval using Sensirion's software.
- The Sensirion SGP40 sensors do not report absolute VOC concentrations in ppm; the sensors only report VOC index or raw signal values in the sensor output file.
- VOC index ranges from 0 to 500; VOC index is calculated based on raw signal values, T and RH using Sensirion's proprietary gas index algorithm; the raw signal in ticks is proportional to the logarithm of the resistance of the sensing layer. (Source: https://sensirion.com/media/documents/296373BB/6203C5DF/Sensirion_Gas_Sensors_Datasheet_SGP40.pdf)
- For all data analyses in this report, the VOC index values were represented as isobutylene concentrations according to the conversion equations provided by Sensirion (https://sensirion.com/media/documents/4B4D0E67/6436C169/GAS_AN_SGP4x_BuildingStandards_D1.pdf); these calculated equivalent isobutylene concentrations are "only valid under laboratory conditions" and were used for comparisons with the reference instruments.
- In this report VOC index values were represented as isobutylene concentrations, for the purpose of estimating sensor detection limit, steady state concentrations, $R^2$, mean bias error and accuracy. Please note that these quantities may differ depending on the actual test gas species used.

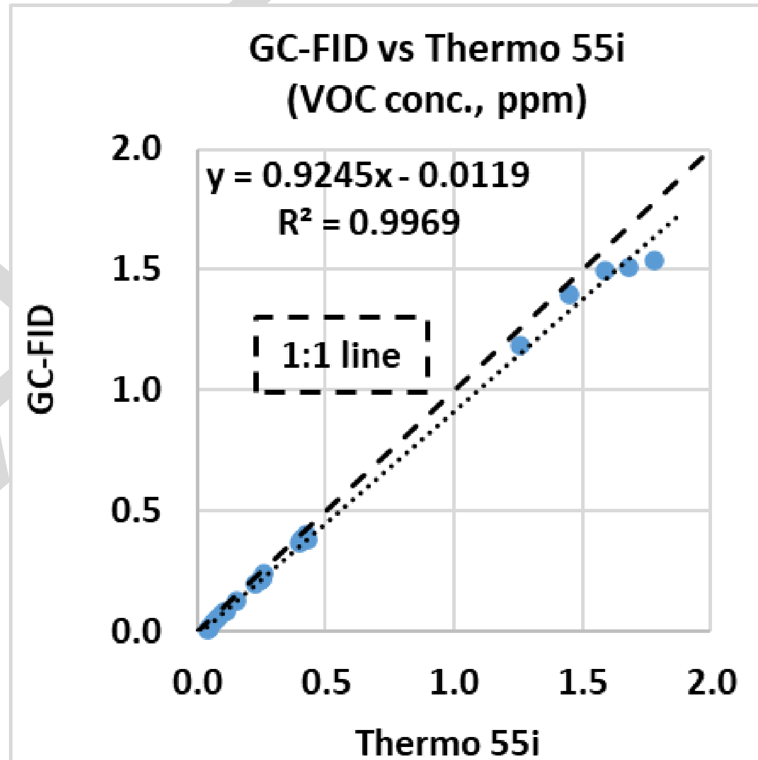
# VOC Blend Results

# GC-FID vs Thermo 55i: VOC Blend

**Beginning of Evaluation**




**End of Evaluation**



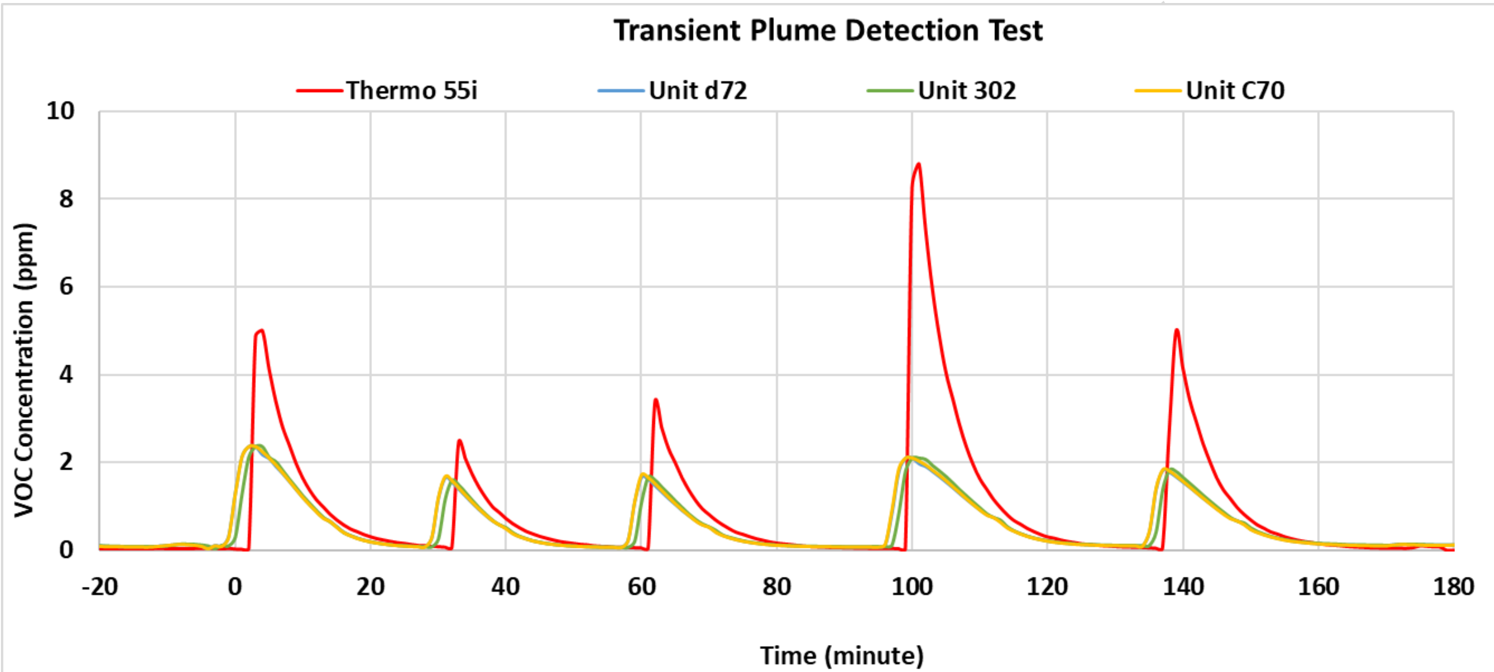

- Very strong correlations between the Thermo 55i and GC-FID ($R^2 > 0.97$).
- The two reference instruments reported similar VOC concentrations at both the beginning and the end of evaluation.

# Phase 1: Transient Plume Detection



| Testing Phase #1 | Method | Parameters Evaluated |
|---|---|---|
| Transient Plume Detection | 5 VOC plume events at various concentrations in randomized order | • Response time<br>• % of peak detection |

# Sensirion SGP40 vs Thermo 55i



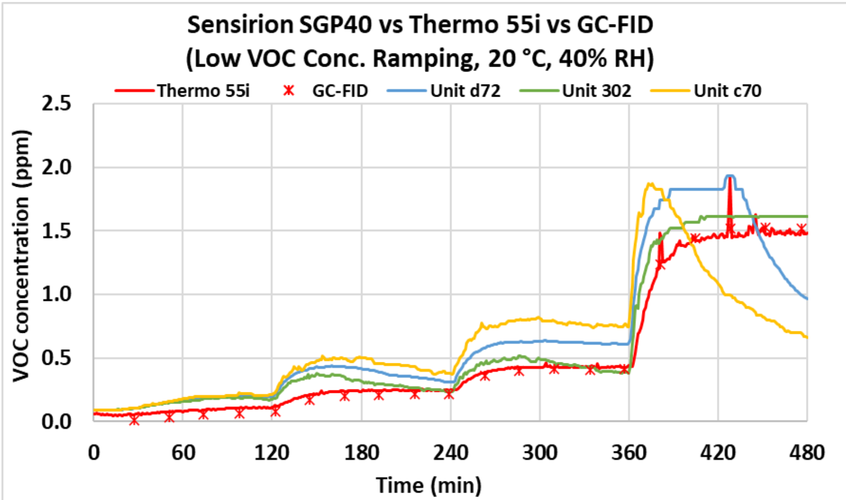

- The Sensirion SGP40 sensors responded to 100% of the VOC peaks generated.
- The Sensirion SGP40 sensors responded to the VOC peaks as fast as the Thermo 55i detected the peaks; there is effectively no measurable time delay in plume detection by the Sensirion SGP40 sensors (and that any apparent delay of the reference instrument is due to different sampling times of the sensors vs. the reference).

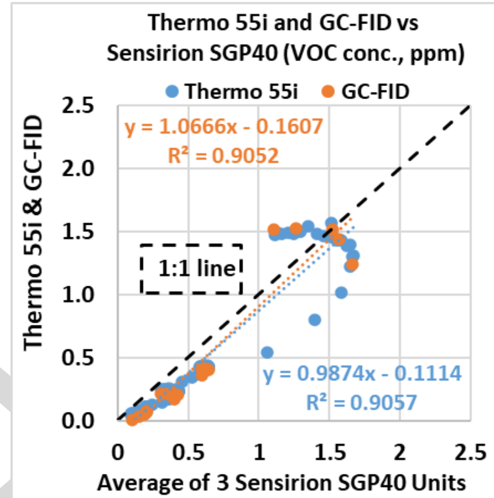
# Phase 2: Initial Concentration Ramping

| Testing Phase #2 | Method | Parameters Evaluated |
| --- | --- | --- |
| Initial Concentration Ramping | • Low conc. ramping with VOC blend (0.06 to 1.6 ppm)<br>• High conc. ramping with VOC blend (2 to 8 ppm)<br>• Low conc. ramping with benzene-only (0.015 to 0.4 ppm)<br>• High conc. ramping with benzene-only (0.5 to 2 ppm) | • Sensor Detection limit, $R^2$, Accuracy, Precision, IMV, data recovery |

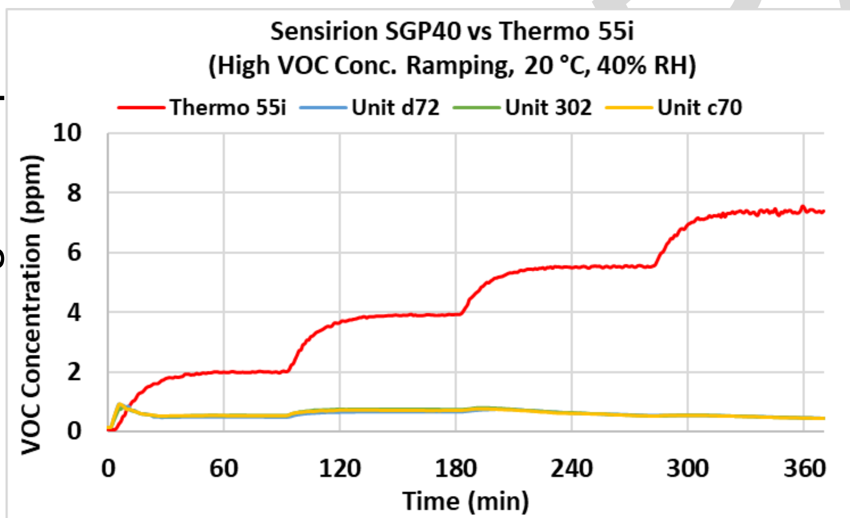
# Sensirion SGP40 vs Thermo 55i vs GC-FID

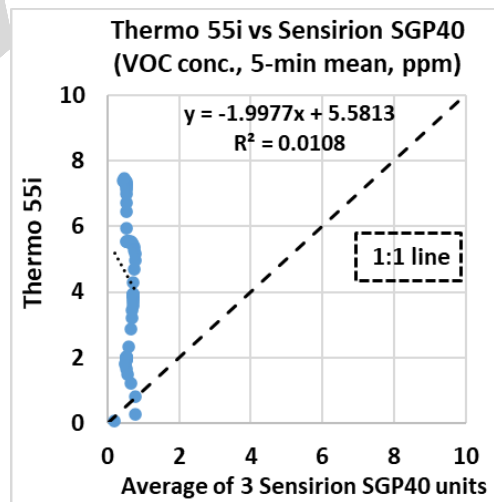
Low Ramp




High Ramp



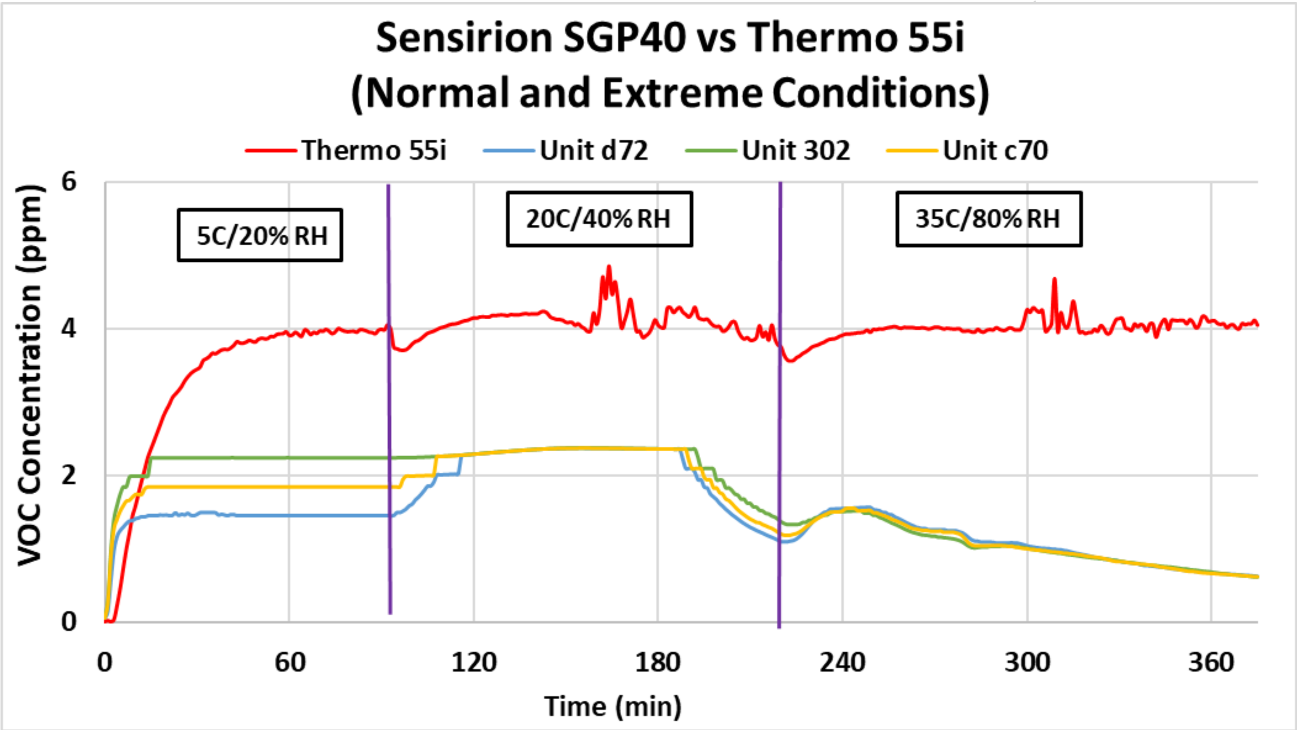

- The Sensirion SGP40 sensors tracked well with the concentration variation as recorded by the reference instruments at concentrations below 1 ppm; the sensors did not track the VOC concentrations when they were > 1 ppm.
- The Sensirion SGP40 sensors showed very strong correlation ($R^2$ ~ 0.91) and no correlation ($R^2$ ~ 0.01) with the reference instruments in the low and high concentration ramps, respectively.

# Phase 3: Effect of Temperature and Relative Humidity



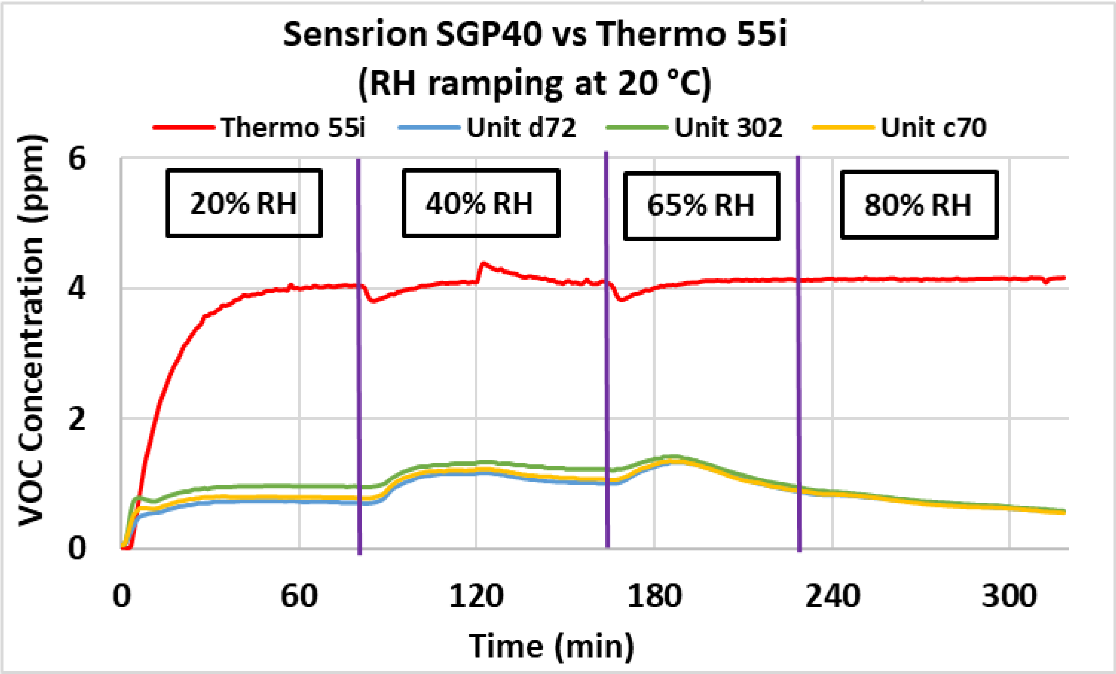
| Testing Phase #3 | Method | Parameters Evaluated |
|---|---|---|
| Effect of Temperature and RH | • Extreme Conditions: hot/humid; cold/dry and VOC = 4ppm<br>• RH interference: 15% to 80% RH; T = 20°C and VOC = 4 ppm<br>• T interference: 20°C to 10°C to 30°C to 20°C; RH = 40% and VOC = 4 ppm<br>• *T interference: 20°C to 10°C to 30°C to 20°C; AH = constant and VOC = 4 ppm | • Climate susceptibility, Accuracy, Precision, IMV, data recovery |

# Normal and Extreme Conditions



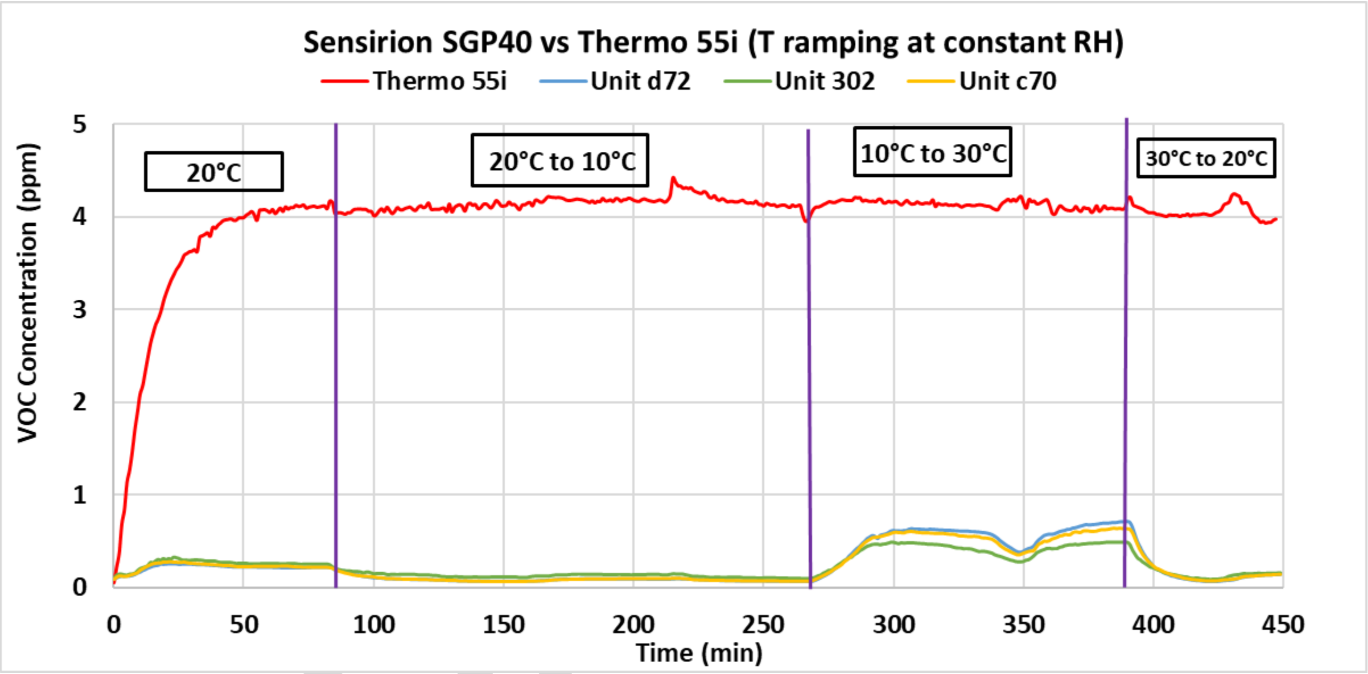

- The Sensirion SGP40 sensors showed a slight increase in mean VOC concentration as T/RH increased from 5°C/20% RH to 20°C/40% RH, and then decreased significantly as temperature/RH was further increased to 35°C/80% RH.

# RH Interference



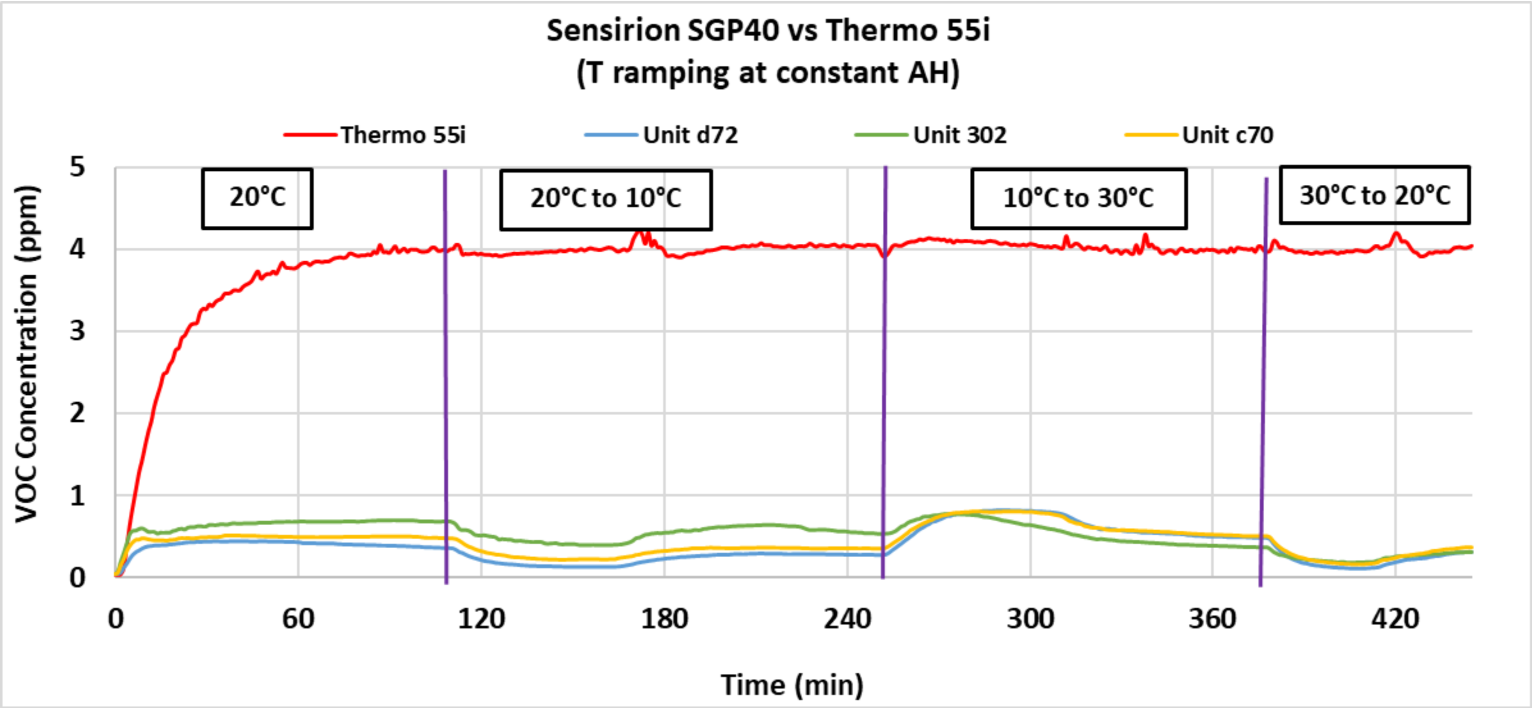

- RH had minimal effect on the VOC concentrations measured by the Thermo 55i as RH increased from 20% to 80%, with temperature held constant at 20°C.
- The Sensirion SGP40 sensors initially showed an increase in VOC concentration as the RH increased from 20% to 40%, and then showed decreasing VOC concentrations as the RH further increased to 65% and 80%.

# Temperature Interference at Constant RH




- The Temperature interference test was conducted at constant RH setpoint of 40%.
- T had minimal effect on the VOC concentrations measured by the Thermo 55i.
- A temperature change at constant RH setpoint appears to cause sensor response to move in the same direction, i.e. the sensors' VOC reading increases when temperature increases and vice versa, after steady-state temperature and RH conditions are realized.

# Temperature Interference at Constant AH





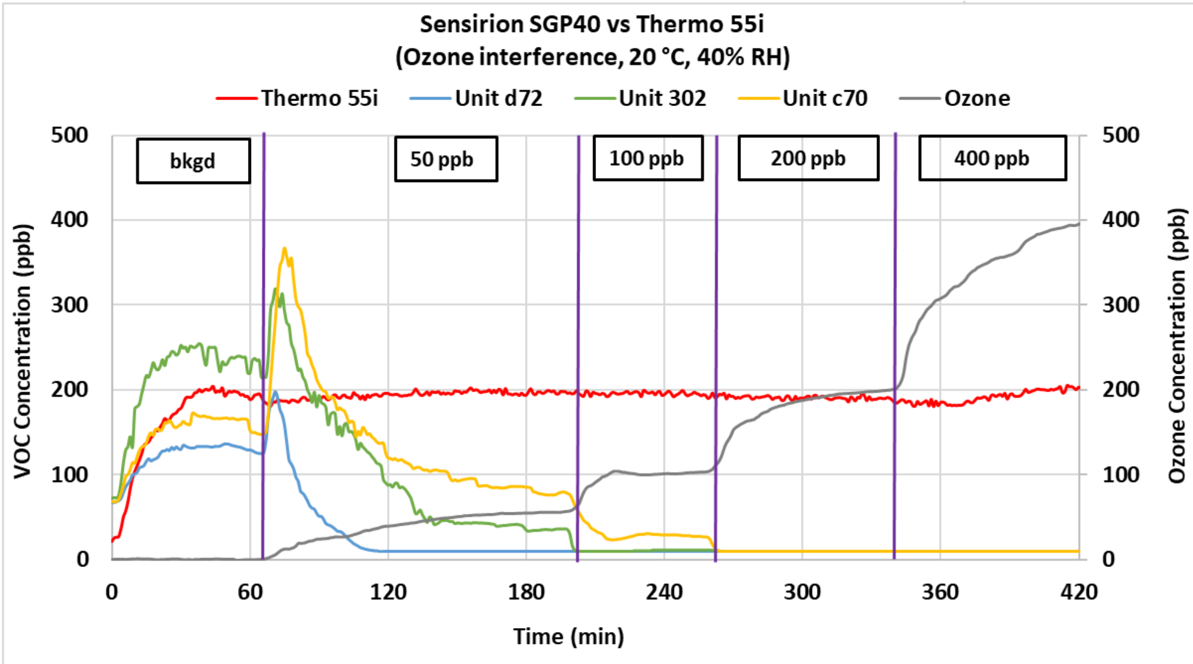

- The Temperature interference at constant AH setpoint was conducted at the moisture content corresponding to 20°C and 40% RH.
- T had minimal effect on the VOC concentrations measured by the Thermo 55i.
- A temperature change at constant AH setpoint does not appear to cause sensor response to change much, after steady-state temperature and AH conditions are realized. However, sensor response does change in the same direction as temperature during transient temperature and AH periods.

# Phase 4: Effect of Gaseous Interferents



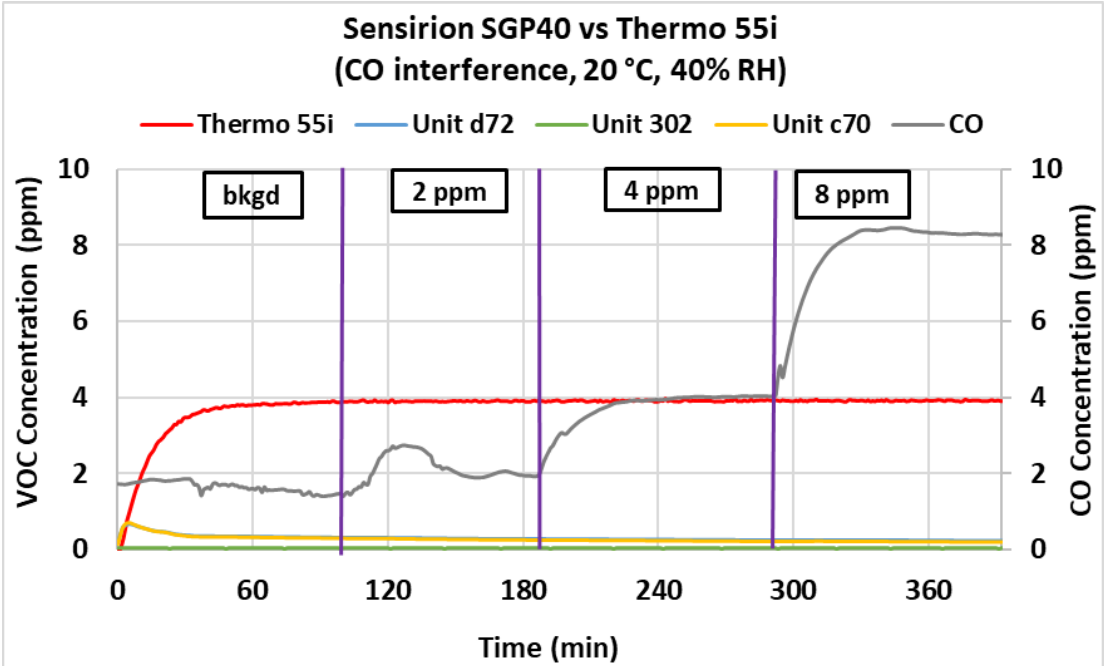
| Testing Phase #4 | Method | Parameters Evaluated |
|---|---|---|
| Effect of gaseous interferents | • Ozone (1 to 400 ppb; 20 °C/40% RH and VOC = 200 ppb)<br>• Carbon Monoxide (background to 8 ppm; 20 °C/40% RH and VOC = 4 ppm)<br>• Carbon Dioxide (background to 8000 ppm; 20 °C/40% RH and VOC = 4 ppm) | • Response to interferents, Accuracy, Precision, IMV, data recovery |

# Ozone Interferent



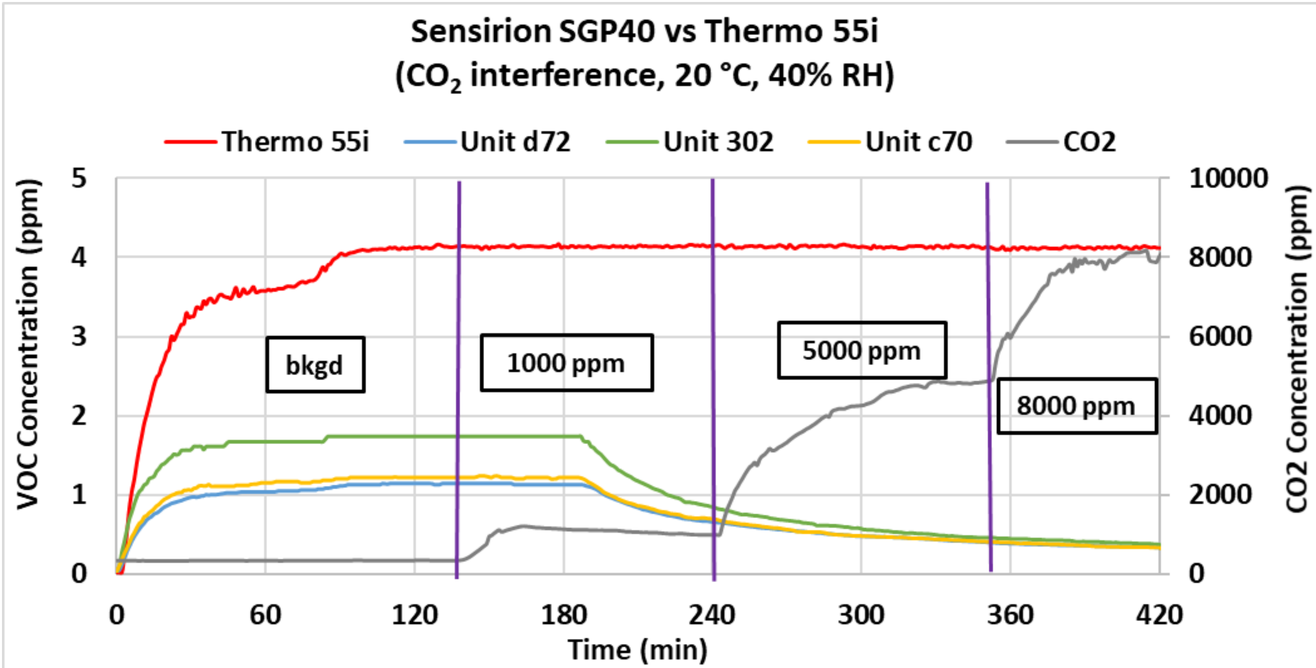

- Ozone interferent test: sensors were subjected to increasing ozone concentration from background level to 400 ppb while holding VOC concentration constant at 0.2 ppm.
- Ozone had minimal effect on the VOC concentrations measured by the Thermo 55i.
- The Sensirion SGP40 sensors VOC concentrations decreased as ozone concentration increased from background value of 0.2 to ~ 400 ppb.

# CO Interferent




- CO interferent test: sensors were subjected to increasing CO concentration from background level to 8ppm while holding VOC concentration constant at ~4 ppm.
- CO had minimal effect on the VOC concentrations measured by the Thermo 55i.
- The Sensirion SGP40 sensors showed a slight decrease in VOC concentrations as CO increased from a background value of ~1.7 ppm to ~8 ppm. However Unit 302 was flatlined during the entire duration of the CO interference test.

# $CO_2$ Interferent

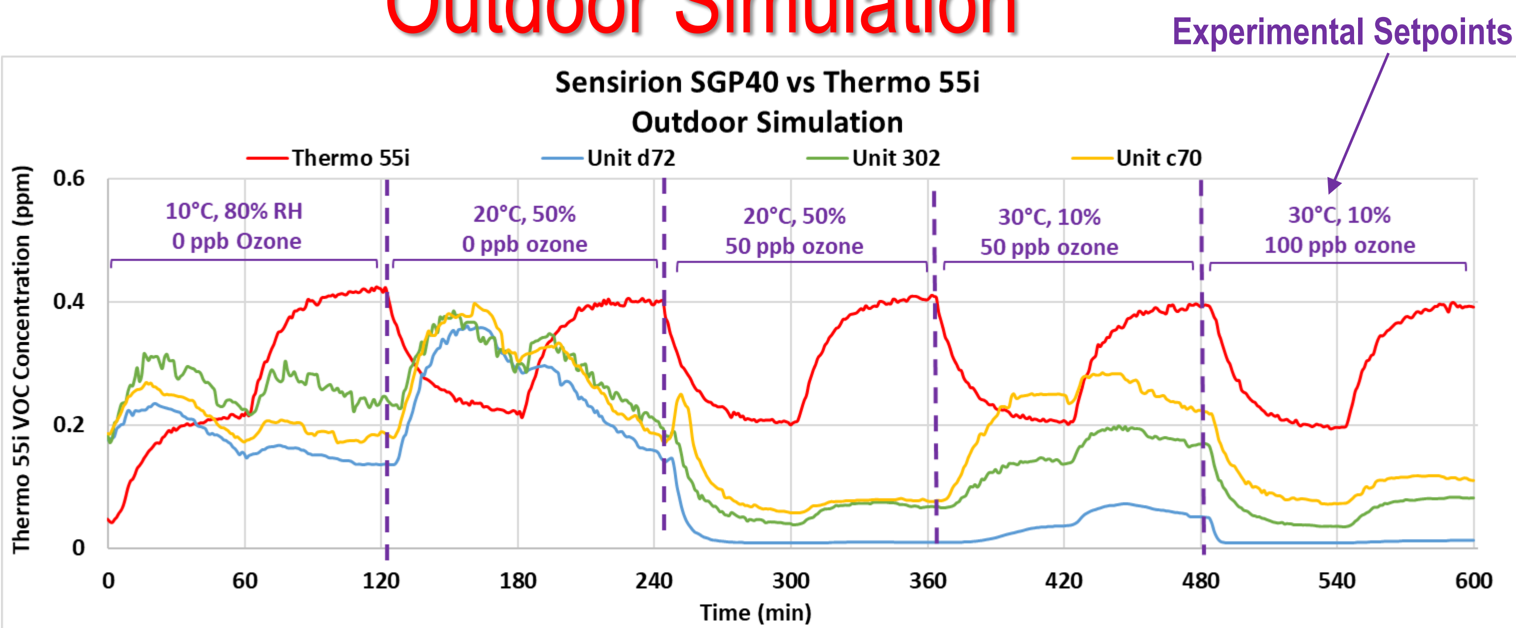


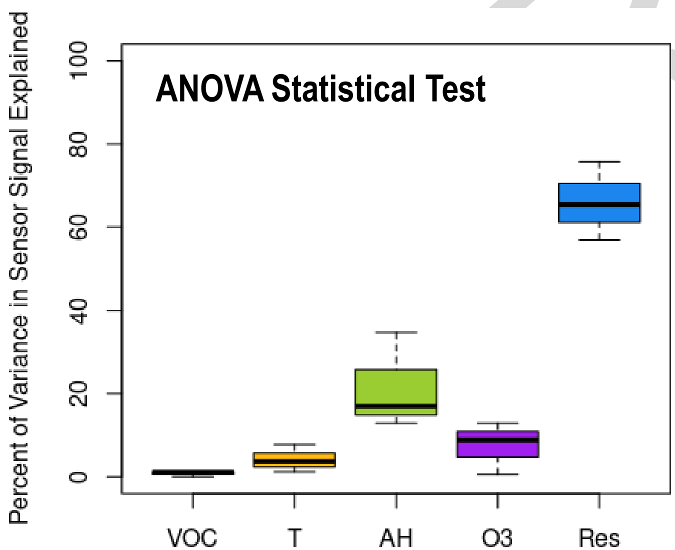

- $CO_2$ interferent test: sensors were subjected to increasing $CO_2$ concentration from background level to 8 ppm while holding VOC concentration constant at ~4 ppm.
- $CO_2$ had minimal effect on the VOC concentrations measured by the Thermo 55i.
- The Sensirion SGP40 sensors' VOC concentration remained constant as $CO_2$ increased from a background value of ~353 ppm to ~1000 ppm then decreased as $CO_2$ increased from 1000 ppm to 8000 ppm.

# Phase 5:
# Outdoor Simulation

| Testing Phase #5 | Method | Parameters Evaluated |
|---|---|---|
| Outdoor Simulation | • Various combination of Ozone (0 to 100 ppb) and VOC (200 to 400 ppb) concentrations, T (10 to 30 °C) and RH (10 to 80%) | • Accuracy, Precision, IMV, data recovery, Analysis of Variance (ANOVA) |

# Outdoor Simulation




- The sensors generally did not track well with the VOC concentration variation as recorded by Thermo 55i.
- **AH** explained ~ 21% of the variance on average, at least for expected ambient conditions when VOC T, AH, and ozone are included in the ANOVA statistical test; followed by **ozone** (~8%) and T (~ 4%). VOC explained < 1% of the variance on average.

# Phase 6: Final Concentration Ramping



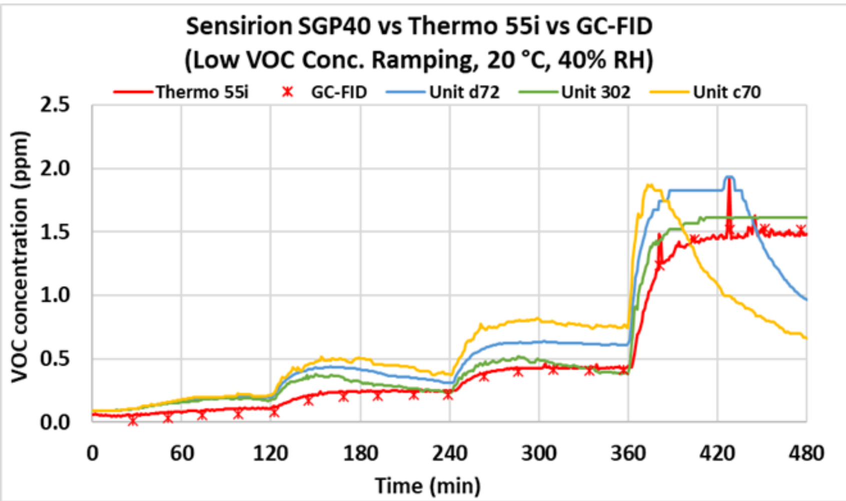
| Testing Phase #6 | Method | Parameters Evaluated |
|---|---|---|
| Final Concentration Ramping | • Low conc. ramping with VOC blend (0.06 to 1.6 ppm)<br>• High conc. ramping with VOC blend (2 to 8 ppm)<br>• Low conc. ramping with benzene-only (0.015 to 0.4 ppm)<br>• High conc. ramping with benzene-only (0.5 to 2 ppm) | • Detection limit, $R^2$, Accuracy, Precision, IMV, data recovery |

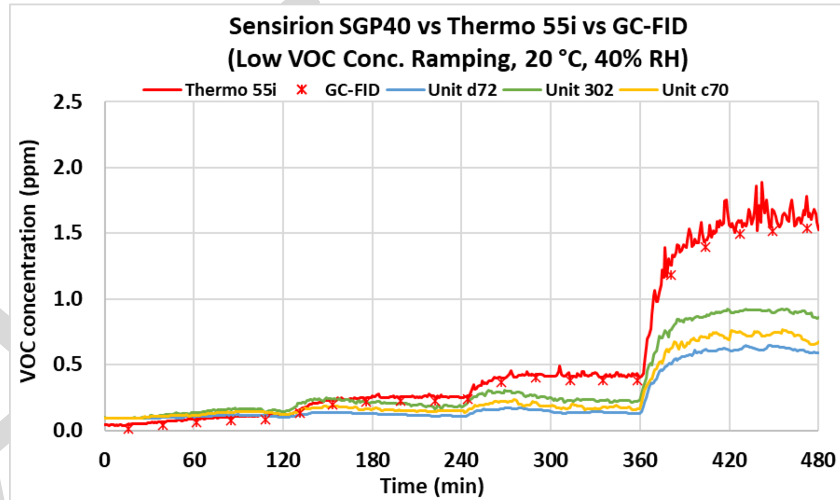
# Sensirion SGP40 vs Thermo 55i vs GC-FID

Initial Ramp

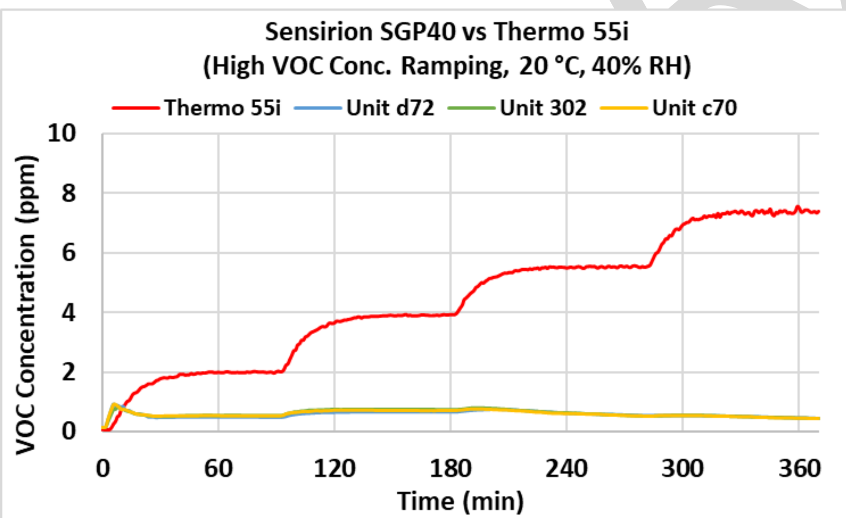
Final Ramp

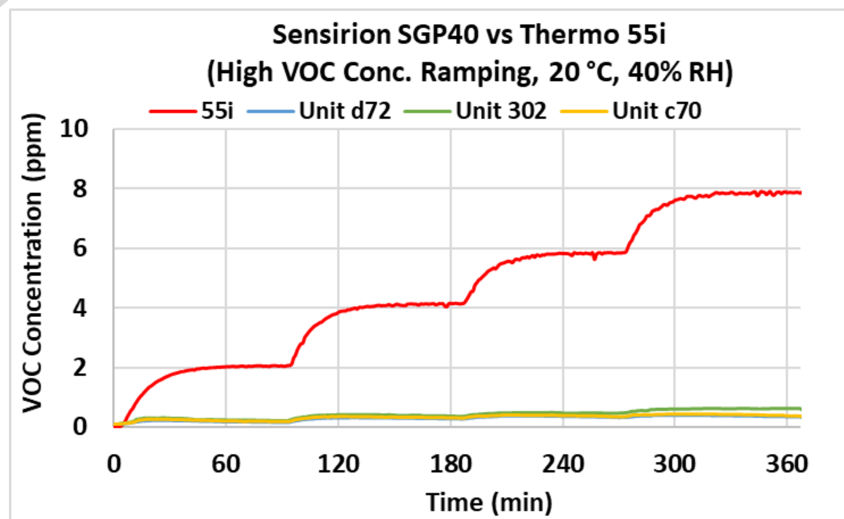
Low Ramp




High Ramp



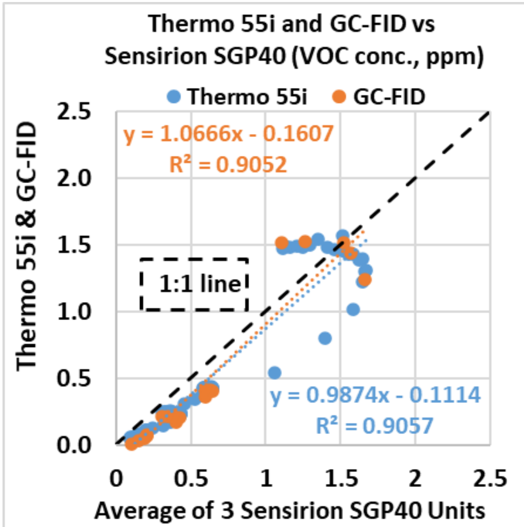



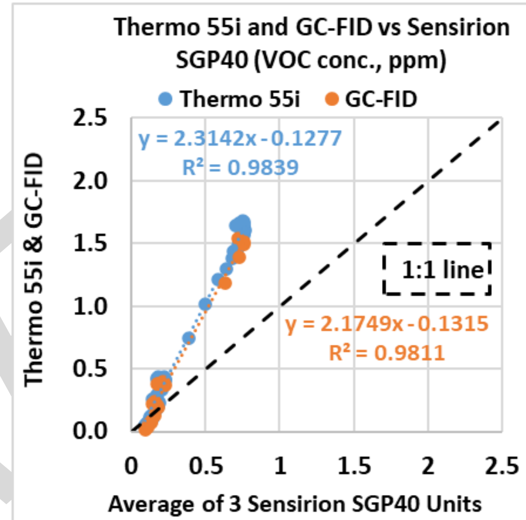
# Sensirion SGP40 vs Thermo 55i vs GC-FID

Initial Ramp

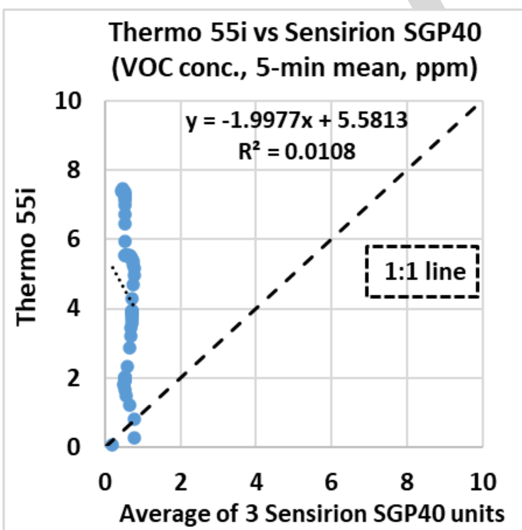
Final Ramp

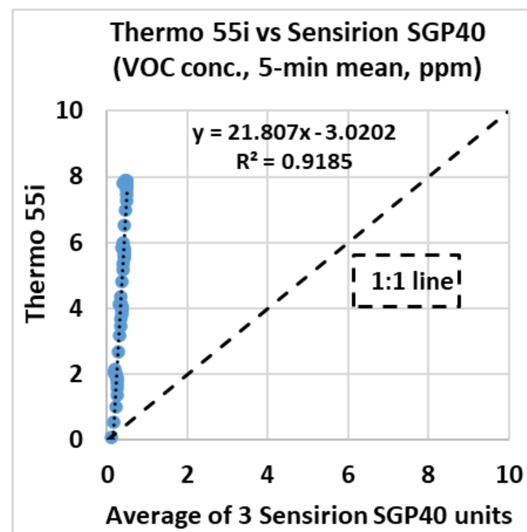
Low Ramp



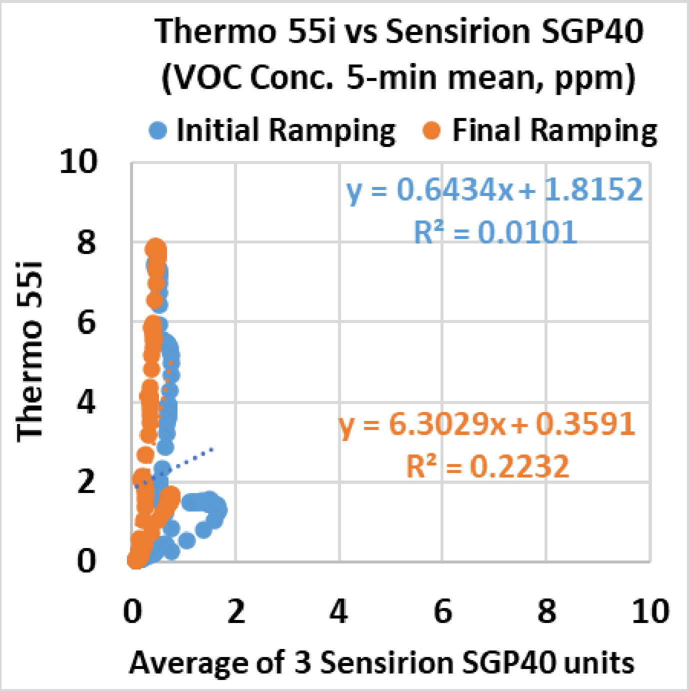

High Ramp



# Short-Term Sensor Response Change

- Short-term sensor response change is characterized as the change in reference-sensor regression between the initial and final concentration ramping experiments




- The sensors generally underestimated the VOC concentrations as measured by the VOC reference instrument. The sensors showed stronger correlations with the reference instrument in the final ramps than the initial ramps for the VOC blend. The sensor response was less sensitive to VOC concentration variations in the final concentration ramping than in the initial ramping. The sensors may have shifted to a lower VOC concentration baseline in the final concentration ramping.

# Summary Statistics

## Initial Ramp

| Sensors | | | | | Thermo 55i | | | GC-FID | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Nominal VOC Conc., ppm** | Avg, ppm | Precision, % | IMV, % | SDL, ppm | Ref avg, ppm | Sensor Bias Error, ppm | Sensor Accuracy, % | Ref avg, ppm | Sensor Bias Error, ppm | Sensor Accuracy, % |
| **0.06** | 0.20 | 99.4 | 14.8 | Unit d72: 0.23-0.75<br>Unit 302: 0.05-0.17<br>Unit c70: 0.53-1.71 | 0.11 | 0.09 | 20.2 | 0.08 | 0.13 | -65.1 |
| **0.2** | 0.32 | 99.4 | 44.1 | | 0.25 | 0.07 | 69.9 | 0.22 | 0.09 | 58.2 |
| **0.4** | 0.59 | 99.8 | 62.2 | | 0.43 | 0.16 | 63.3 | 0.41 | 0.17 | 58.9 |
| **1.6** | 1.14 | 99.3 | 79.9 | | 1.49 | -0.35 | 76.4 | 1.52 | -0.41 | 72.8 |
| **2** | 0.52 | 99.9 | 13.6 | | 2.0 | -1.5 | 25.7 | | | |
| **4** | 0.70 | 99.9 | 15.0 | | 3.9 | -3.2 | 18.0 | | | |
| **6** | 0.55 | 99.4 | 2.1 | | 5.5 | -5.0 | 9.8 | | | |
| **8** | 0.45 | 99.6 | 2.0 | | 7.4 | -7.0 | 6.1 | | | |

# Summary Statistics

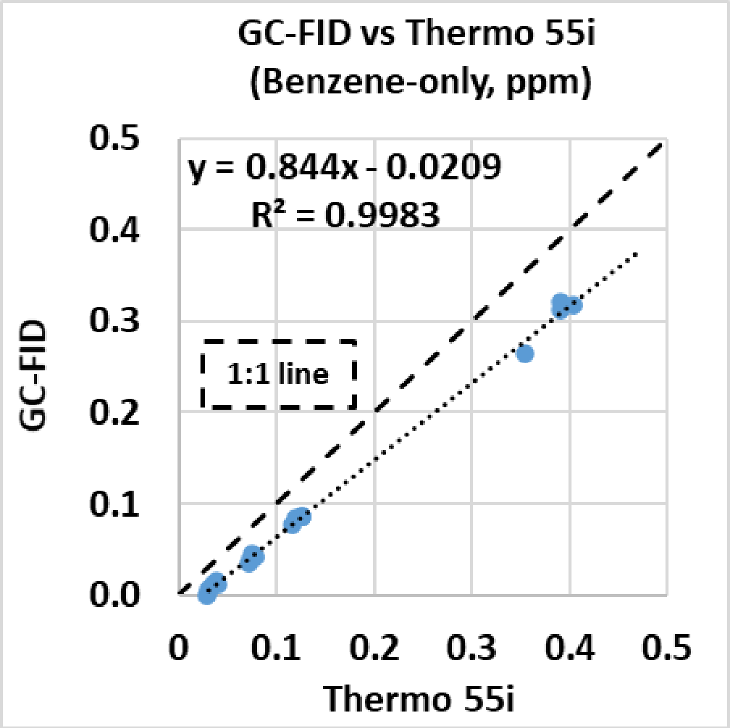
## Final Ramping

| Sensors | | | | | Thermo 55i | | | GC-FID | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Nominal VOC Conc., ppm** | Avg, ppm | Precision, % | IMV, % | SDL, ppm | Ref avg, ppm | Sensor Bias Error, ppm | Sensor Accuracy, % | Ref avg, ppm | Sensor Bias Error, ppm | Sensor Accuracy, % |
| **0.06** | 0.13 | 99.0 | 33.2 | Unit d72: 0.09-0.31<br>Unit 302: 0.07-0.22<br>Unit c70: 0.09-0.29 | 0.11 | 0.02 | 83.1 | 0.08 | 0.05 | 40.7 |
| **0.2** | 0.15 | 99.5 | 49.5 | | 0.26 | -0.11 | 57.5 | 0.24 | -0.09 | 62.6 |
| **0.4** | 0.18 | 99.7 | 50.6 | | 0.42 | -0.25 | 41.7 | 0.38 | -0.21 | 44.2 |
| **1.6** | 0.73 | 99.5 | 39.1 | | 1.64 | -0.91 | 44.6 | 1.54 | -0.81 | 47.4 |
| **2** | 0.19 | 99.3 | 28.1 | | 2.1 | -1.9 | 9.3 | | | |
| **4** | 0.33 | 99.6 | 24.4 | | 4.1 | -3.8 | 7.9 | | | |
| **6** | 0.40 | 99.5 | 28.8 | | 5.8 | -5.4 | 6.8 | | | |
| **8** | 0.45 | 99.0 | 56.5 | | 7.9 | -7.4 | 5.7 | | | |

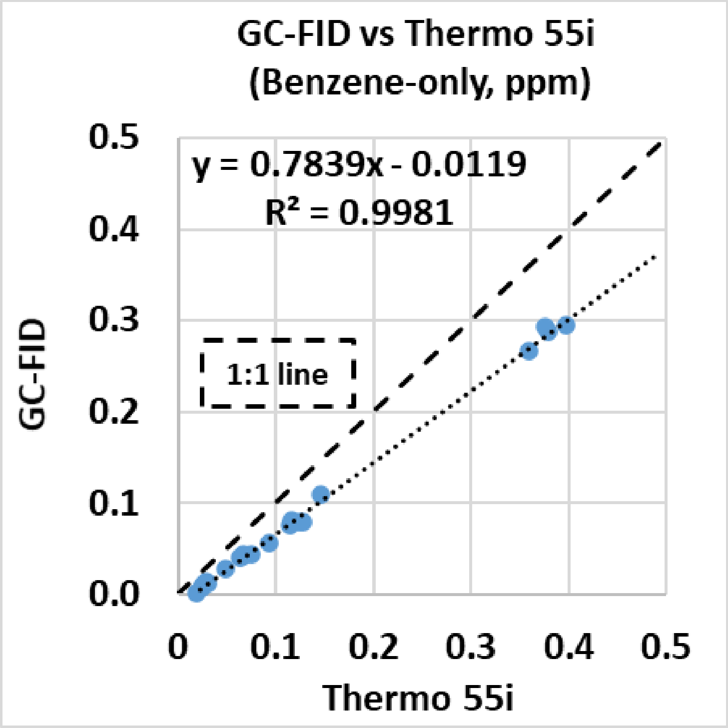
# Benzene-Only Results

# GC-FID vs Thermo 55i: Benzene-only

**Beginning of Evaluation**




**End of Evaluation**



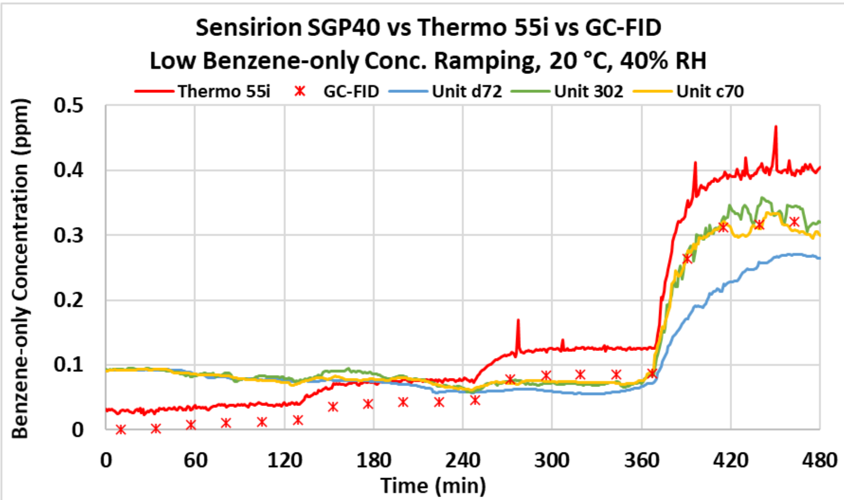

- Very strong correlations between the Thermo 55i and GC-FID ($R^2 > 0.99$).
- The two reference instruments reported similar VOC concentrations at both the beginning and the end of evaluation.

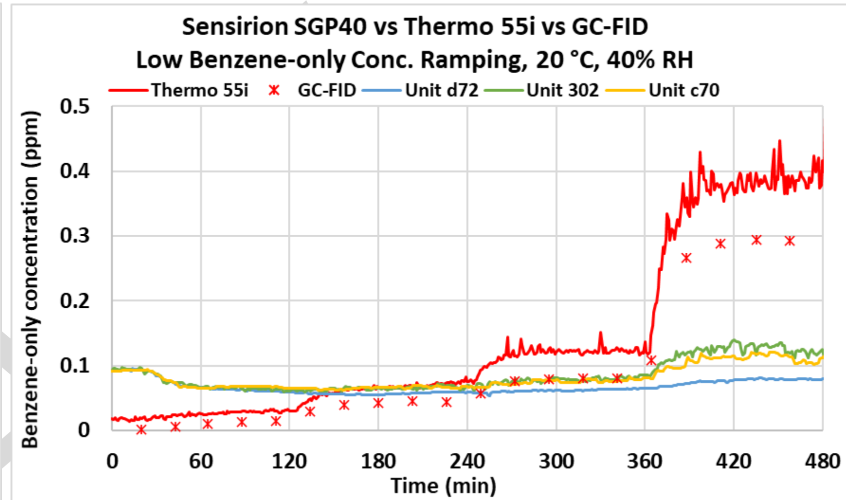
# Sensirion SGP40 vs Thermo 55i vs GC-FID

Initial Ramp

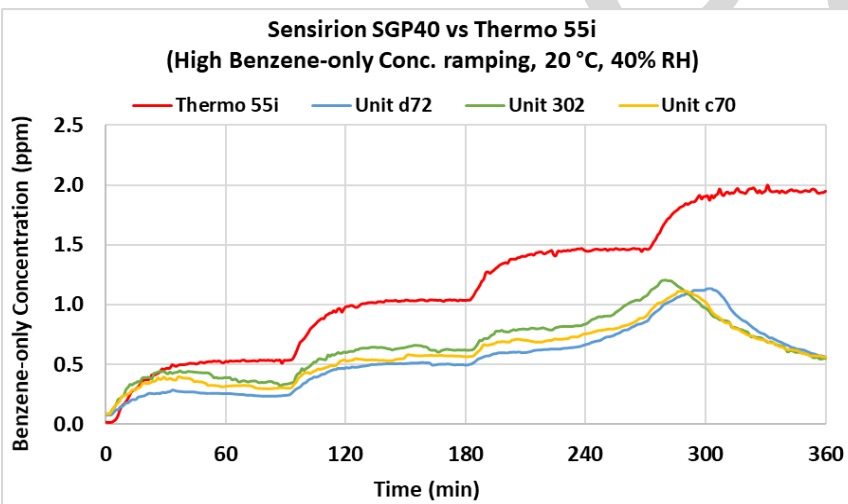
Final Ramp

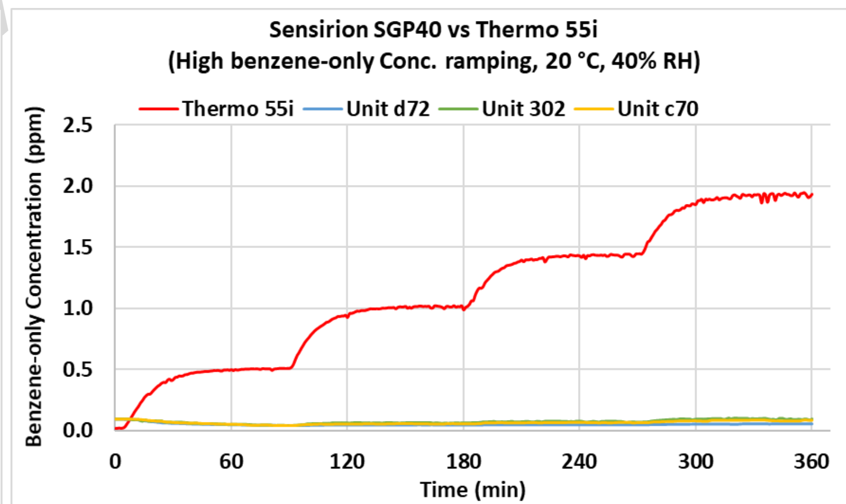
Low Ramp




High Ramp



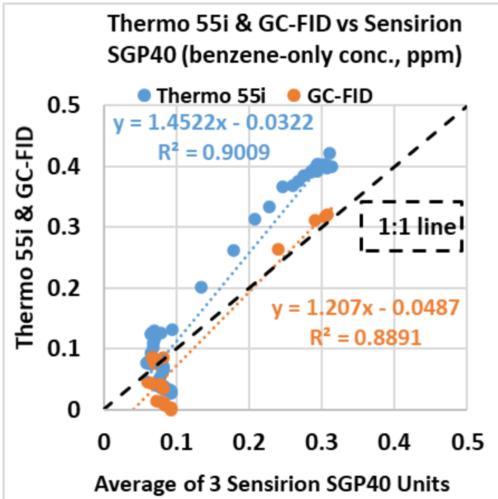



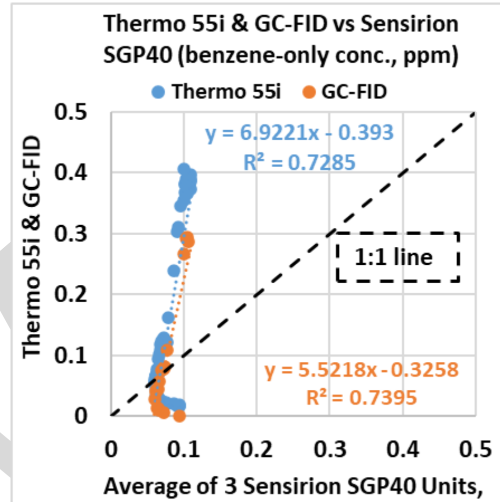
# Sensirion SGP40 vs Thermo 55i vs GC-FID

Initial Ramp

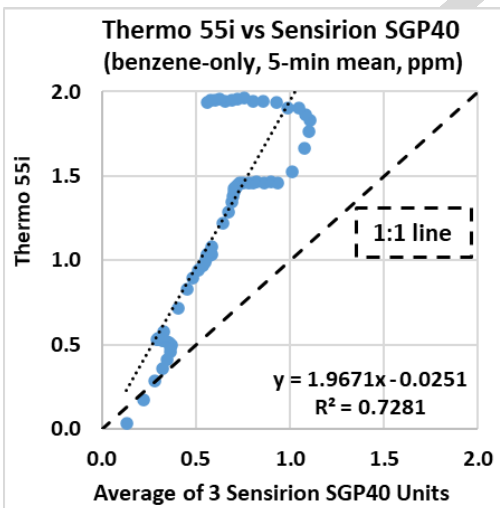
Final Ramp

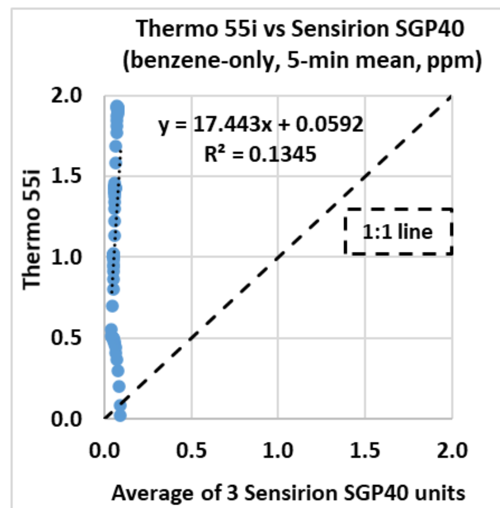
Low Ramp



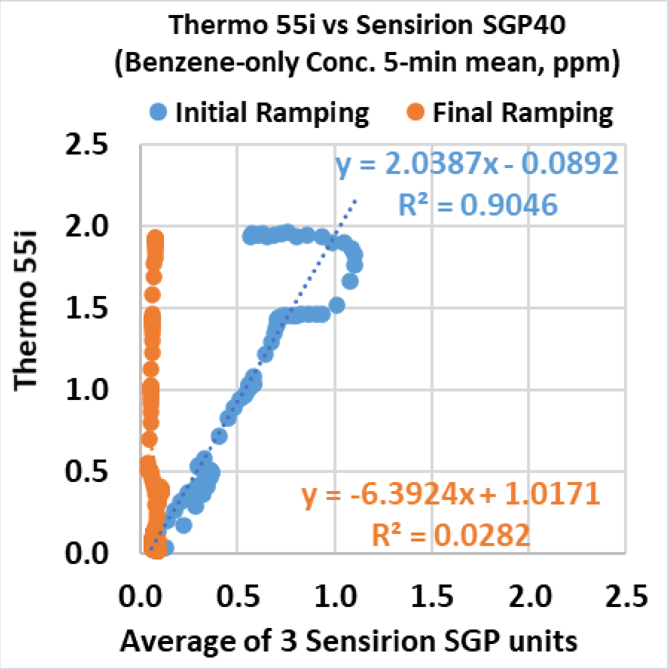

High Ramp



# Short-Term Sensor Response Change: Benzene-only

- Short-term sensor response change is characterized as the change in reference-sensor regression between the initial and final concentration ramping experiments




- The sensors tracked the Benzene-only concentrations as measured by the reference instruments in the initial ramping but did not track Benzene-only concentrations in the final ramping. The sensor response was less sensitive to benzene-only concentration variations in the final concentration ramping than in the initial ramping.

# Summary Statistics - Benzene-only

## Initial Ramping

| Sensors | | | | | Thermo 55i | | | GC-FID | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Nominal VOC Conc., ppm** | Avg, ppm | Precision, % | IMV, % | SDL, ppm | Ref avg, ppm | Sensor Bias Error, ppm | Sensor Accuracy, % | Ref avg, ppm | Sensor Bias Error, ppm | Sensor Accuracy, % |
| **0.015** | 0.08 | 99.6 | 8.5 | Unit d72: 0.05-0.17<br>Unit 302: 0.04-0.12<br>Unit c70: 0.04-0.11 | 0.04 | 0.04 | -0.2 | 0.02 | 0.06 | -283.8 |
| **0.05** | 0.06 | 99.4 | 10.6 | | 0.08 | -0.01 | 82.1 | 0.05 | 0.01 | 69.6 |
| **0.1** | 0.07 | 98.7 | 14.2 | | 0.13 | -0.06 | 55.6 | 0.09 | -0.02 | 79.9 |
| **0.4** | 0.30 | 99.6 | 18.9 | | 0.40 | -0.10 | 74.0 | 0.32 | -0.01 | 95.8 |
| **0.5** | 0.30 | 99.5 | 37.2 | | 0.53 | -0.23 | 56.3 | | | |
| **1.0** | 0.57 | 99.8 | 21.3 | | 1.04 | -0.47 | 54.7 | | | |
| **1.5** | 0.87 | 98.9 | 22.7 | | 1.46 | -0.59 | 59.8 | | | |
| **2.0** | 0.60 | 99.1 | 4.4 | | 1.95 | -1.35 | 30.6 | | | |

# Summary Statistics - Benzene-only

## Final Ramping

| Sensors | | | | | Thermo 55i | | | GC-FID | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Nominal VOC Conc., ppm** | Avg, ppm | Precision, % | IMV, % | SDL, ppm | Ref avg, ppm | Sensor Bias Error, ppm | Sensor Accuracy, % | Ref avg, ppm | Sensor Bias Error, ppm | Sensor Accuracy, % |
| **0.015** | 0.06 | 99.6 | 10.6 | Unit d72: 0.20-0.67<br>Unit 302: 0.05-0.15<br>Unit c70: 0.05-0.16 | 0.03 | 0.03 | -10 | 0.01 | 0.05 | -253.3 |
| **0.05** | 0.06 | 99.5 | 14.1 | | 0.07 | -0.01 | 87.1 | 0.04 | 0.02 | 53.1 |
| **0.1** | 0.08 | 98.5 | 24.0 | | 0.12 | -0.05 | 60.8 | 0.08 | -0.01 | 91.0 |
| **0.4** | 0.10 | 99.4 | 41.0 | | 0.39 | -0.29 | 26.0 | 0.29 | -0.19 | 35.7 |
| **0.5** | 0.04 | 99.3 | 9.6 | | 0.51 | -0.47 | 8.5 | | | |
| **1.0** | 0.05 | 99.6 | 34.8 | | 1.01 | -0.96 | 5.3 | | | |
| **1.5** | 0.06 | 99.4 | 43.7 | | 1.44 | -1.37 | 4.2 | | | |
| **2.0** | 0.07 | 99.4 | 52.7 | | 1.93 | -1.85 | 3.9 | | | |

# Discussion

- **Data Recovery:** The Sensirion SGP40 sensors showed 100% data recovery for all experiments.
- **Intra-model variability:** low to high variability was observed among the Sensirion SGP40 sensors for all experiments.
- **Phase 1: Transient Plume Detection**
  - The sensors responded to 100% of the plumes and responded to the VOC peaks as fast as the Thermo 55i detected the peaks; there was effectively no measurable time delay in plume detection by the Sensirion SGP40 sensors.
- **Phase 2**: **Initial Concentration Ramping**
  - ***Coefficient of Determination – VOC Blend***: The Sensirion SGP40 sensors showed very strong and no correlation/linear response with the corresponding reference low and high VOC ramping data, respectively ($R^2$ ~ 0.91 for low VOC conc. ramping and $R^2$ ~ 0.01 for high VOC conc. ramping).
  - ***Coefficient of Determination – Benzene-only***: The Sensirion SGP40 sensors showed strong correlation/linear response with both the corresponding reference low and high benzene-only ramping data ($R^2$ ~ 0.89 for low VOC conc. ramping and $R^2$ ~ 0.73 for high VOC conc. ramping).
- **Phase 3: Effect of Temperature and RH**
  - ***Precision:*** The precision of the Sensirion SGP40 sensors was ~97-100% for temperature and RH interference testing.

# Discussion

- **Phase 3: Effect of Temperature and RH**
  - ***Climate susceptibility:*** The Sensirion SGP40 sensors initially showed an increase in VOC concentration as RH increased from 20% to 40%, and then showed decreasing VOC concentrations as RH further increased to 65% and 80%. A temperature change at constant RH setpoint appears to cause sensor response to move in the same direction, i.e. the sensors' VOC reading increases when temperature increases and vice versa, after steady-state temperature and RH conditions are realized. A temperature change at constant AH setpoint does not appear to cause sensor response to change much, after steady-state temperature and AH conditions are realized. However, sensor response does change in the same direction as temperature during transient temperature and AH periods.
- **Phase 4: Effects of Gaseous Interferents**
  - **Ozone**
    - ***Precision:*** High precision (~100%) was observed among the sensors.
    - ***Responses to Ozone:*** The Sensirion SGP40 sensors VOC concentrations decreased as ozone concentration increased from background value of 0.2 to ~ 400 ppb.
  - **CO**
    - ***Precision:*** High precision (~100%) for sensor raw signal was observed among the sensors.
    - ***Responses to CO:*** The Sensirion SGP40 sensors showed a slight decrease in VOC concentrations as CO increased from a background value of ~1.7 ppm to ~8 ppm.
  - **$CO_2$**
    - ***Precision:*** High precision (~100%) for sensor raw signal was observed among the sensors.
    - ***Responses to $CO_2$:*** The Sensirion SGP40 sensors' VOC concentration remained constant as $CO_2$ increased from a background value of ~353 ppm to ~1000 ppm then decreased as $CO_2$ increased from 1000 ppm to 8000 ppm.

# Discussion

- **Phase 5: Outdoor Simulation**
  - The sensors did not track well with the Thermo 55i when exposed to a combination of T, RH, ozone and VOC concentrations.
  - **AH** explained ~ 21% of the variance on average, at least for expected ambient conditions when VOC T, AH, and ozone are included in the ANOVA statistical test; followed by **ozone** (~8%) and **T** (~ 4%). **VOC** explained < 1% of the variance on average.
- **Phase 6**: **Final Concentration Ramping**
  - ***Coefficient of Determination – VOC Blend***: The Sensirion SGP40 sensors showed very strong correlation/linear response with the corresponding reference VOC ramping data, respectively ($R^2$ ~ 0.98 for low VOC conc. ramping and $R^2$ ~ 0.92 for high VOC conc. ramping).
  - ***Coefficient of Determination – Benzene-only***: The Sensirion SGP40 sensors showed strong and very weak correlation/linear response with the corresponding reference low benzene only ramping ($R^2$ ~ 0.73) and high benzene only data ($R^2$ ~ 0.13), respectively.
  - ***Short-term Sensor Response:*** In general, the sensors underestimated the VOC concentrations as measured by the VOC reference instrument. The sensors showed stronger correlations with the reference instrument at the final ramping than the initial ramping for the VOC ramps. For benzene-only ramps, The sensors tracked the Benzene-only concentrations as measured by the reference instruments in the initial ramping but did not track Benzene-only concentrations in the final ramping. The sensor response was less sensitive to VOC/benzene-only concentration variations in the final concentration ramping than in the initial ramping. The sensor baseline may have shifted to a lower VOC/benzene-only concentration baseline in the final concentration ramping.