Laboratory Evaluation: PurpleAir PA-II-FLEX*

South Coast AQMD

AQ-SPEC
Air Quality Sensor Performance Evaluation Center

*Manufacturer now calls this product the PurpleAir Flex Air Quality Monitor

Background

Five **PurpleAir PA-II-FLEX** sensors (units IDs: 680_1, 680_3, 688_1, 688_2, 688_3) 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**).

<u>PurpleAir PA-II-FLEX (*5 units tested*)</u>:

- VOC Sensor – Metal Oxide (PurpleAir PA-II-FLEX, non-FEM)
  - Sensor outputs unitless "Experimental VOC IAQ" values, not ppm
  - VOC operable range: unknown
  - Limit of detection: unknown
  - Measurement interval: 2-min
  - Indoor air quality monitoring
- Measures: VOC (Index; not in ppm)
- Unit cost: ~$289
- Units IDs: 680_1, 680_3, 688_1, 688_2, 688_3

PurpleAir PA-II-FLEX

Thermo 55i

GC-FID

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

- **<u>Thermo Fisher 55i</u>**
  - Measures: methane (CH_4) and total 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 PurpleAir PA-II-FLEX and Data Handling

- The PurpleAir PA-II-FLEX sensors do not report absolute VOC concentrations in ppm; the sensors only report a unitless “Experimental VOC (Bosch Static IAQ)” value which ranges from 0 to 500. Hereafter we will refer to this value as a “VOC index”.

- There were two variations of PurpleAir PA-II-FLEX sensors tested in this evaluation, and the results are presented with respect to the specific raw VOC sensor throughout this report:
    - One set with an <u>older</u> Bosch BME680 T/RH/VOC sensor (units 680_1 and 680_3); and
    - One set with a <u>newer</u> Bosch BME688 T/RH/VOC sensor (Units 688_1, 688_2, 688_3)

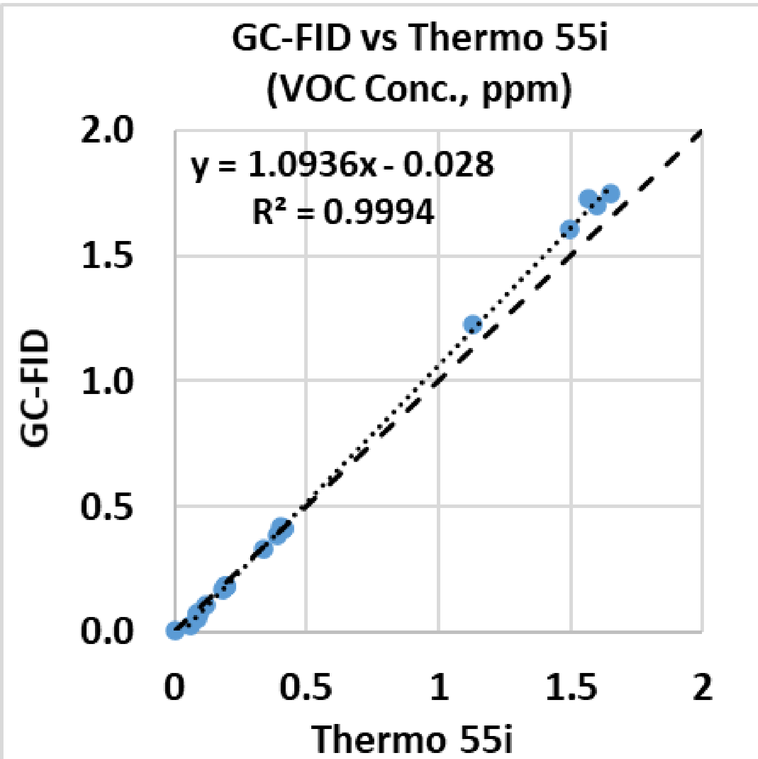
- Accuracy, MAE, MBE, and sensor’s detection limit cannot be evaluated because the sensors only report VOC index values

- *Statement by PurpleAir: The data as presented comes from the PurpleAir 7.04 firmware specific implementation of the BME680/688 sensor. It is by no means the only way to interpret or configure the BME680/688 sensors. PurpleAir uses a basic interface with the BME680/BME688 sensors and does not implement "AI gas training".*

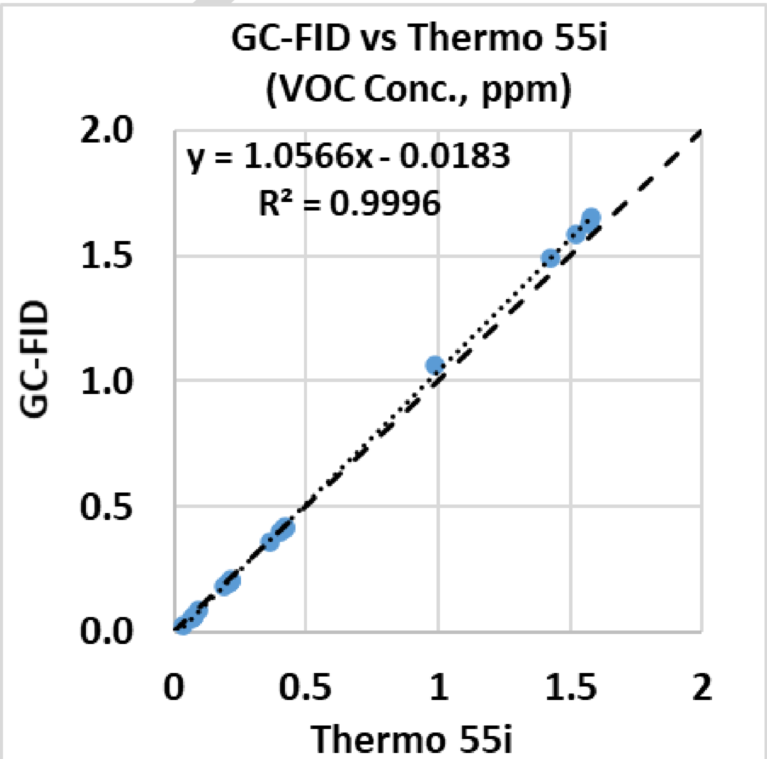
VOC Blend Results

GC-FID vs Thermo 55i: VOC Blend

Beginning of Evaluation



End of Evaluation

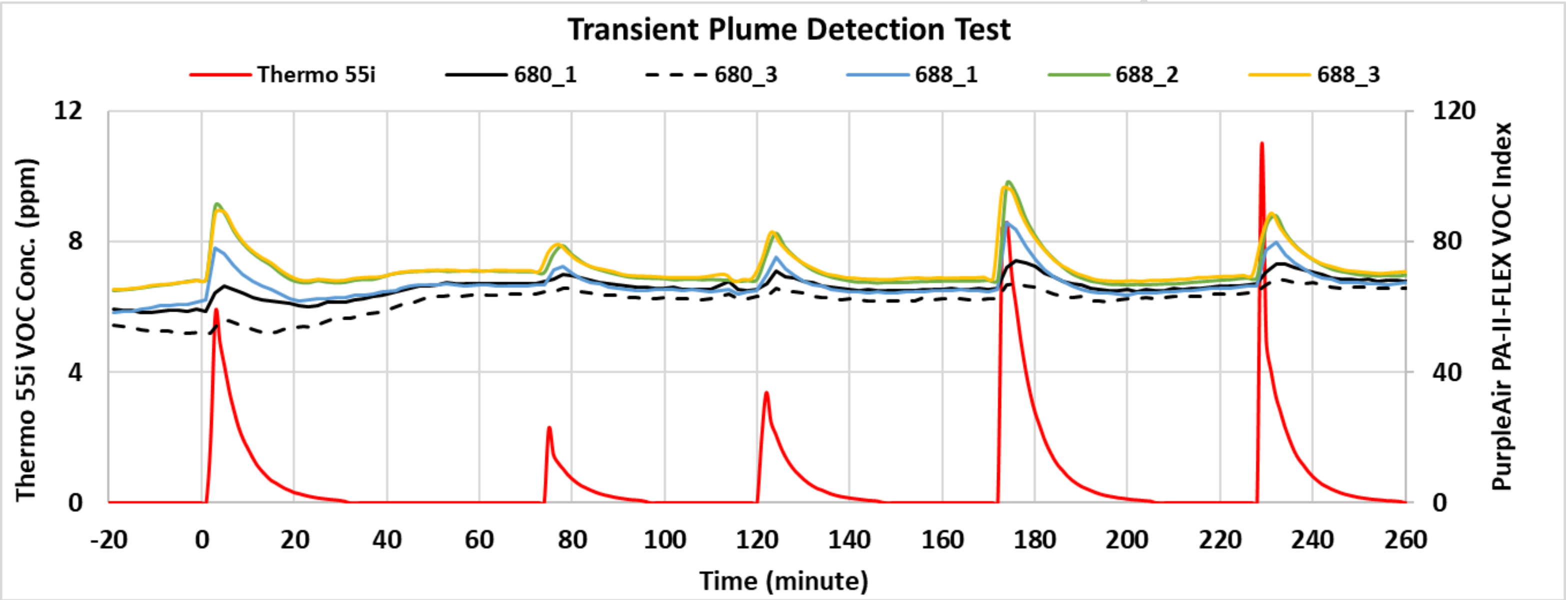


- Very strong correlations between the Thermo 55i and GC-FID ($R^2 > 0.99$).
- The two reference instruments reported similar VOC concentrations at both the beginning and the end of evaluation.

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 • % of peak detection

PurpleAir PA-II-FLEX vs Thermo 55i



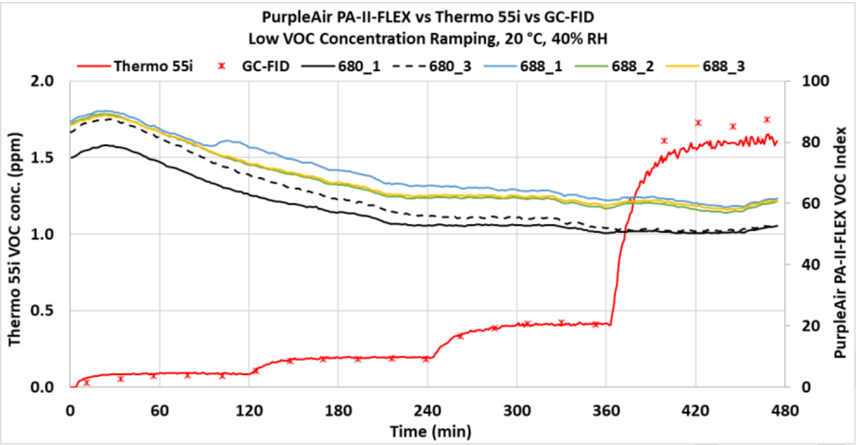
- The PurpleAir PA-II-FLEX sensors responded to 100% of the VOC peaks generated.
- The PurpleAir PA-II-FLEX sensors showed ~ 2-3 minutes delay in plume detection compared to the Thermo 55i.

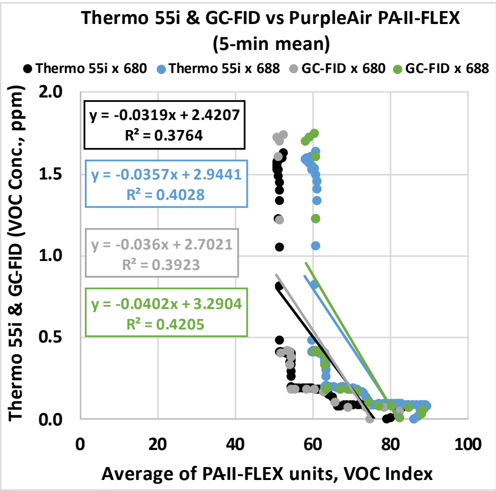
Phase 2: Initial Concentration Ramping

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

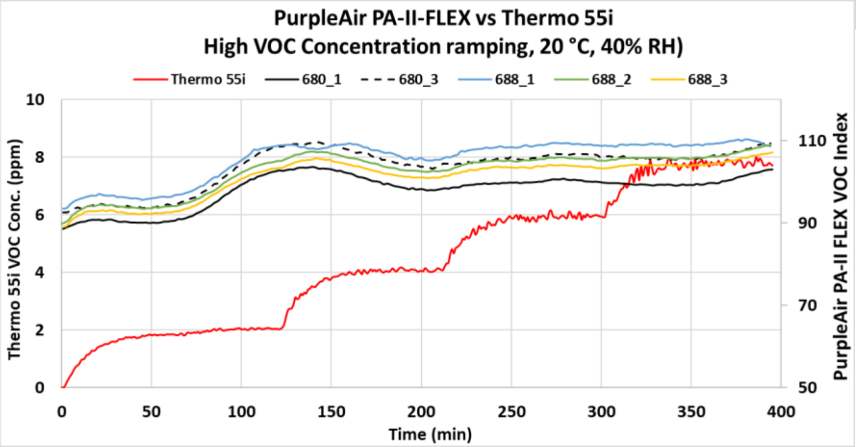
PurpleAir PA-II-FLEX vs Thermo 55i vs GC-FID

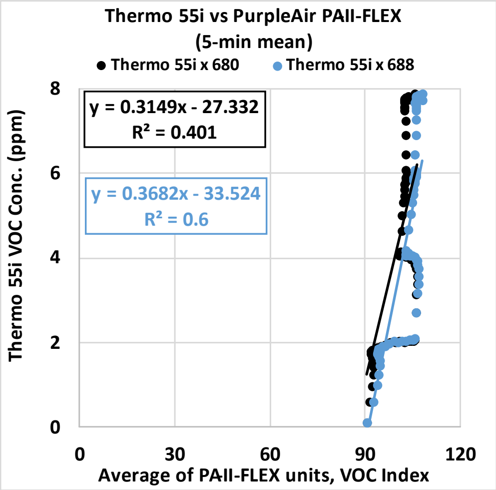
Low Ramp





High Ramp



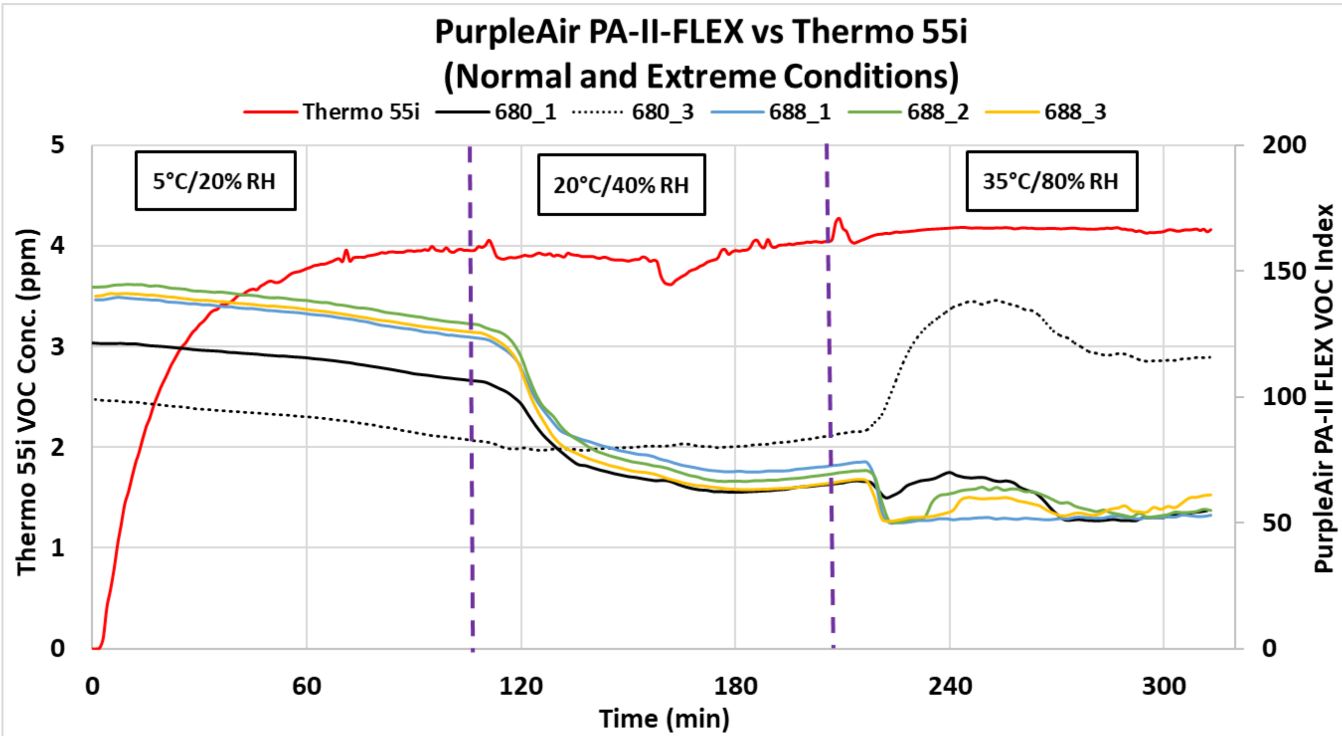


- The PurpleAir PA-II-FLEX sensors did not track the VOC concentration variation as recorded by the reference instruments.
- The PurpleAir PA-II-FLEX sensors showed negative correlations in the low concentration ramp and weak to moderate correlations ($0.40 < R^2 < 0.61$) in the high concentration ramp against the reference instruments
- BME680 and BME688 sensors showed similar relative behaviors

Phase 3: Effect of Temperature and Relative Humidity

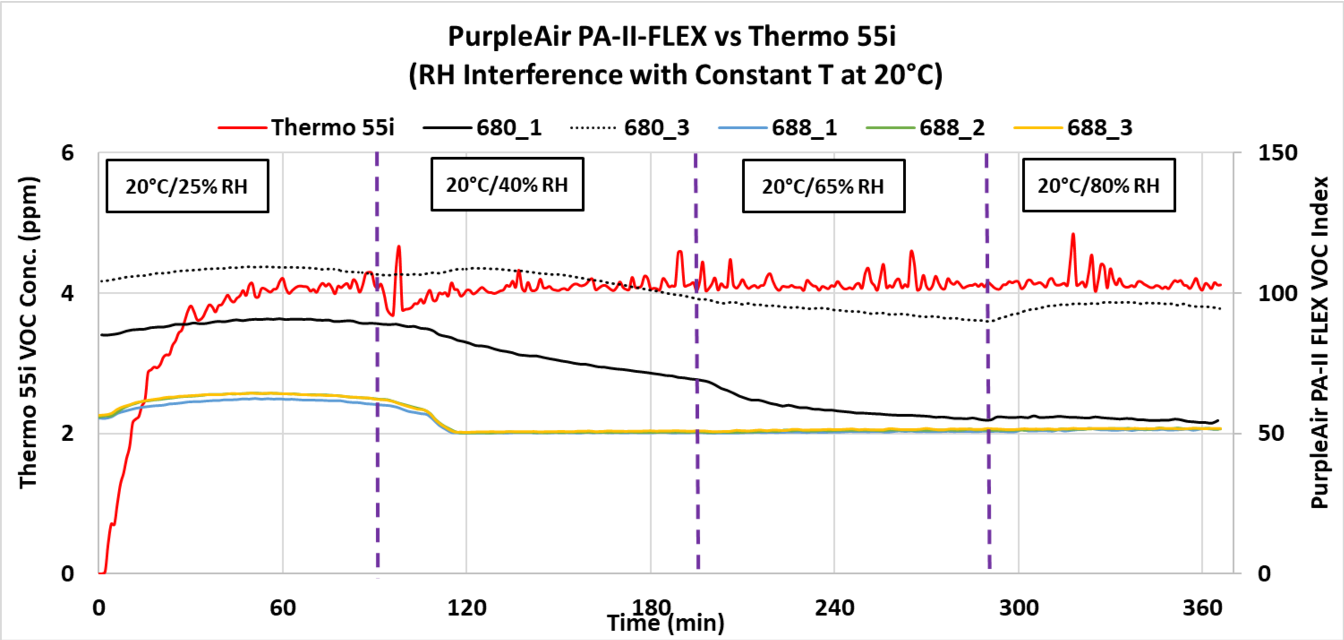
Testing Phase #3	Method	Parameters Evaluated
Effect of Temperature and RH	• Extreme Conditions: hot/humid; cold/dry and VOC = 4ppm • RH interference: 15% to 80% RH; T = 20°C and VOC = 4 ppm • T interference: 20°C to 10°C to 30°C to 20°C; RH = 40% and VOC = 4 ppm • T interference: 20°C to 10°C to 30°C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

Normal and Extreme Conditions



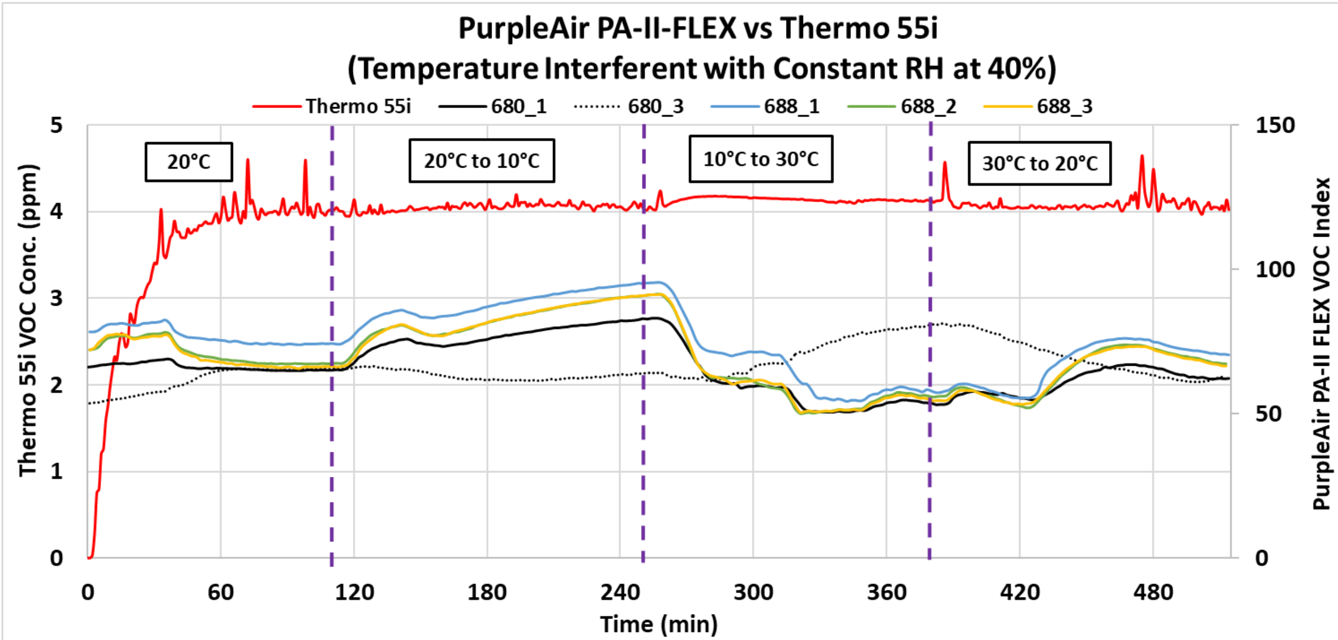
- The PurpleAir PA-II-FLEX sensors (except Unit 680_3) showed a significant decrease in mean VOC index values as T/RH increased from 5°C/20% RH to 20°C/40% RH, and then decreased further as temperature/RH was further increased to 35°C/80% RH. Unit 680_3 showed a slight increase in VOC index values as T/RH increased from 5°C/20% RH to 20°C/40% RH, and a more significant increased as temperature/RH was further increased to 35°C/80% RH.

RH Interference



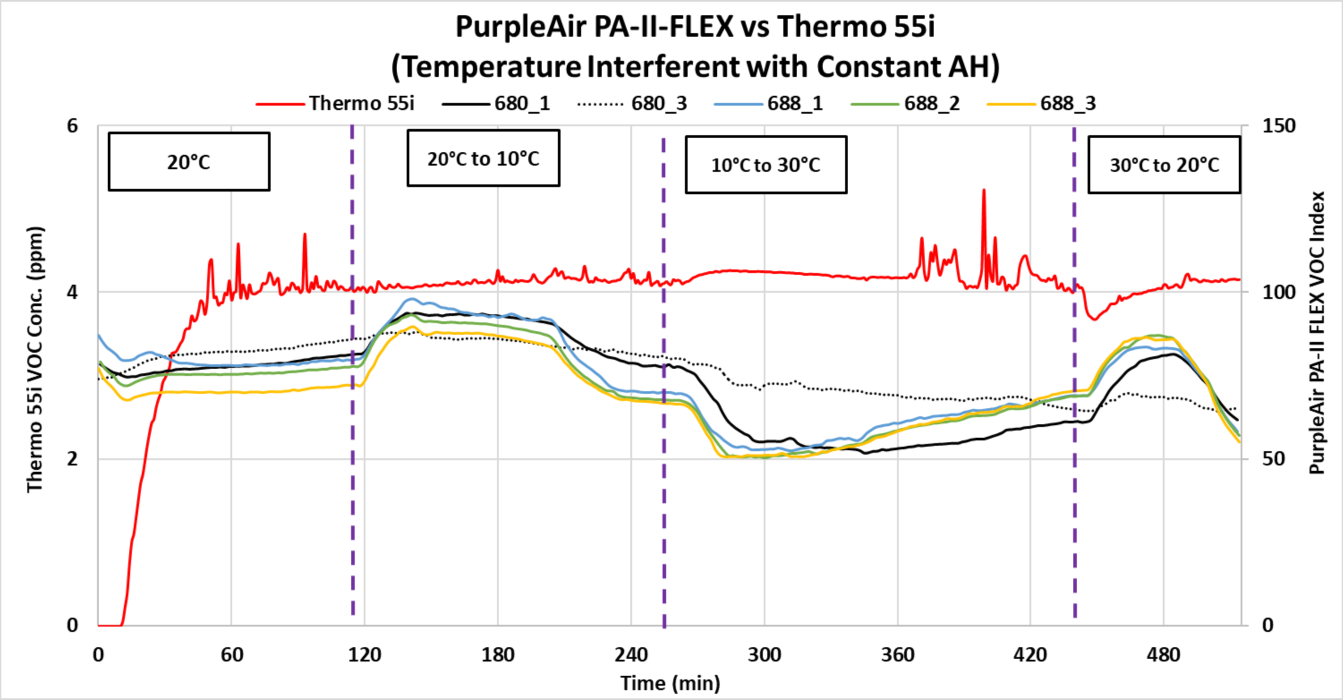
- RH had minimal effect on the VOC concentrations measured by the Thermo 55i as RH increased from 20% to 80%, with temperature held constant at 20°C.
- The PurpleAir PA-II-FLEX sensors' VOC index values decreased as RH increased from 20% to 40% and then remained stable for the BME688 sensors at subsequently higher RH levels. The VOC index values decreased as RH increased from 20% to 80% for the BME680 sensors, except that Unit 680_3 showed a slight increase as RH increased from 65% to 80%.

Temperature Interference at Constant RH



- The Temperature interference test was conducted at constant RH of 40%.
- T had minimal effect on the VOC concentrations measured by the Thermo 55i.
- A temperature change at constant RH appears to cause sensor response to move in the opposite direction, i.e. the sensors' VOC reading increases when temperature decreases and vice versa, after steady-state temperature and RH conditions are realized; except for Unit 680_3, whose response seemed to move in the same direction as temperature changes.

Temperature Interference at Constant Absolute Humidity (AH)

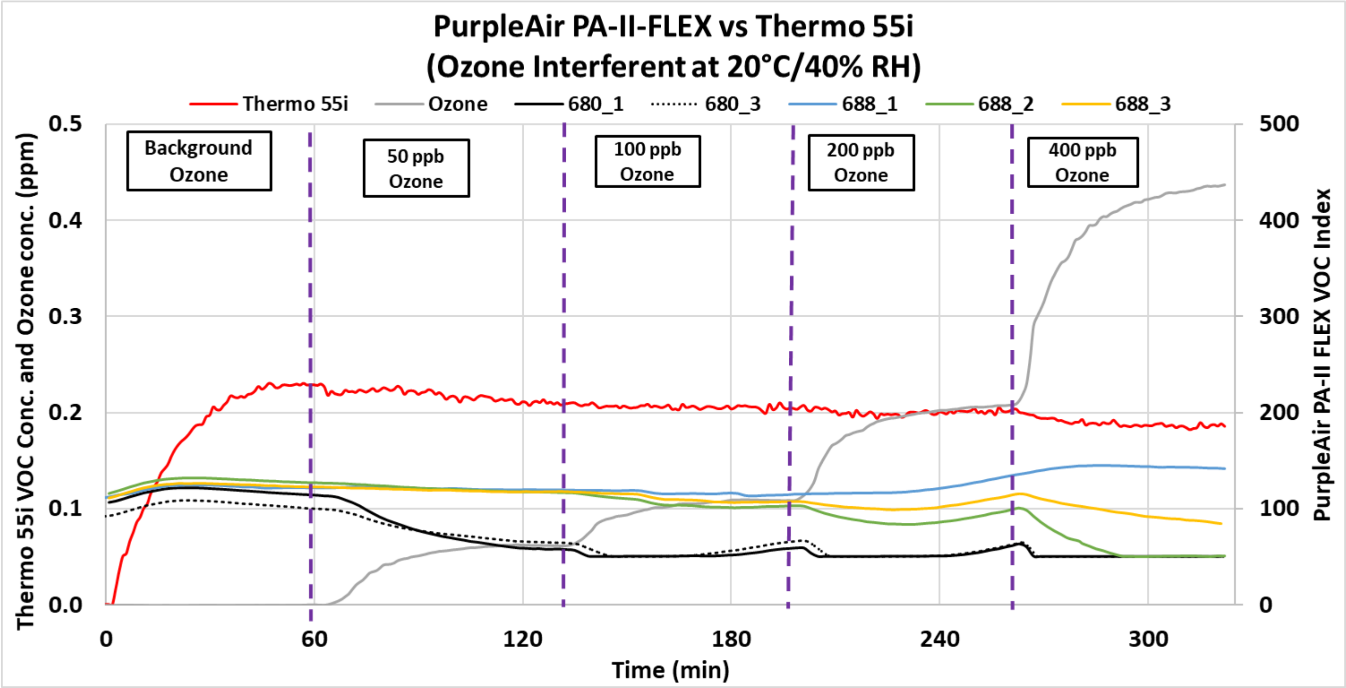


- The Temperature interference at constant AH setpoint was conducted at the moisture content corresponding to 20°C and 40% RH.
- T had minimal effect on the average VOC concentrations measured by the Thermo 55i.
- A temperature change at constant AH setpoint appeared to cause the sensor response to change in the opposite direction of temperature change. The change in sensor response was not as significant in Unit 680_3 compared to the other sensor units.

Phase 4: Effect of Gaseous Interferents

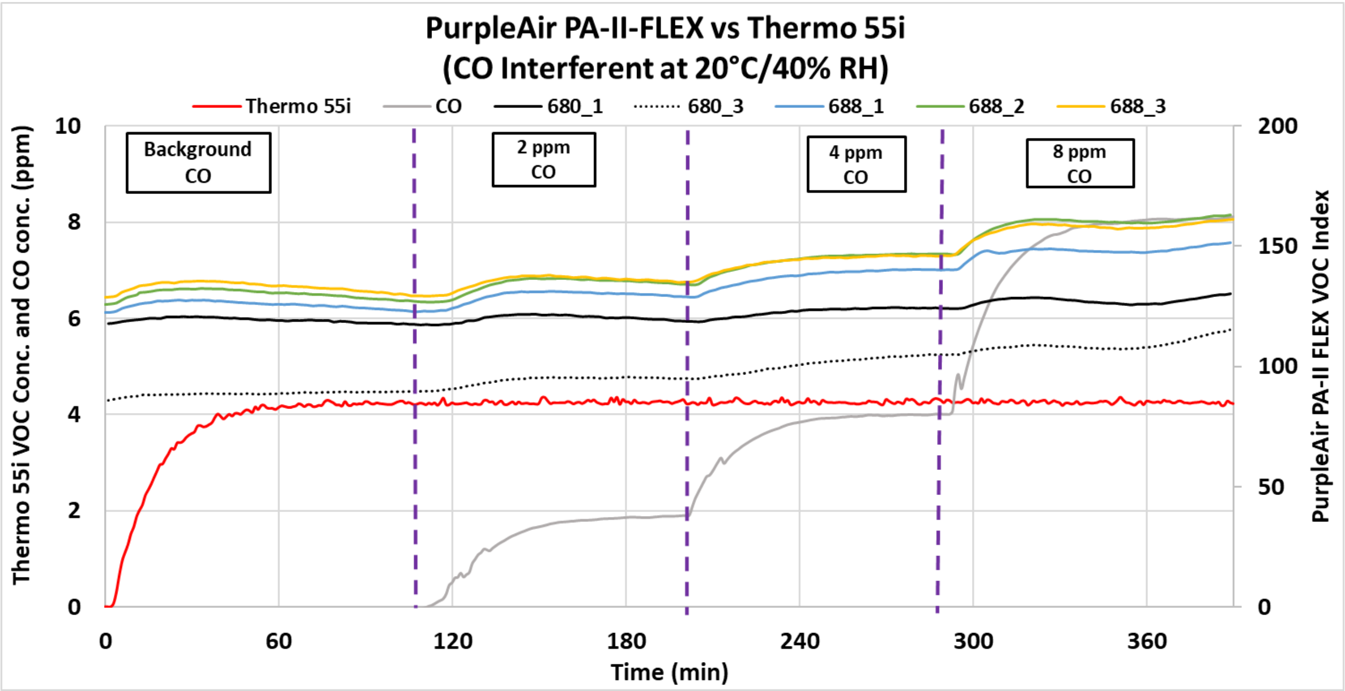
Testing Phase #4	Method	Parameters Evaluated
Effect of gaseous interferents	• Ozone (1 to 400 ppb; 20 °C/40% RH and VOC = 200 ppb) • Carbon Monoxide (background to 8 ppm; 20 °C/40% RH and VOC = 4 ppm) • Carbon Dioxide (background to 8000 ppm; 20 °C/40% RH and VOC = 4 ppm)	• Response to interferents,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

Ozone Interferent



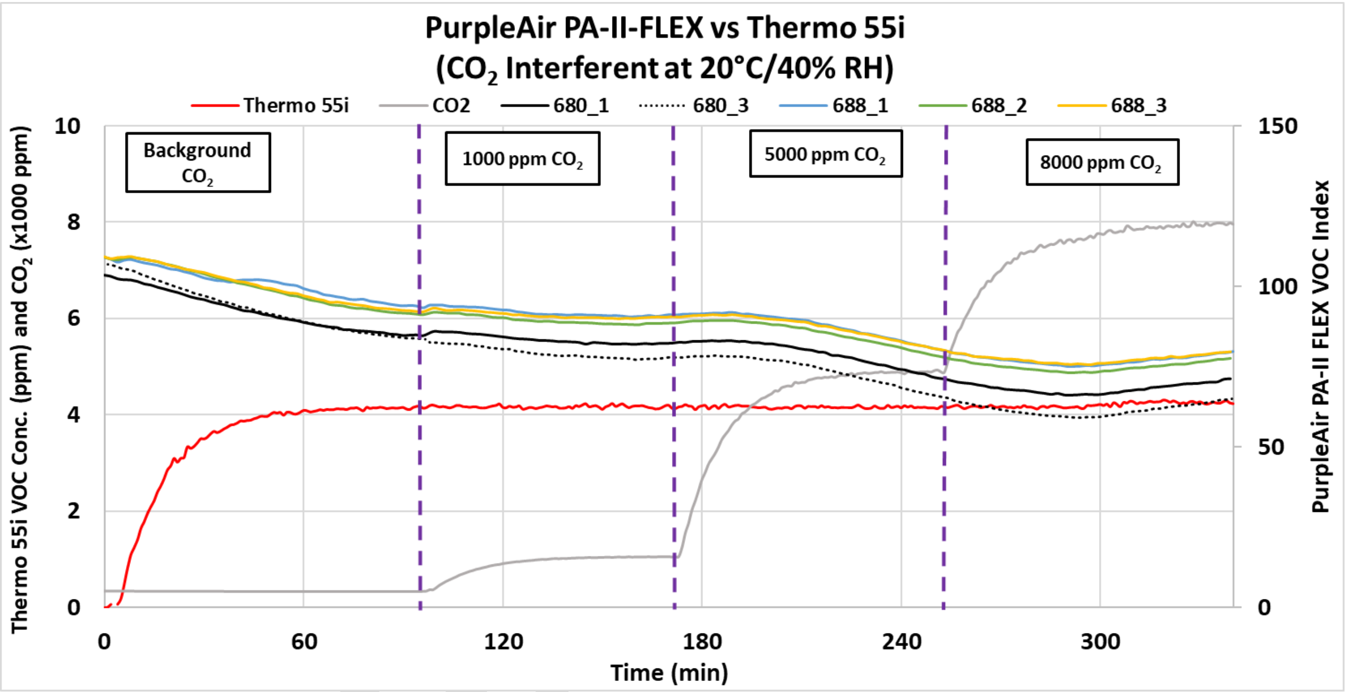
- Ozone interferent test: sensors were subjected to increasing ozone concentration from background level to 400 ppb while holding VOC concentration constant at 0.2 ppm.
- Ozone had minimal effect on the VOC concentrations measured by the Thermo 55i.
- The PurpleAir PA-II-FLEX sensors VOC concentrations decreased significantly as ozone concentration increased from background value of 0.2 to ~ 400 ppb for the BME680 sensors. the BME688 sensors did not show significant change in response until ozone concentrations reached 200 ppb and the sensors decreased significantly at 400 ppb ozone for Units 688_2 and 688_3 but not unit 688_1.

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 PurpleAir PA-II-FLEX sensors' VOC index values tracked CO concentrations as CO increased from background to ~8 ppm.

CO_2 Interferent

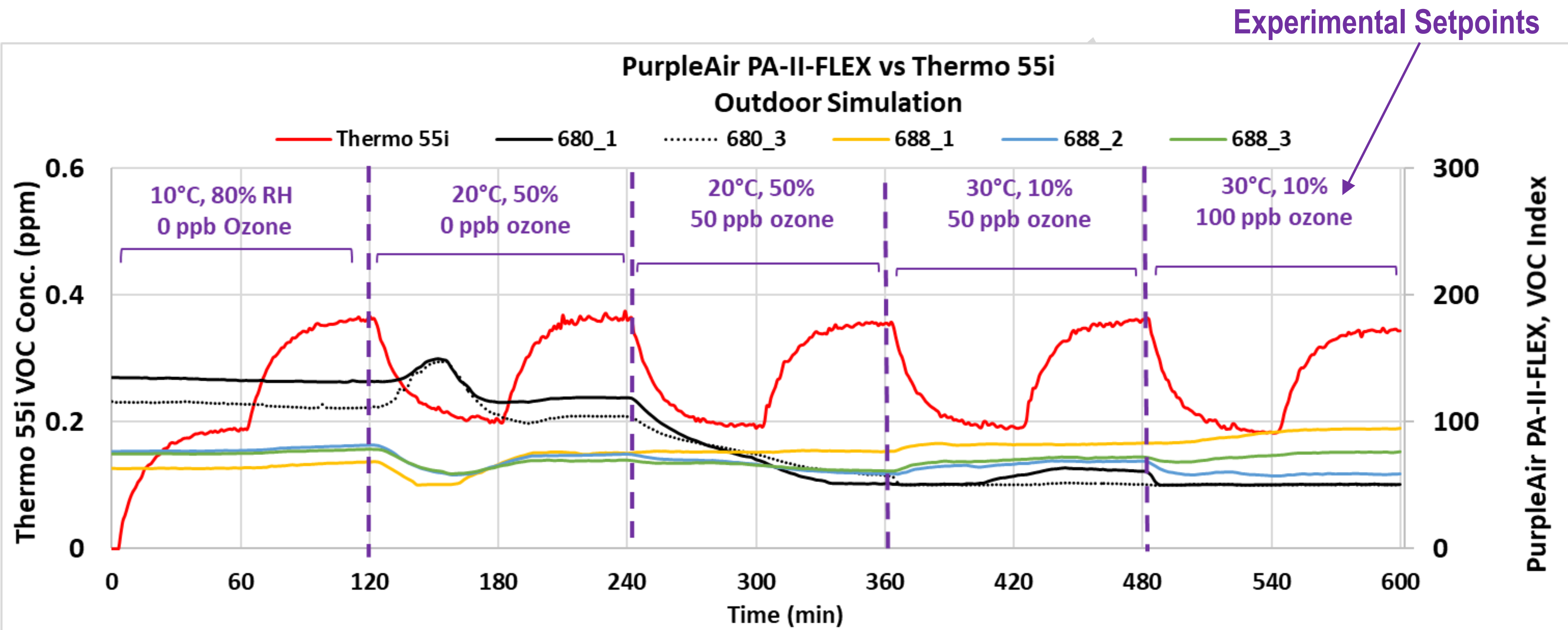


- CO_2 interferent test: sensors were subjected to increasing CO_2 concentration from background level to 8 ppm while holding VOC concentration constant at ~4 ppm.
- CO_2 had minimal effect on the VOC concentrations measured by the Thermo 55i.
- The PurpleAir PA-II-FLEX sensors' VOC index values decreased as CO_2 increased from a background value of ~340 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%)	• Analysis of Variance (ANOVA)

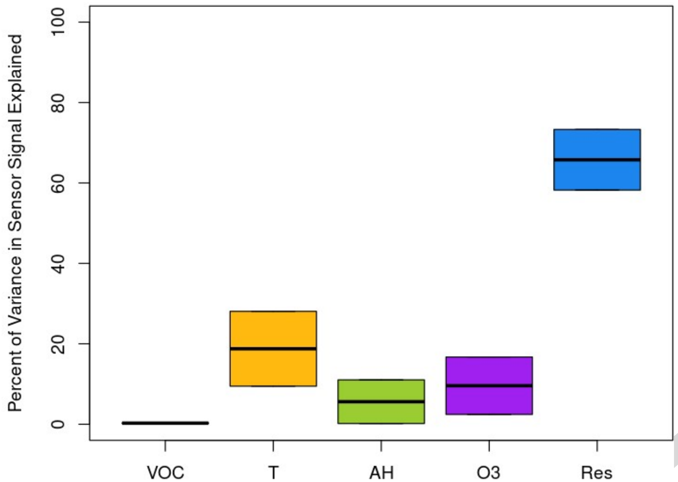
Outdoor Simulation



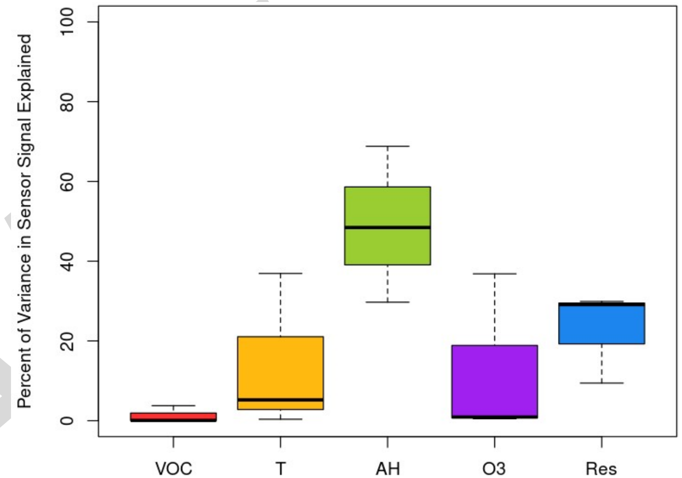
- The sensors generally did not track well with the VOC concentration variation as recorded by Thermo 55i.

Outdoor Simulation

ANOVA Statistical Test for PA-II-FLEX containing BME680 sensors



ANOVA Statistical Test for PA-II-FLEX containing BME688 sensors



	Variance explained by explanatory variables, %				
	REF	T	AH	OZONE	RES
680_1	0.3	**9.5**	0.2	**16.7**	73.3
680_3	0.2	**28.1**	**11.0**	2.4	58.2
688_1	3.8	**36.9**	**29.7**	0.5	29.1
688_2	0.1	5.2	**48.4**	**36.8**	9.4
688_3	0.0	0.4	**68.8**	0.9	29.9

Notes:
"REF" is the Thermo 55i reference VOC monitor reading
"RES" is the residual, or variance that is not explained by the other variables

- VOC concentration as measured by the Thermo 55i explained < 1% of the PA-II-FLEX VOC index variance on average.
- Overall, **T (~ 19% on average)** appears to be the more important driver for VOC Index response in the BME680 sensors, while **AH (~ 50% on average)** was more important for BME688 sensors. **Ozone** in some cases also accounts for a significant amount of the variance, as seen for Units 680_1**(16.7%)** and 688_2 **(36.8%)**.

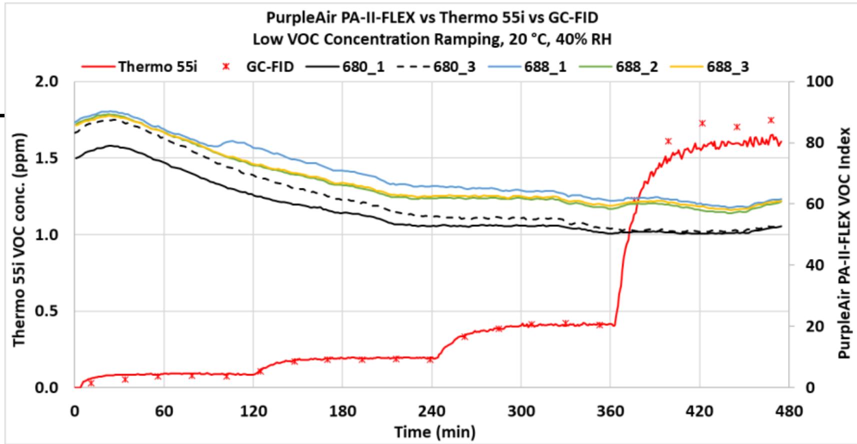
Phase 6: Final Concentration Ramping

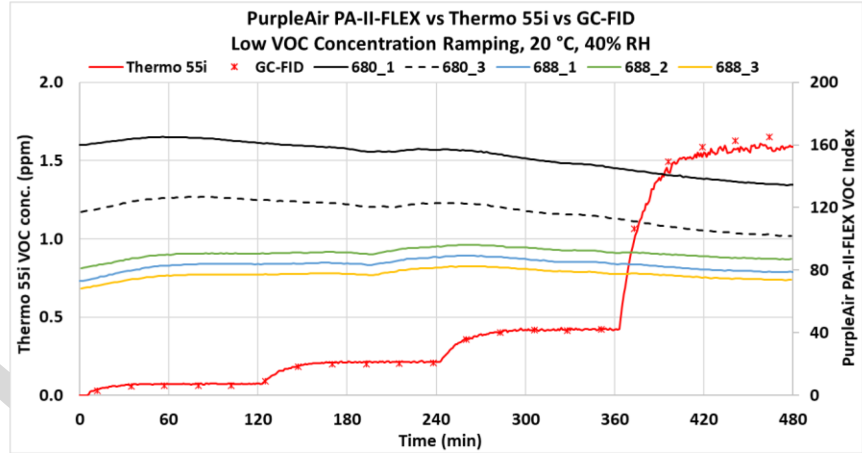
Testing Phase #6	Method	Parameters Evaluated
Final Concentration Ramping	• Low conc. ramping with VOC blend (0.06 to 1.6 ppm) • High conc. ramping with VOC blend (2 to 8 ppm) • Low conc. ramping with benzene-only (0.015 to 0.4 ppm) • High conc. ramping with benzene-only (0.5 to 2 ppm)	• R^2, Precision,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

PurpleAir PA-II-FLEX vs Thermo 55i vs GC-FID

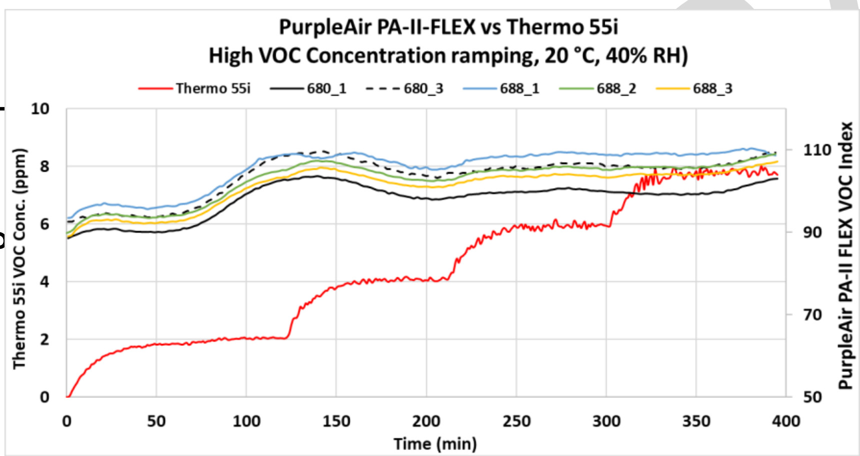
Initial Ramp | Final Ramp

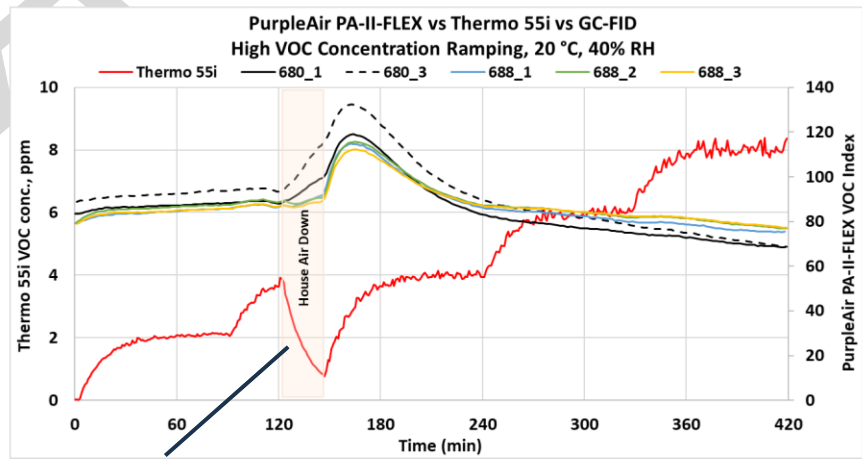
Low Ramp





High Ramp





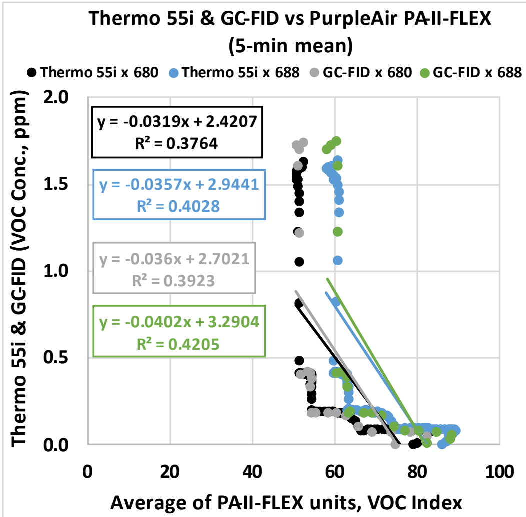
Note: VOC injection inadvertently stopped during this experiment due to temporary loss of lab air pressure. All the sensors actually reported an increase in VOC Index when the reference VOC concentrations decreased. Upon resuming VOC injection, all sensors reported an even greater increase in VOC Index initially, then eventually decreased.

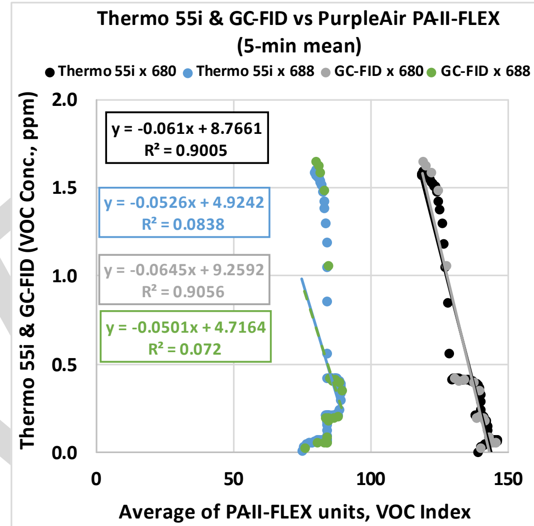
PurpleAir PA-II-FLEX vs Thermo 55i vs GC-FID

Initial Ramp

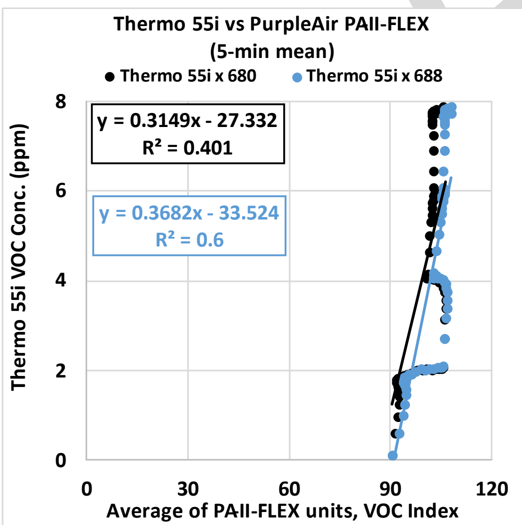
Final Ramp

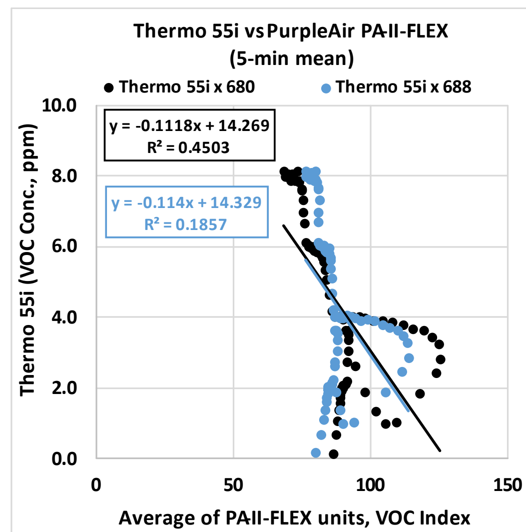
Low Ramp





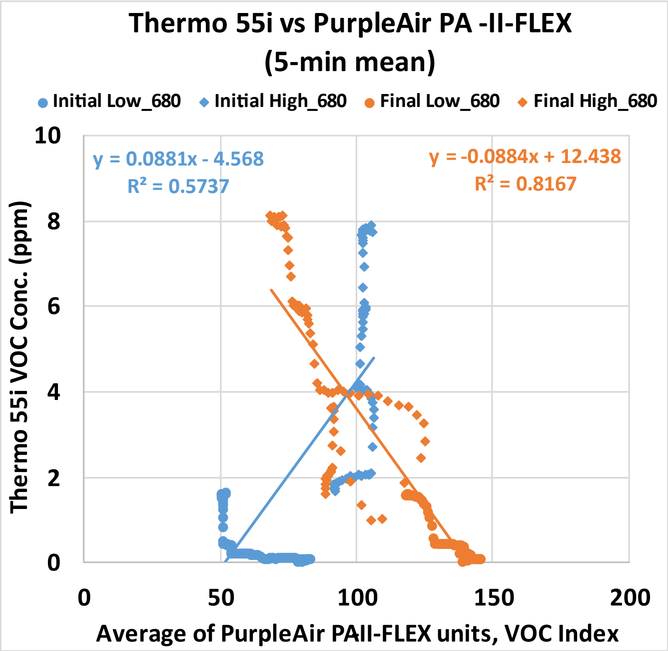
High Ramp

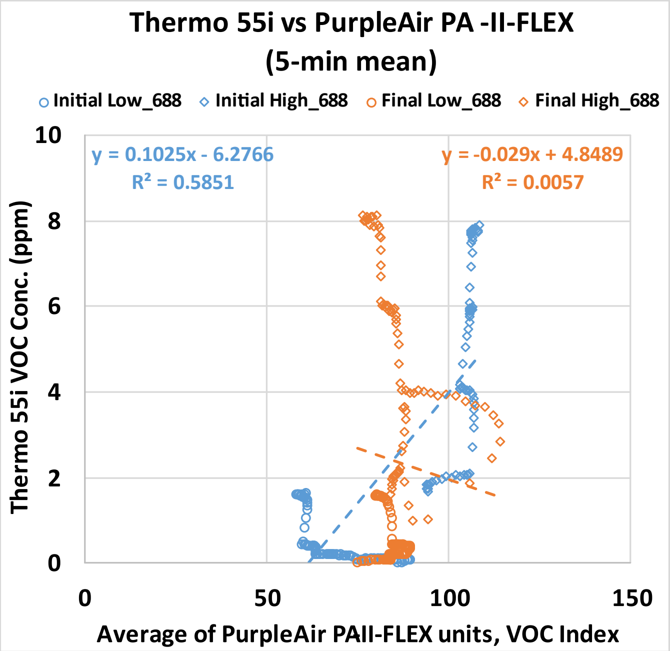




Short-Term Sensor Response Change

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





- Combining data from both low and high concentration ramps of the VOC blend, correlations of the PurpleAir PA-II-Flex units changed from positive during the initial ramps to negative in the final ramps, regardless of raw VOC sensor.

Summary Statistics

Initial Ramp

Sensors							Thermo 55i	GC-FID
Nominal VOC Conc., ppm	**Avg, VOC Index**		**Precision, %**		**IMV, %**		**Ref avg, ppm**	**Ref avg, ppm**
	680	**688**	**680**	**688**	**680**	**688**		
0.06	68.0	76.5	99.5	99.7	10.0	7.1	0.09	0.08
0.2	54.6	63.4	99.8	99.9	5.9	6.4	0.19	0.18
0.4	51.9	60.3	99.7	99.8	3.4	4.5	0.41	0.41
1.6	51.9	59.9	99.7	99.6	1.1	2.2	1.61	1.75
2	104.0	104.5	99.6	99.7	5.2	5.1	2.0	[redacted]
4	101.0	103.0	99.9	100.0	5.5	4.3	4.1	[redacted]
6	103.5	106.1	99.9	99.9	6.2	5.1	6.0	[redacted]
8	105.4	108.1	99.8	99.8	6.0	3.0	7.8	[redacted]

Summary Statistics

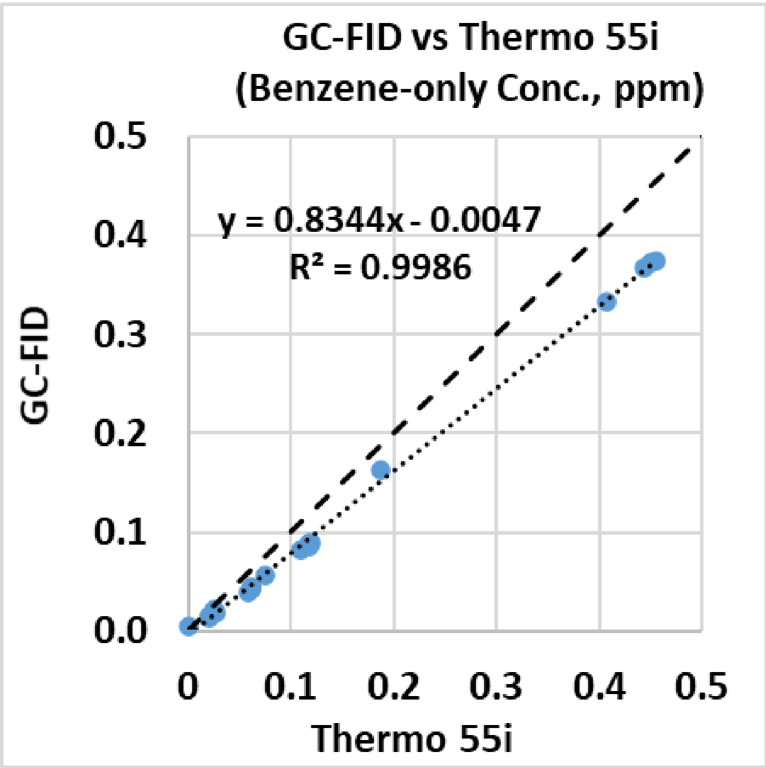
Final Ramp

Sensors							Thermo 55i	GC-FID
Nominal VOC Conc., ppm	Avg, VOC Index		Precision, %		IMV, %		Ref avg, ppm	Ref avg, ppm
	680	688	680	688	680	688		
0.06	143.8	83.8	99.9	100	25.4	16.1	0.07	0.06
0.2	139.7	87.7	99.9	99.9	24.9	15.5	0.21	0.21
0.4	130.3	85.0	99.8	99.8	24.8	16.1	0.42	0.42
1.6	118.5	79.9	99.9	100.0	27.4	16.6	1.58	1.65
2	90.7	86.0	99.9	99.9	6.2	2.0	2.1	
4	89.4	88.9	99.3	99.5	7.5	0.9	4.0	
6	77.8	82.2	99.7	99.8	5.2	2.9	6.0	
8	69.3	76.9	99.8	99.8	1.1	3.2	8.0	

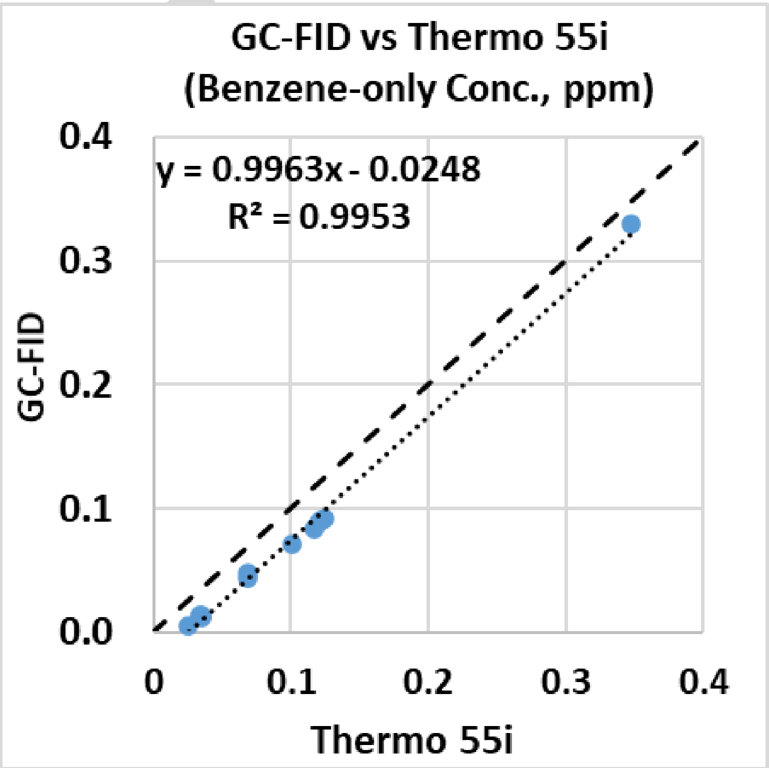
Benzene-Only Results

GC-FID vs Thermo 55i: Benzene-only

Beginning of Evaluation



End of Evaluation



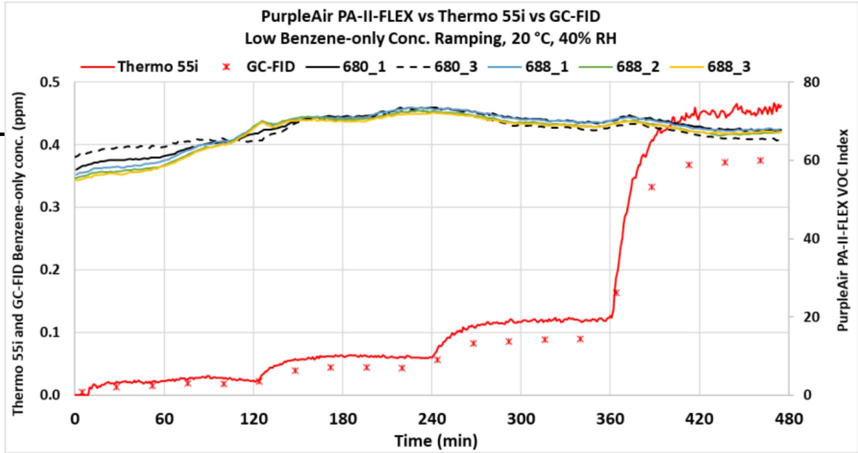
- Very strong correlations between the Thermo 55i and GC-FID ($R^2 > 0.99$).
- The two reference instruments reported similar VOC concentrations at both the beginning and the end of evaluation.

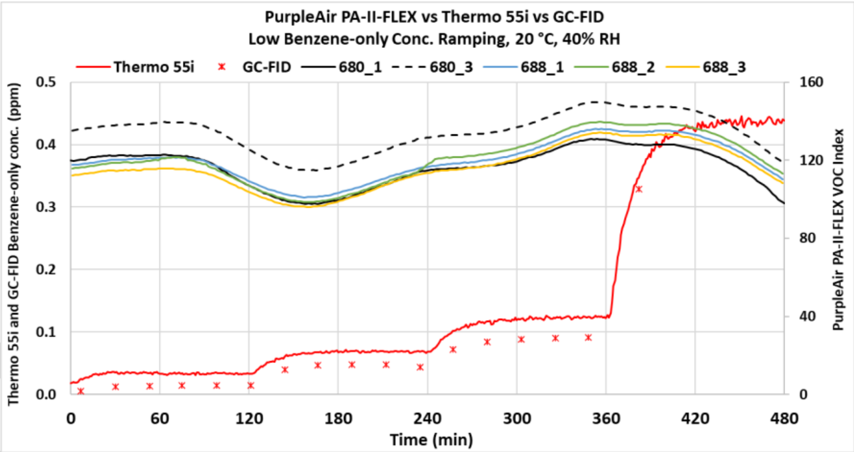
PurpleAir PA-II-FLEX vs Thermo 55i vs GC-FID

Initial Ramp

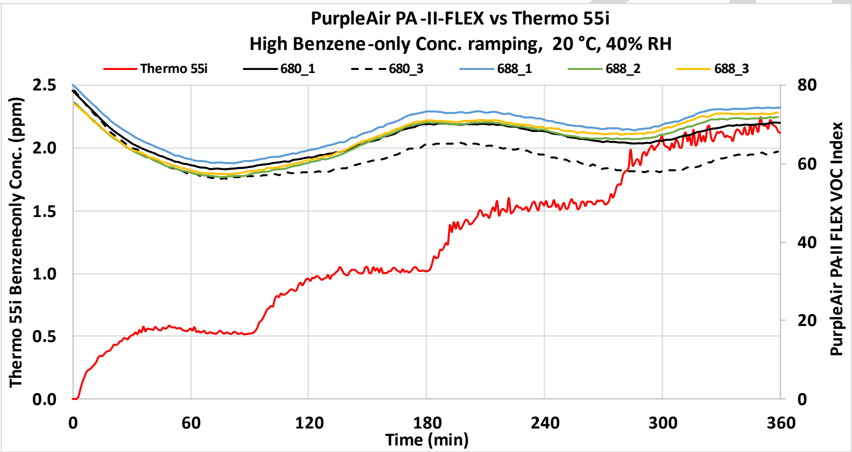
Final Ramp

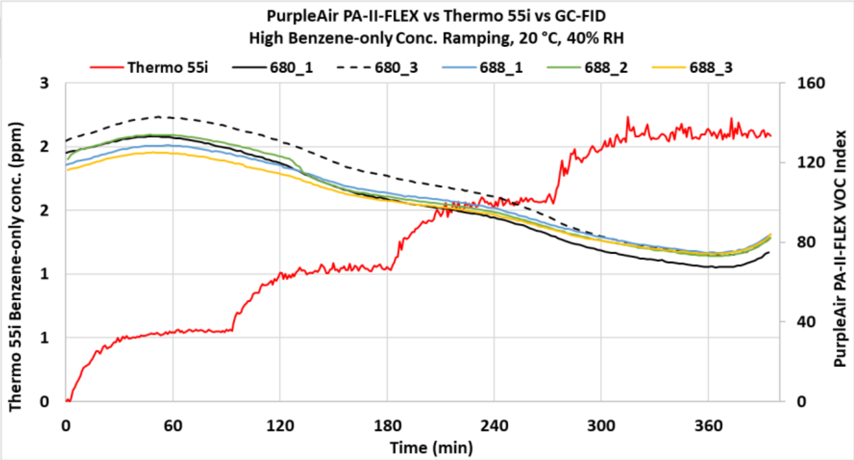
Low Ramp





High Ramp

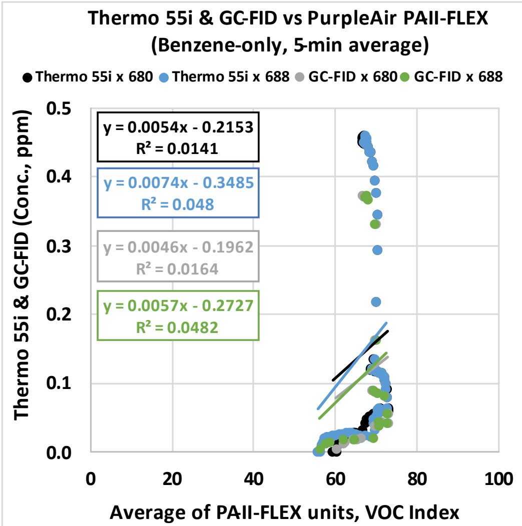


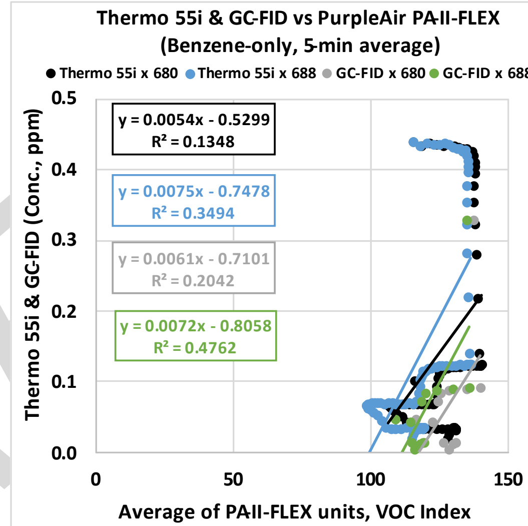


PurpleAir PA-II-FLEX vs Thermo 55i vs GC-FID

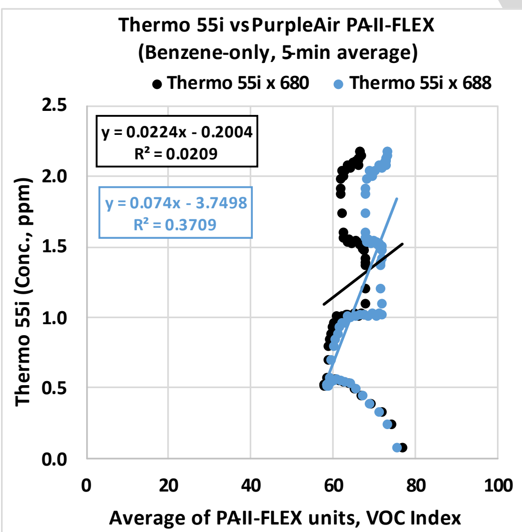
Initial Ramp | Final Ramp

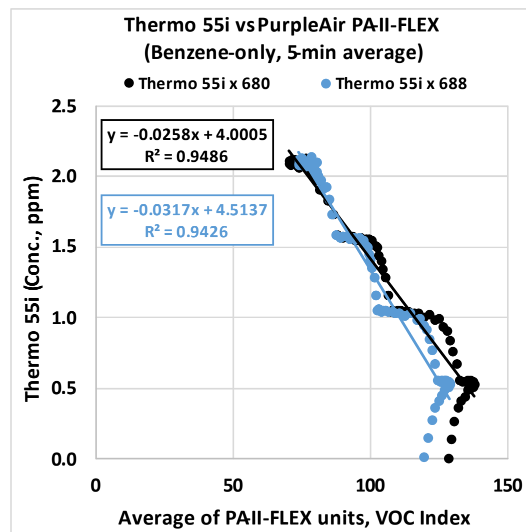
Low Ramp





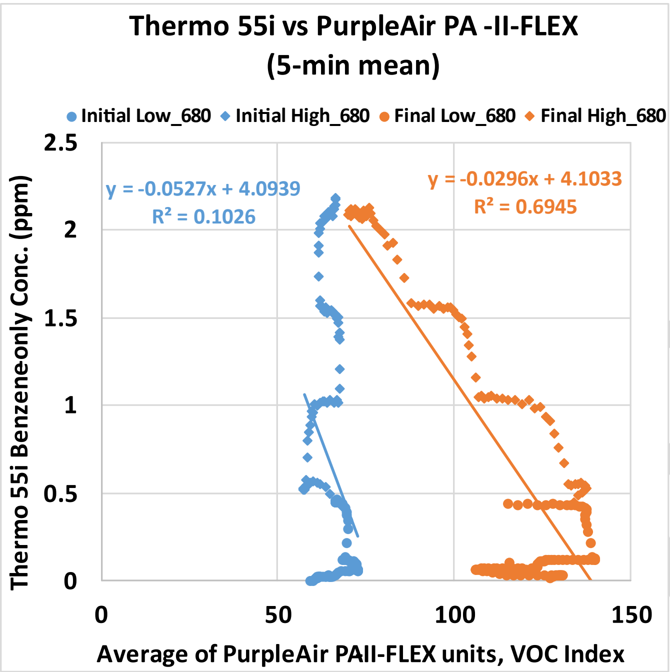
High Ramp

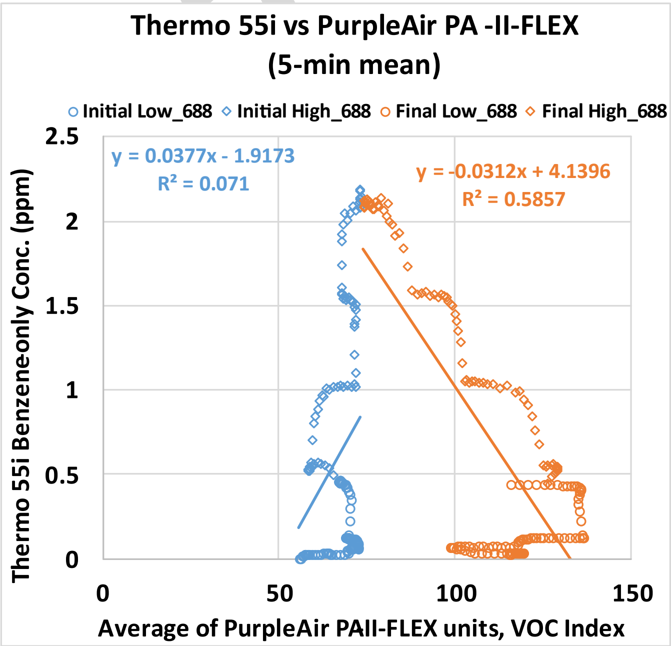




Short-Term Sensor Response Change: Benzene-only

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





- Combining data from both low and high concentration ramps of the benzene-only experiments, correlations of the PurpleAir PA-II-Flex were negative in all cases, except for the initial concentration ramp experiment with the Bosch BME688 units.

Summary Statistics - Benzene-only

Initial Ramp

Sensors							Thermo 55i	GC-FID
Nominal VOC Conc., ppm	**Avg, VOC Index**		**Precision, %**		**IMV, %**		**Ref avg, ppm**	**Ref avg, ppm**
	680	**688**	**680**	**688**	**680**	**688**		
0.015	65.3	65.6	99.8	99.4	0.5	0.9	0.03	0.02
0.06	72.9	72.5	100.00	100.00	1.1	2.0	0.06	0.04
0.10	68.8	69.0	99.9	99.9	2.6	1.5	0.12	0.09
0.40	66.5	67.5	99.9	99.9	3.5	1.3	0.46	0.37
0.5	57.7	58.3	99.9	99.9	4.3	6.1	0.52	
1.0	66.2	70.4	99.6	99.6	8.6	4.0	1.02	
1.5	63.2	68.1	99.7	99.9	10.0	3.9	1.56	
2.0	66.4	73.0	99.9	99.9	11.6	3.4	2.16	

Summary Statistics - Benzene-only

Final Ramp

Sensors							Thermo 55i	GC-FID
Nominal VOC Conc., ppm	Avg, VOC Index		Precision, %		IMV, %		Ref avg, ppm	Ref avg, ppm
	680	688	680	688	680	688		
0.015	120.4	110.3	99.3	99.4	15.9	5.1	0.03	0.01
0.06	121.3	113.4	99.6	99.6	13.9	2.8	0.07	0.04
0.10	139.9	136.0	99.9	99.9	13.5	4.2	0.12	0.09
0.40	113.7	114.8	99.0	99.2	17.7	4.3	0.44	N/A
0.5	134.5	126.5	99.7	99.8	7.9	7.1	0.55	
1.0	109.0	104.1	99.7	99.7	10.8	3.7	1.05	
1.5	91.5	90.5	99.3	99.5	10.3	2.7	1.57	
2.0	74.1	78.5	98.9	98.9	8.5	2.4	2.10	

Discussion

- **Data Recovery:** The PurpleAir PA-II-FLEX sensors showed 100% data recovery for all experiments.

- **Intra-model variability:** Low to moderate variability was observed among the PurpleAir PA-II-FLEX sensors for all experiments. Generally units containing the Bosch BME680 raw VOC sensor had greater variability than those containing the Bosch BME688 raw VOC sensor.

- **Phase 1: Transient Plume Detection**
  - The sensors responded to 100% of the plumes and showed ~ 2-3 minutes delay in plume detection compared to the Thermo 55i. The sensors may be useful in detecting short-lived, sudden changes in VOC when all other potential influencing factors (e.g. climate or non-VOC interfering gases) are steady.

- **Phase 2**: **Initial Concentration Ramping**
  - ***Coefficient of Determination – VOC Blend***: The PurpleAir PA-II-FLEX sensors showed negative correlations in the low concentration ramp and weak to moderate correlations ($0.40 < R^2 < 0.61$) in the high concentration ramp against the reference instruments
  - ***Coefficient of Determination – Benzene-only***: The PurpleAir PA-II-FLEX sensors showed no correlation ($0.01 < R^2 < 0.05$) for any sensors in the low benzene-only concentration ramp. In the high benzene-only concentration ramp, there was no correlation ($R^2 = 0.02$) for the Bosch BME680 units and weak correlation ($R^2 = 0.37$) for the Bosch BM688 units.

Discussion

- **Phase 3: Effect of Temperature and RH**

  - ***Extreme Conditions:*** The PurpleAir PA-II-FLEX sensors generally showed a decrease in VOC index values as T/RH increased from 5°C/20% RH to 20°C/40% RH, and then decreased further as temperature/RH was further increased to 35°C/80% RH.

  - ***RH Interference at Constant Temperature:*** In this particular test, the PurpleAir PA-II-FLEX sensors generally showed a decrease in VOC index as RH increased from 25% to 80% while temperature was maintained at 20°C.

  - ***Temperature Interference at Constant Relative Humidity:*** In this particular test, the PurpleAir PA-II-FLEX sensors generally showed a VOC index response moving in the opposite direction of a change in temperature, i.e. the sensors' VOC reading increased when temperature decreased and vice versa.

  - ***Temperature Interference at Constant Absolute Humidity:*** In this particular test, the PurpleAir PA-II-FLEX sensors generally showed a VOC index response moving in the opposite direction of a change in temperature, i.e. the sensors' VOC reading increased when temperature decreased and vice versa.

Discussion

- **Phase 4: Effects of Gaseous Interferents**

  - **Ozone**
    - ***Responses to Ozone:*** The PurpleAir PA-II-FLEX sensors VOC index readings generally decreased as ozone concentration increased from background value to ~ 400 ppb.
  - **CO**
    - ***Responses to CO:*** The PurpleAir PA-II-FLEX sensors VOC index readings generally increased as CO increased from background value to ~8 ppm.
  - **CO_2**
    - ***Responses to CO_2:*** The PurpleAir PA-II-FLEX sensors VOC index readings generally decreased as CO_2 increased from background value to ~8,000 ppm.

- **Phase 5: Outdoor Simulation**
  - The sensors' VOC index values did not track well with the Thermo 55i VOC values when exposed to a combination of T, RH, ozone and VOC concentrations.
  - Overall, **T (~ 19% on average)** appears to be the more important driver for VOC Index response in the BME680 set of sensors, while **AH (~ 50% on average)** was more important for BME688 set of sensors. **Ozone** in some cases also accounts for a significant % of the variance, as seen for Units 680_1**(16.7%)** and 688_2 **(36.8%)**.

Discussion

➢ **Phase 6**: **Final Concentration Ramping**

- ***Coefficient of Determination – VOC Blend***: The PurpleAir PA-II-FLEX sensors showed negative correlations with the reference VOC monitor data in both the low and high concentration ramp experiments, regardless of raw sensor variant.
- ***Coefficient of Determination – Benzene-only***: The PurpleAir PA-II-FLEX sensors showed very weak and weak correlation/linear response with the corresponding reference low benzene-only ramping data ($0.13 < R^2 < 0.21$ for BME680 sensors and $0.34 < R^2 < 0.48$ for BME688 sensors). For the high concentration ramp, both the BME680s and BME688 units showed negative correlations with the corresponding reference benzene-only data
- ***Short-term Sensor Response Change:*** In general, the sensors demonstrated vastly different behavior at the end of the evaluation compared to the beginning of the evaluation, regardless of sensor variant, whether they were tested with a VOC blend or with benzene-only, and regardless of the concentration of VOC. In some cases the regression slope between the reference VOC readings the sensor VOC index values exhibited a sign change from the beginning to the end of the evaluation.

➢ **Additional Commentary**

- Statements cannot be made about the PurpleAir PA-II FLEX sensors' accuracy or detection limit, because these metrics are not calculable when the sensor output is a unitless VOC index.