

# Laboratory Evaluation

## Igienair Zaack AQI



# Outline

1. Background
2. CO
3. O<sub>3</sub>
4. NO<sub>2</sub>
5. PM<sub>2.5</sub>
6. PM<sub>10</sub>

DRAFT

# Background

Three Igienair Zaack AQI (hereinafter Zaack AQI) sensors (units IDs: 1264, 1271, 1332) were field-tested at the South Coast AQMD Rubidoux fixed ambient monitoring station (11/13/2020 to 01/08/2021) under ambient environmental conditions. Following field testing, the units were subjected to further laboratory testing in the South Coast AQMD Sensor Environmental Test Chamber 2 (SENTEC-2) under controlled pollutant concentration, temperature, and relative humidity conditions. Unit 1332 experienced issues with the particle sensor and was excluded from any further laboratory particle tests.

## Zaack AQI (3 units tested for gas-phase pollutants;

## 2 units tested for particle pollutants):

- Gas Sensors: Electrochemical; non-FEM (Alphasense)
- Particle Sensor – Optical; non-FEM (Alphasense OPC R1)
- Each unit measures: O<sub>3</sub> (ppb), NO<sub>2</sub> (ppb), CO (ppb), PM<sub>1.0</sub>, PM<sub>2.5</sub> and PM<sub>10</sub> ( $\mu\text{g}/\text{m}^3$ ), T (°C), RH (%)
- Units also measure VOC (ppb) and CO<sub>2</sub> (ppm)
- **Unit cost: \$3000 + \$1199 Yearly calibration and maintenance contract**
- Time resolution: 30-sec
- Units IDs: 1264, 1271, 1332 (Unit 1332 data excluded from analysis from particle experiments)



## Reference instruments:

- CO instrument (FRM, T300U, Teledyne, San Diego, CA); cost: ~\$15,000
  - Time resolution: 1-min
- O<sub>3</sub> instrument (FEM, T400, Teledyne, San Diego, CA); cost: ~\$9,000
  - Time resolution: 1-min
- NO<sub>x</sub> instrument (FRM, T200, Teledyne, San Diego, CA); cost: ~\$13,000
  - Time resolution: 1-min
- PM<sub>2.5/10</sub> instrument (FEM, T640x, Teledyne, San Diego, CA); cost: ~\$37,000
  - Time resolution: 1-min
- PM<sub>10</sub> instrument (non-FEM, APS, TSI, Shoreview, MN); cost: ~\$55,000
  - Time resolution: 1-min

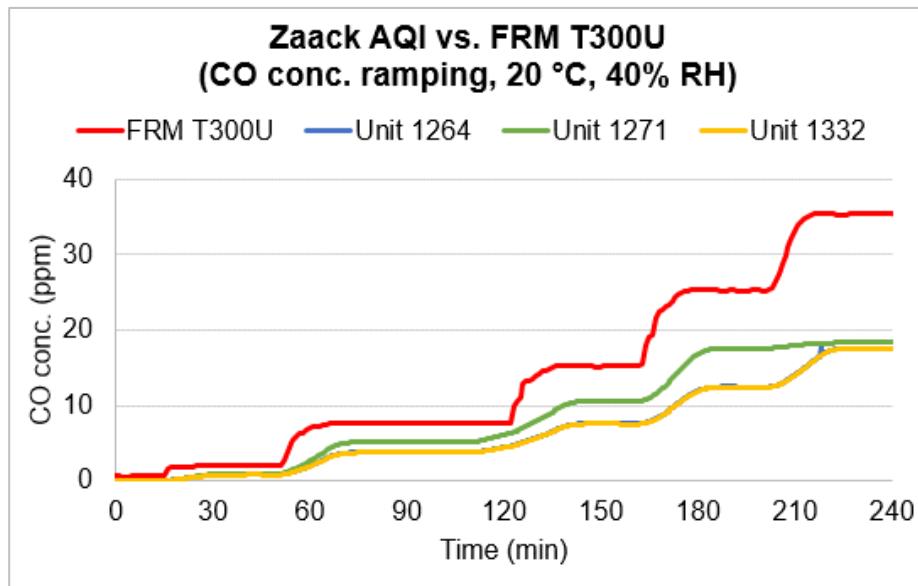


# CO

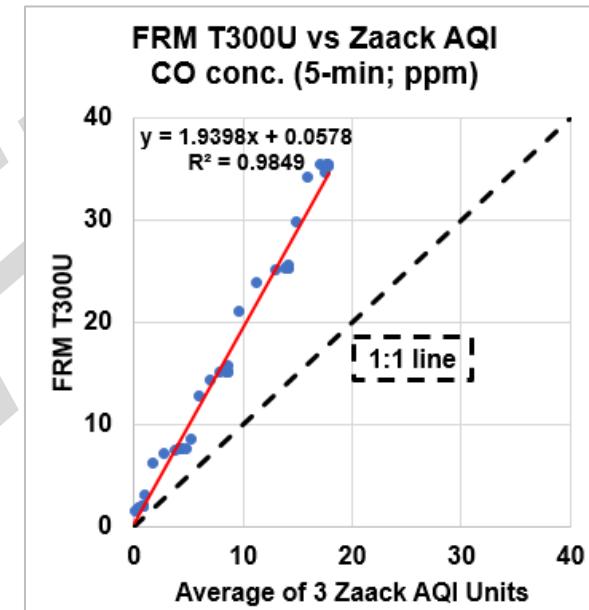
- 1. FRM T300U vs Zaack AQI**
- 2. Accuracy, data recovery, and intra-model variability**
- 3. Precision**
- 4. Climate susceptibility**
- 5. Discussion**

# Zaack AQI vs FRM T300U (CO)

## Coefficient of Determination



- The FRM T300U instrument reported a baseline of ~ 0.6 ppm and the Zaack AQI sensors reported baseline values ~ 0 ppm
- The three Zaack AQI sensors tracked the CO concentration variations recorded by FRM T300U instrument
- The Zaack AQI sensors underestimated the CO concentration as recorded by the FRM T300U instrument



- The Zaack AQI sensors showed very strong correlations with the corresponding FRM T300U CO conc. ( $R^2 > 0.98$ )

# Accuracy: Zaack AQI vs FRM T300U (CO)

- Accuracy (20 °C and 40% RH)

Steady State (#)	Sensor mean (ppm)	FRM T300U (ppm)	Accuracy (%)
1	0.87	2.03	42.8%
2	4.53	7.71	58.8%
3	8.57	15.19	56.4%
4	14.11	25.29	55.8%
5	17.78	35.41	50.2%

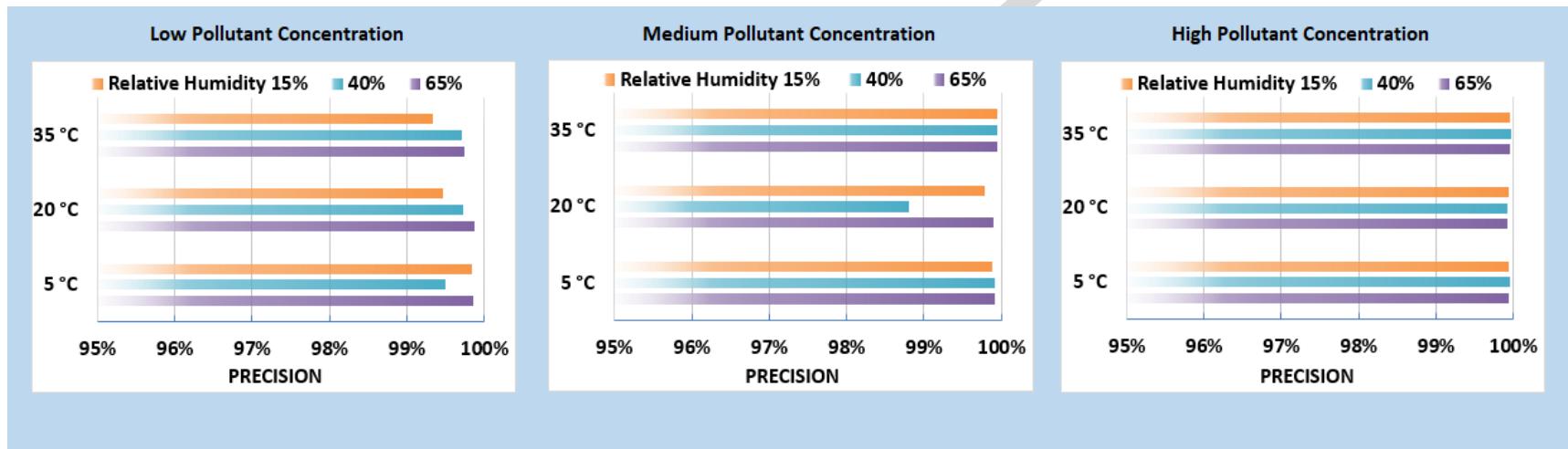
- Accuracy of the three Zaack AQI sensors ranged from 42.8% to 58.8%. The sensors underestimated the FRM T300U measurements at all CO concentrations at 20 °C and 40% RH.

## Zaack AQI Data Recovery and Intra-model Variability

- Data recovery for CO measurements was 99.8%, 99.9%, and 99.8% for Units 1264, 1271, and 1332, respectively.
- Moderate CO concentration variations were observed between the three units at 20° C and 40% RH, at 2, 7.5, and 15 ppm CO as measured by the FRM T300U.

# Precision: Zaack AQI (CO)

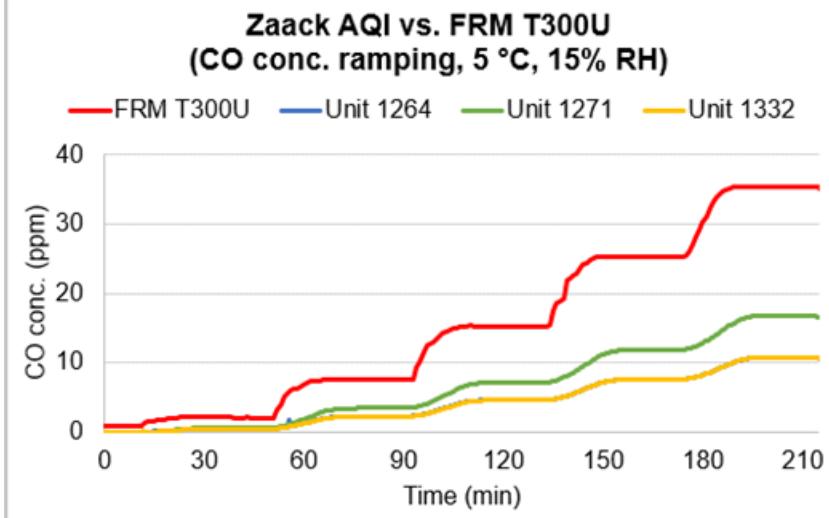
- Precision (Effect of CO conc., temperature and relative humidity)



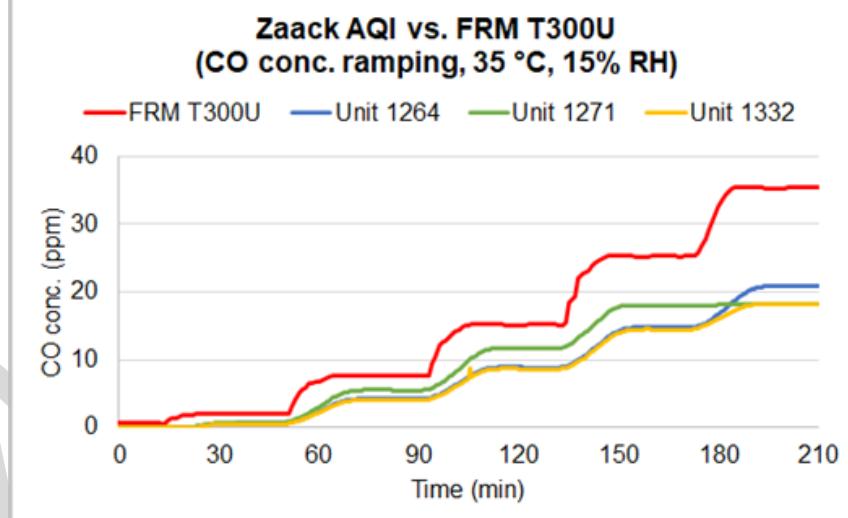
- Overall, the three Zaack AQI sensors showed high precision for all combinations of low, medium and high CO conc., T, and RH.

# Climate Susceptibility: Zaack AQI (CO)

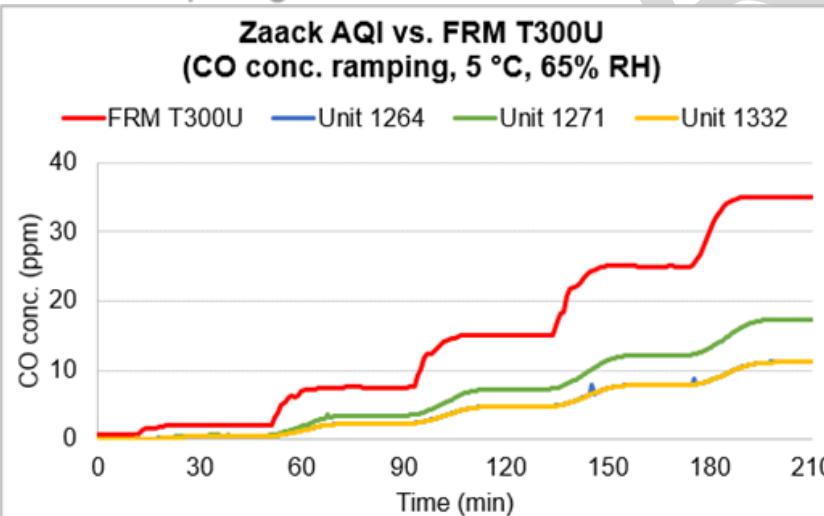
Low Temp-Low RH



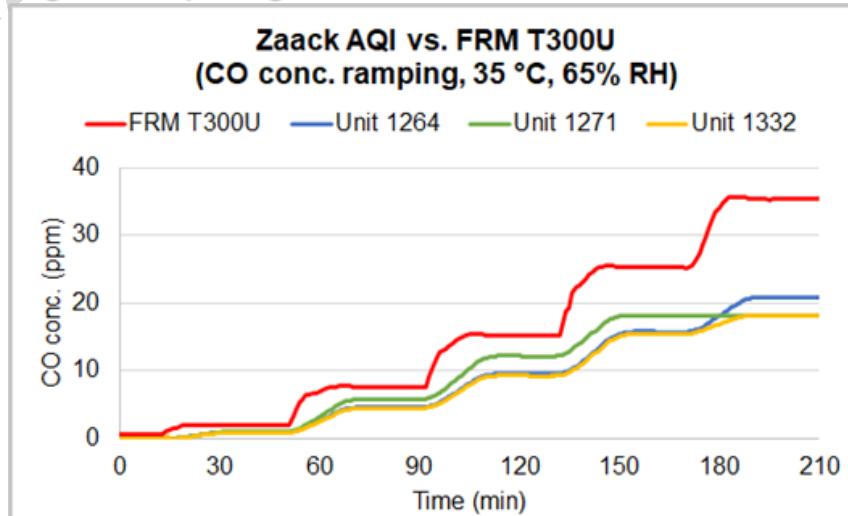
High Temp-Low RH



Low Temp-High RH



High Temp-High RH



# Discussion: CO

- **Accuracy:** The three Zaack AQI sensors showed accuracy ranged from 42.8% to 58.8%. (refer to slide 6)
- **Precision:** The three Zaack AQI sensors exhibited high precision during all tested conditions (CO concentration, T and RH). (refer to slide 7)
- **Intra-model variability:** Moderate CO measurement variations were observed among the three Zaack AQI sensors at 20 °C and 40% RH. (refer to slide 6)
- **Data recovery:** Data recovery for CO measurements was 99.8%, 99.9%, and 99.8% for Units 1264, 1271, and 1332, respectively (refer to slide 6)
- **Baseline:** At all conditions, FRM T300U CO instrument baseline was ~ 0.6 ppm, while the sensors' baseline was ~ 0 ppm.
- **Response time:** Response time could not be studied due to the system design of the chamber system. With a 1.6 m<sup>3</sup> chamber volume and the max gas flow of 20 LPM, it was not possible to reach a high pollutant concentration within a short time.
- **Linear Correlation:** Zaack AQI sensors showed very strong correlation/linear response with the corresponding FRM T300U CO measurement data ( $R^2 > 0.98$ ). (refer to slide 5)
- **Interferent:** Sensors were not tested against an interfering gas species.

# Discussion: CO

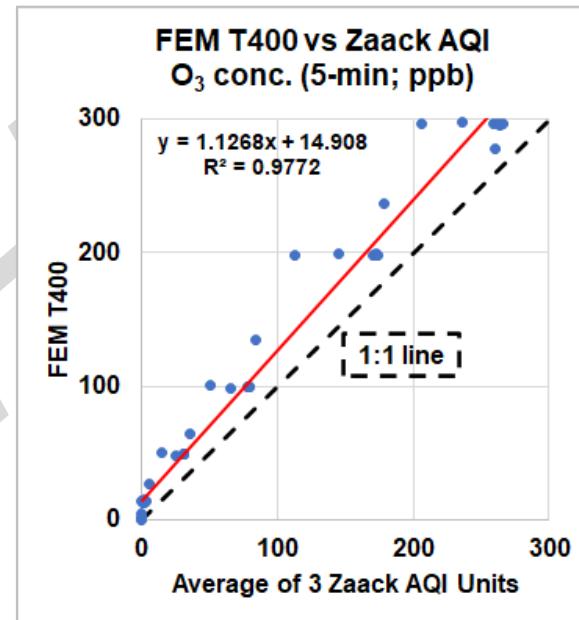
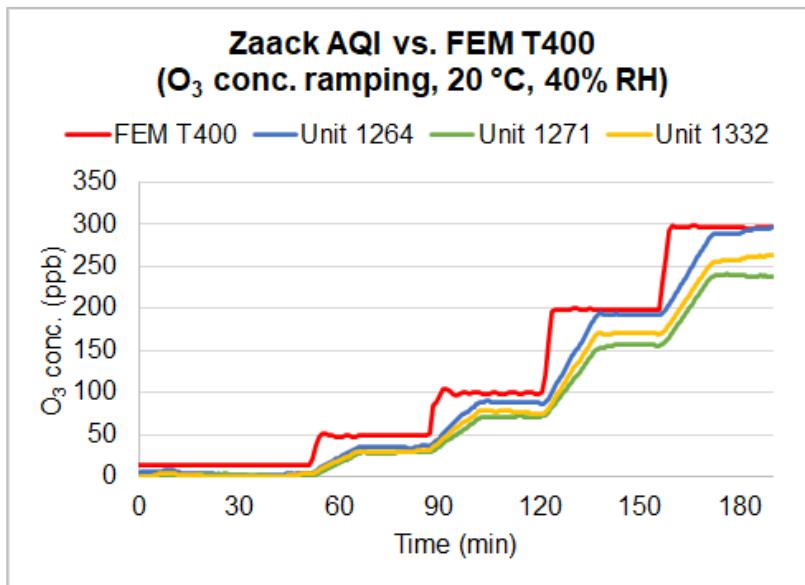
- **Measurement duration:** Zaack AQI sensors report 30-second averaged values.
- **Measurement frequency:** Zaack AQI sensors report 30-second averaged values. The obtained data was used as-is for calculation of statistics (e.g. data recovery, intra-model variability, mean, accuracy, precision), but condensed into 1-minute and 5-minute averages for linear correlation studies against the FRM T300U.
- **Sensor contamination and expiration:** Prior to the laboratory evaluation, the Zaack AQI sensors were tested in the field for two months. The CO laboratory studies lasted for about 10 days with intermittent non-operating periods and a storage period of ~ 11 months. For CO measurements, all three Zaack AQI sensors maintained their functionalities and operated normally throughout the duration of the testing.
- **Concentration range:** 0-20 ppm CO concentration as suggested by the manufacturer. During the laboratory evaluation, the Zaack AQI sensors were challenged with CO concentrations up to 35 ppm. (refer to slide 5)
- **Climate susceptibility:** During the lab studies, temperature and relative humidity had little effect on the precision of CO concentrations as recorded by the Zaack AQI sensors. However, increasing temperature resulted in less underestimation (better agreement) between the sensors and the FRM T300U. (refer to slides 7 and 8)
- **Response to loss of power:** Zaack AQI sensors were powered through the entirety of the lab tests.

O<sub>3</sub>

- 1. FEM T400 vs Zaack AQI**
- 2. Accuracy, data recovery, and intra-model variability**
- 3. Precision**
- 4. Climate susceptibility**
- 5. NO<sub>2</sub> Interferent**
- 6. Discussion**

# Zaack AQI vs FEM T400 ( $O_3$ )

Coefficient of Determination



- The FEM T400 instrument reported a baseline of ~ 0.6 ppb and the Zaack AQI sensors reported baseline values 0 ppb
- The three Zaack AQI sensors tracked the O<sub>3</sub> concentration variations recorded by FEM T400 instrument
- The Zaack AQI sensors underestimated the O<sub>3</sub> concentration as recorded by the FEM T400 instrument

- The Zaack AQI sensors showed very strong correlations with the corresponding FEM T400 O<sub>3</sub> conc. ( $R^2 > 0.97$ )

# Accuracy: Zaack AQI vs FEM T400 ( $O_3$ )

- Accuracy (20 °C and 40% RH)

Steady State (#)	Sensor mean (ppb)	FEM T400 (ppb)	Accuracy (%)
1	1.43	14.26	10.0%
2	31.33	48.98	64.0%
3	78.83	99.51	79.2%
4	173.04	198.60	87.1%
5	263.47	296.62	88.8%

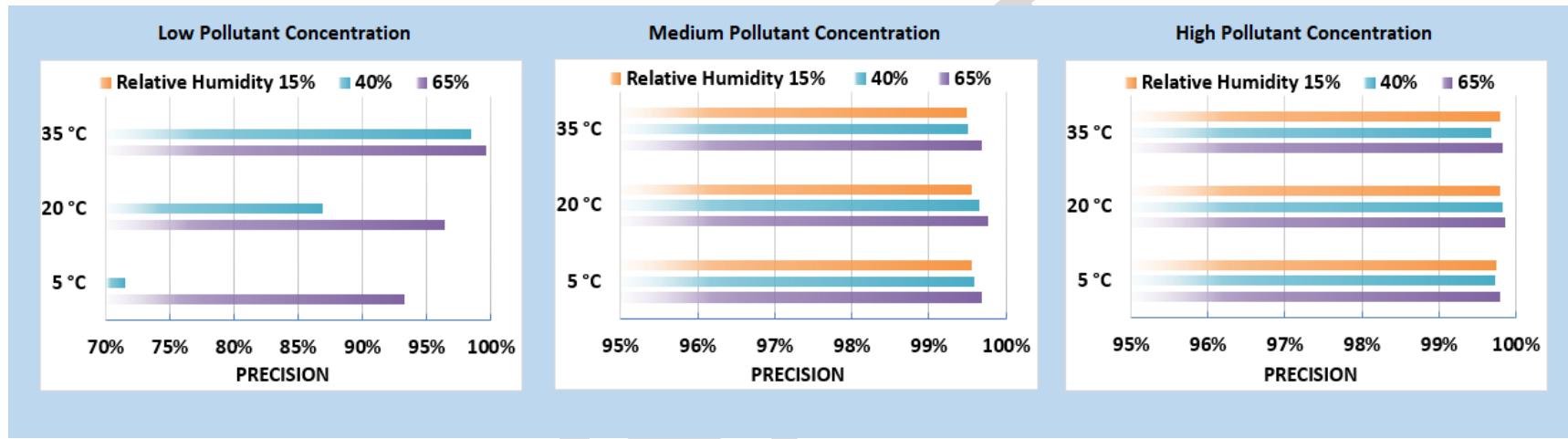
- Accuracy of the three Zaack AQI sensors ranged from 10.0% to 88.8%. The sensors underestimated the FEM T400 measurements at all  $O_3$  concentrations at 20 °C and 40% RH.

## Zaack AQI Data Recovery and Intra-model Variability

- Data recovery for  $O_3$  measurements was 99.8%, 99.8%, and 99.5% for Units 1264, 1271, and 1332, respectively.
- Moderate to high  $O_3$  concentration variations were observed between the three units at 20 °C and 40% RH, at 15, 50, and 100 ppm  $O_3$  as measured by the FEM T400.

# Precision: Zaack AQI ( $O_3$ )

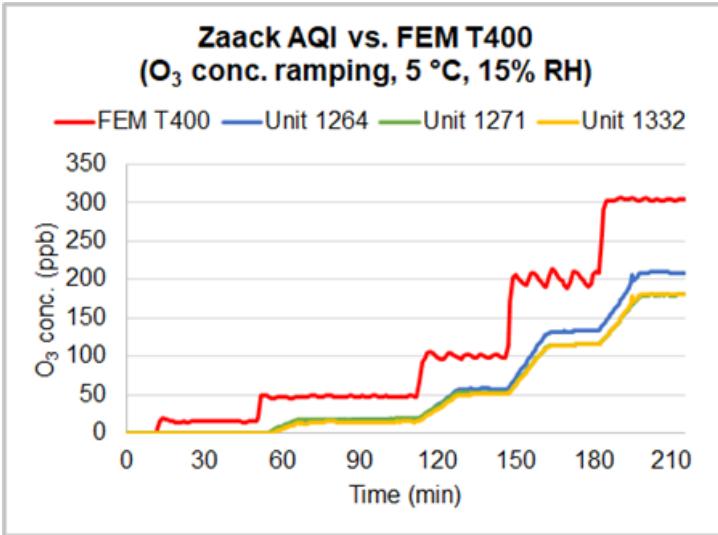
- Precision (Effect of  $O_3$  conc., temperature and relative humidity)



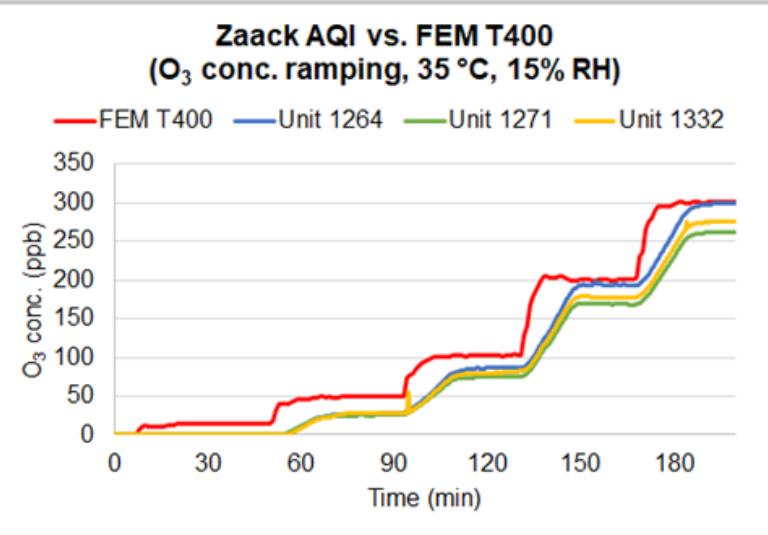
- At low  $O_3$  conc., the three Zaack AQI sensors overall showed high precision except at 40% RH for T less than 20°C
- Note: Precision cannot be calculated at low  $O_3$  conc. at 15% RH because the three Zaack AQI sensors reported all zeros for measurement values.
- Overall, the three Zaack AQI sensors showed high precision for all combinations of medium and high  $O_3$  conc., T, and RH.

# Climate Susceptibility: Zaack AQI ( $O_3$ )

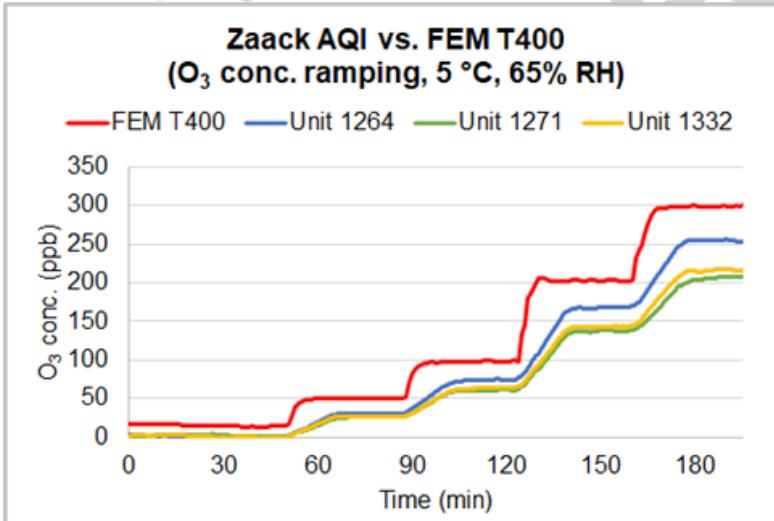
Low Temp-Low RH



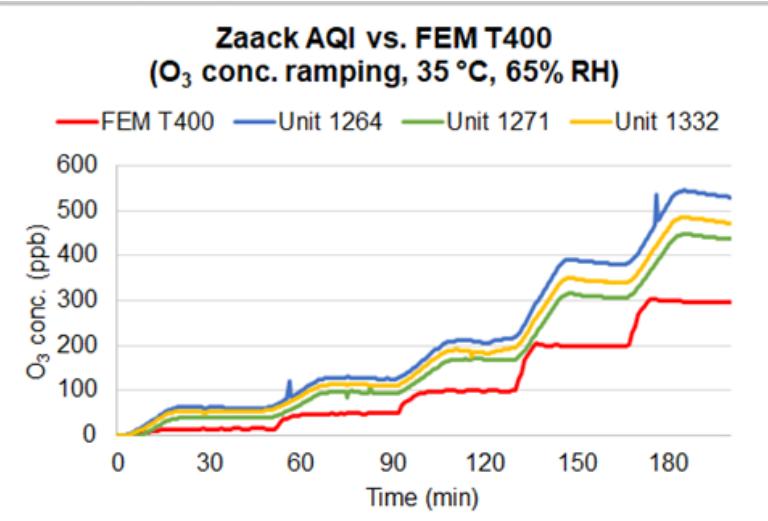
High Temp-Low RH



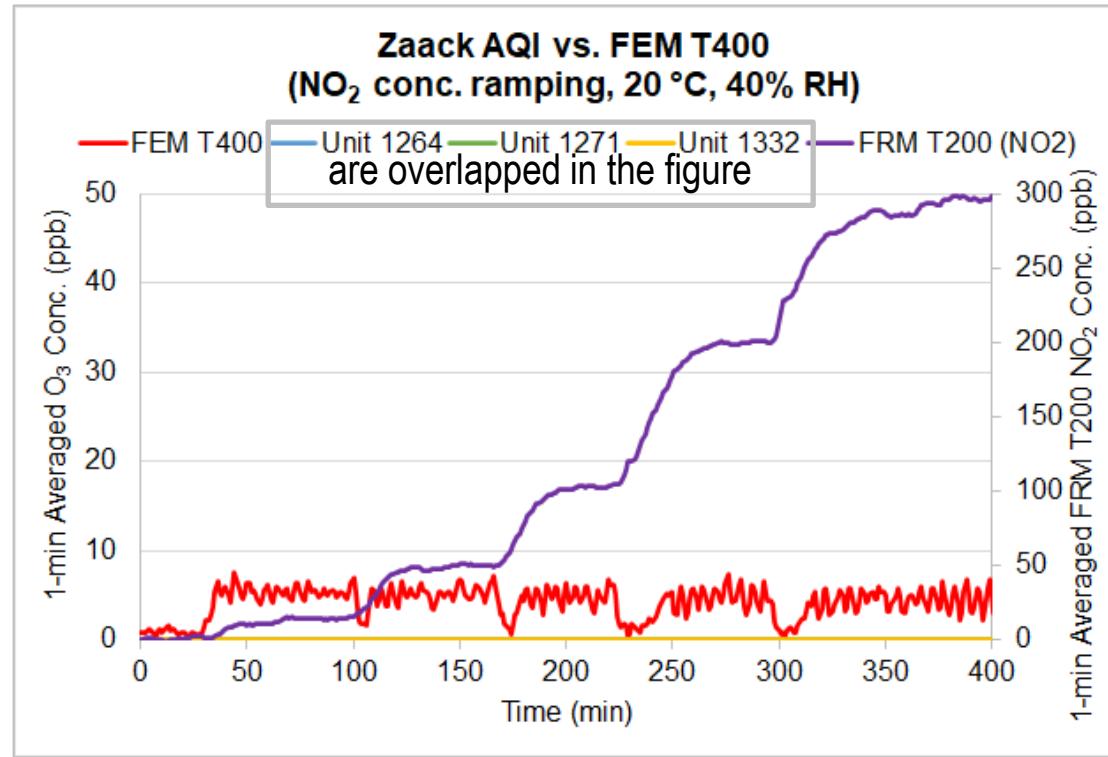
Low Temp-High RH



High Temp-High RH



# NO<sub>2</sub> Interferent: Zaack AQI vs FEM T400 (O<sub>3</sub>)



In the laboratory, the effect of NO<sub>2</sub> interferent is evaluated by exposing sensors to increasing concentrations of NO<sub>2</sub> at 20 °C and 40% RH. As shown in the figure, both the FEM T400 and sensors maintained their baseline readings throughout the NO<sub>2</sub> concentration ramping from 0 to 300 ppb.

# Discussion: O<sub>3</sub>

- **Accuracy:** The three Zaack AQI sensors showed accuracy ranged from 10.0% to 88.8%. (refer to slide 13).
- **Precision:** The three Zaack AQI sensors exhibited high precision at the medium and high O<sub>3</sub> concentrations, during all tested T and RH conditions; at low O<sub>3</sub> concentrations, precision was high except at some low RH and T conditions. (refer to slide 14)
- **Intra-model variability:** Moderate to high O<sub>3</sub> measurement variations were observed among the three Zaack AQI sensors at 20 °C and 40% RH. (refer to slide 13)
- **Data recovery:** Data recovery for O<sub>3</sub> measurements was 99.8%, 99.8%, and 99.5% for Units 1264, 1271, and 1332, respectively (refer to slide 13)
- **Baseline:** At all conditions, FEM T400 O<sub>3</sub> instrument baseline was ~ 0.6 ppb, while the sensors' baseline was 0 ppb.
- **Response time:** Response time could not be studied due to the system design of the chamber system. With a 1.6 m<sup>3</sup> chamber volume and the max gas flow of 20 LPM, it was not possible to reach a high pollutant concentration within a short time.
- **Linear Correlation:** The three Zaack AQI sensors showed very strong correlation/linear response with the corresponding FEM T400 O<sub>3</sub> measurement data ( $R^2 > 0.97$ ) (refer to slide 12)
- **Interferent:** The three Zaack AQI sensors were inert to NO<sub>2</sub> at 20 °C and 40% RH. When NO<sub>2</sub> was increased from 0 to 300 ppb, the sensors maintained their baseline readings (refer to slide 16)

# Discussion: O<sub>3</sub>

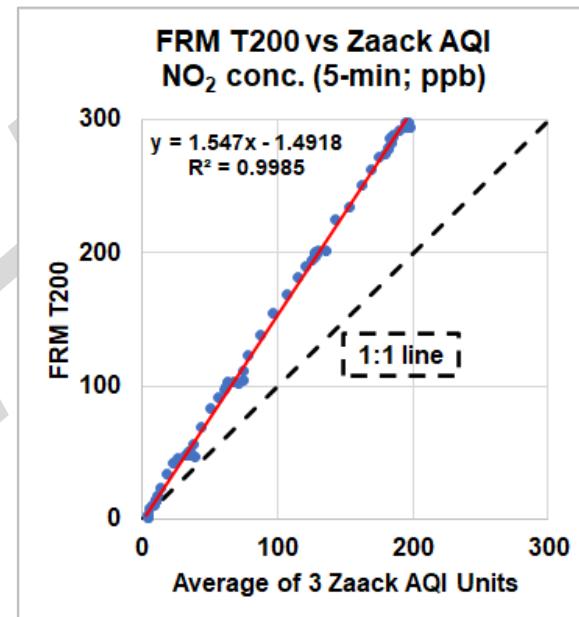
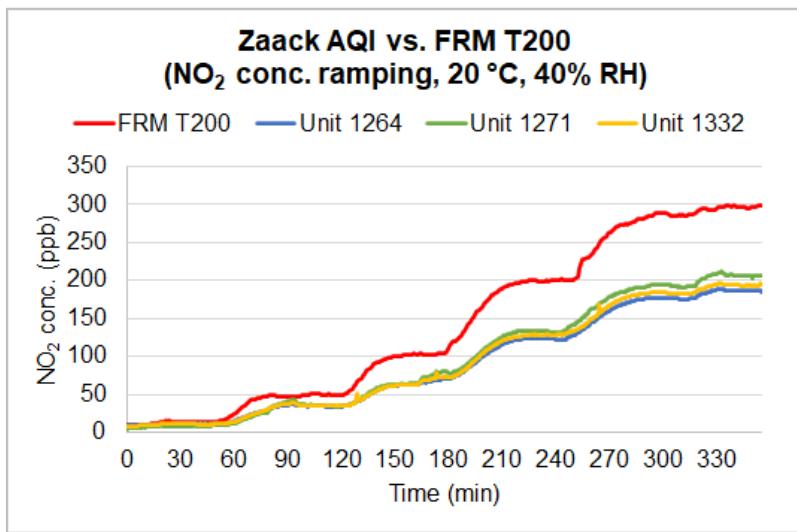
- **Measurement duration:** Zaack AQI sensors report 30-second averaged values.
- **Measurement frequency:** Zaack AQI sensors report 30-second averaged values. The obtained data was used as-is for calculation of statistics (e.g. data recovery, intra-model variability, mean, accuracy, precision), but condensed into 1-minute and 5-minute averages for linear correlation studies against the FEM T400.
- **Sensor contamination and expiration:** Prior to the laboratory evaluation, the Zaack AQI sensors were tested in the field for two months. The O<sub>3</sub> laboratory studies lasted for about 8 days with intermittent non-operating periods and a storage period of ~ 11 months. For O<sub>3</sub> measurements, all three Zaack AQI sensors maintained their functionalities and operated normally throughout the duration of the testing.
- **Concentration range:** 0-20 ppm O<sub>3</sub> concentration as suggested by the manufacturer. During the laboratory evaluation, the Zaack AQI sensors were challenged with O<sub>3</sub> concentrations up to 300 ppb. (refer to slide 12)
- **Climate susceptibility:** During the lab studies, temperature and relative humidity generally had little effect on the precision of O<sub>3</sub> concentrations as recorded by the Zaack AQI sensors, but at dry and cold conditions precision was negatively impacted. Colder and drier conditions generally resulted in more underestimation, while hotter and wetter conditions generally resulted in more overestimation of the sensors compared to the FEM T400. (refer to slides 14 and 15)
- **Response to loss of power:** Zaack AQI sensors were powered through the entirety of the lab tests.

# **NO<sub>2</sub>**

- 1. FRM T200 vs Zaack AQI**
- 2. Accuracy, data recovery, and intra-model variability**
- 3. Precision**
- 4. Climate susceptibility**
- 5. O<sub>3</sub> Interferent**
- 6. Discussion**

# Zaack AQI vs FRM T200 ( $\text{NO}_2$ )

## Coefficient of Determination



- The FRM T200 instrument reported a baseline of ~ 1 ppb and the Zaack AQI sensors reported baseline values ~ 5.5 ppb
- The three Zaack AQI sensors tracked the  $\text{NO}_2$  concentration variations recorded by FRM T200 instrument
- The Zaack AQI sensors underestimated the  $\text{NO}_2$  concentration as recorded by the FRM T200 instrument

- The Zaack AQI sensors showed very strong correlations with the corresponding FRM T200  $\text{NO}_2$  conc. ( $R^2 > 0.99$ )

# Accuracy: Zaack AQI vs FRM T200 ( $\text{NO}_2$ )

- Accuracy (20 °C and 40% RH)

Steady State (#)	Sensor mean (ppb)	FRM T200 (ppb)	Accuracy (%)
1	10.55	13.86	76.1%
2	35.18	50.06	70.3%
3	66.27	102.51	64.7%
4	128.59	200.19	64.2%
5	195.56	297.23	65.8%

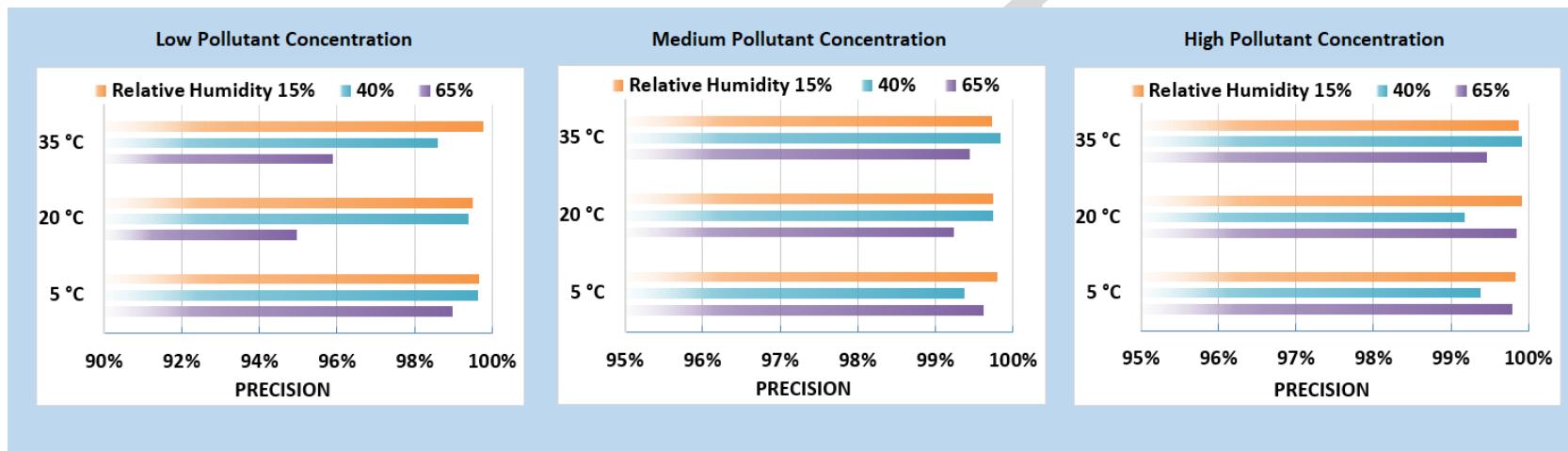
- Accuracy of the three Zaack AQI sensors ranged from 64.2% to 76.1%. The sensors underestimated the FRM T200 measurements at all  $\text{NO}_2$  concentrations at 20 °C and 40% RH.

## Zaack AQI Data Recovery and Intra-model Variability

- Data recovery for  $\text{NO}_2$  measurements was 99.8%, 99.9%, and 99.9% for Units 1264, 1271, and 1332, respectively.
- Low to moderate  $\text{NO}_2$  concentration variations were observed between the three units at 20 °C and 40% RH, at 15, 50, and 100 ppm  $\text{NO}_2$  as measured by the FRM T200.

# Precision: Zaack AQI ( $\text{NO}_2$ )

- Precision (Effect of  $\text{NO}_2$  conc., temperature and relative humidity)

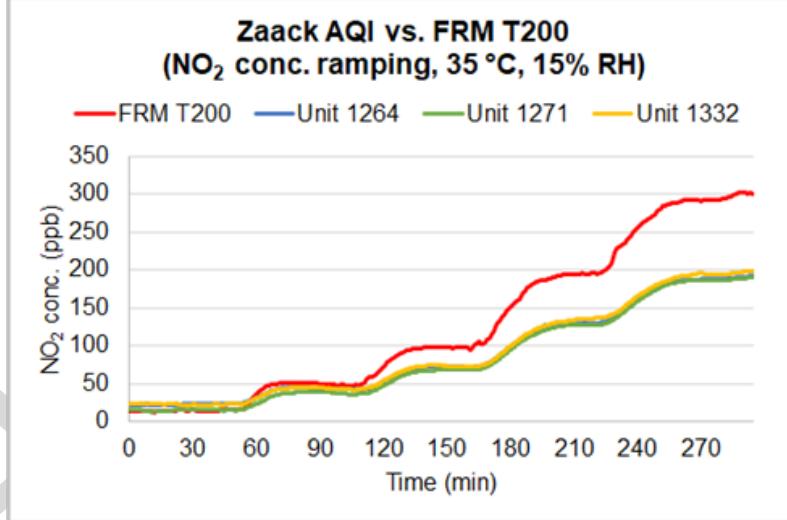
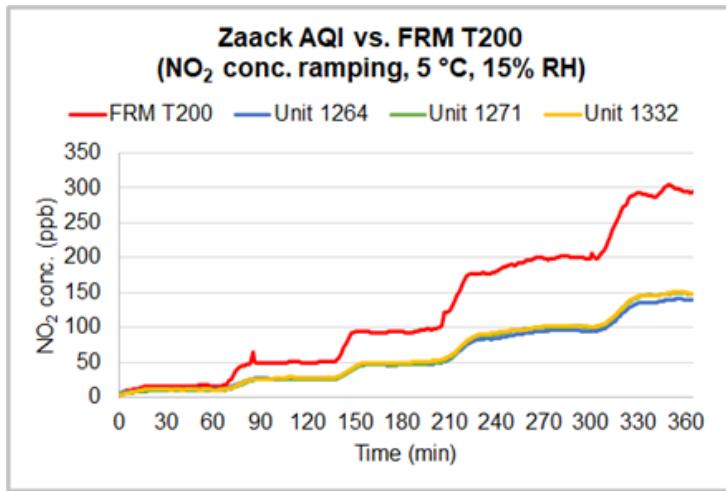


- Overall, the three Zaack AQI sensors showed high precision for all combinations of  $\text{NO}_2$  conc., T, and RH.

# Climate Susceptibility: Zaack AQI ( $\text{NO}_2$ )

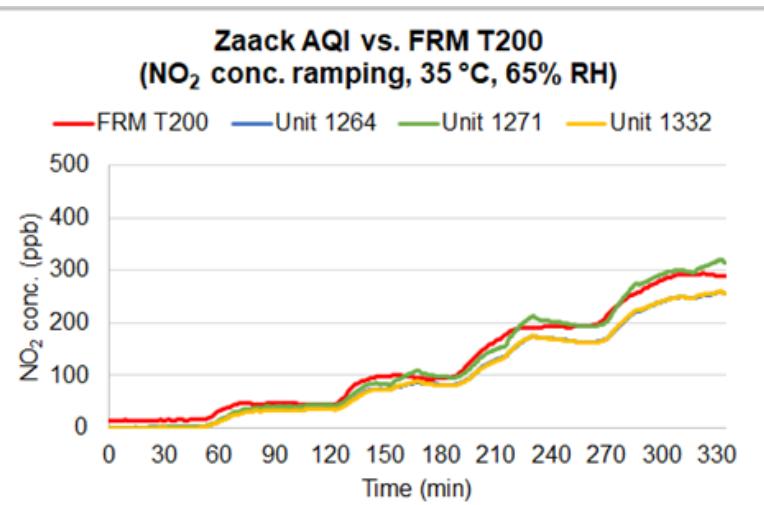
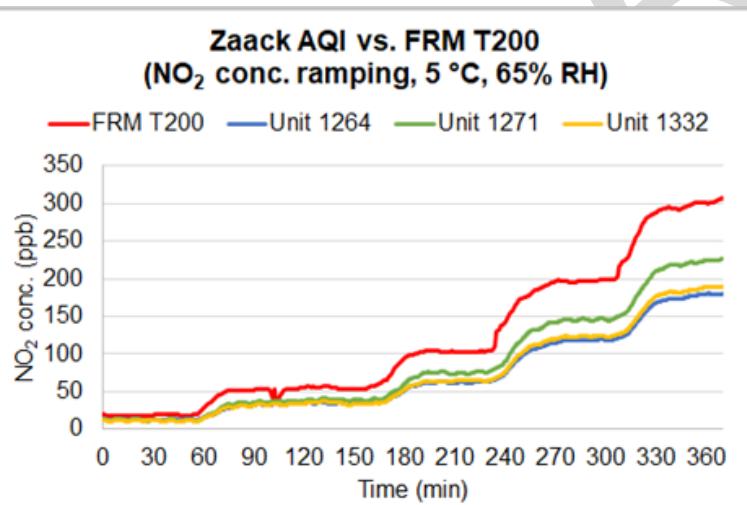
Low Temp-Low RH

High Temp-Low RH

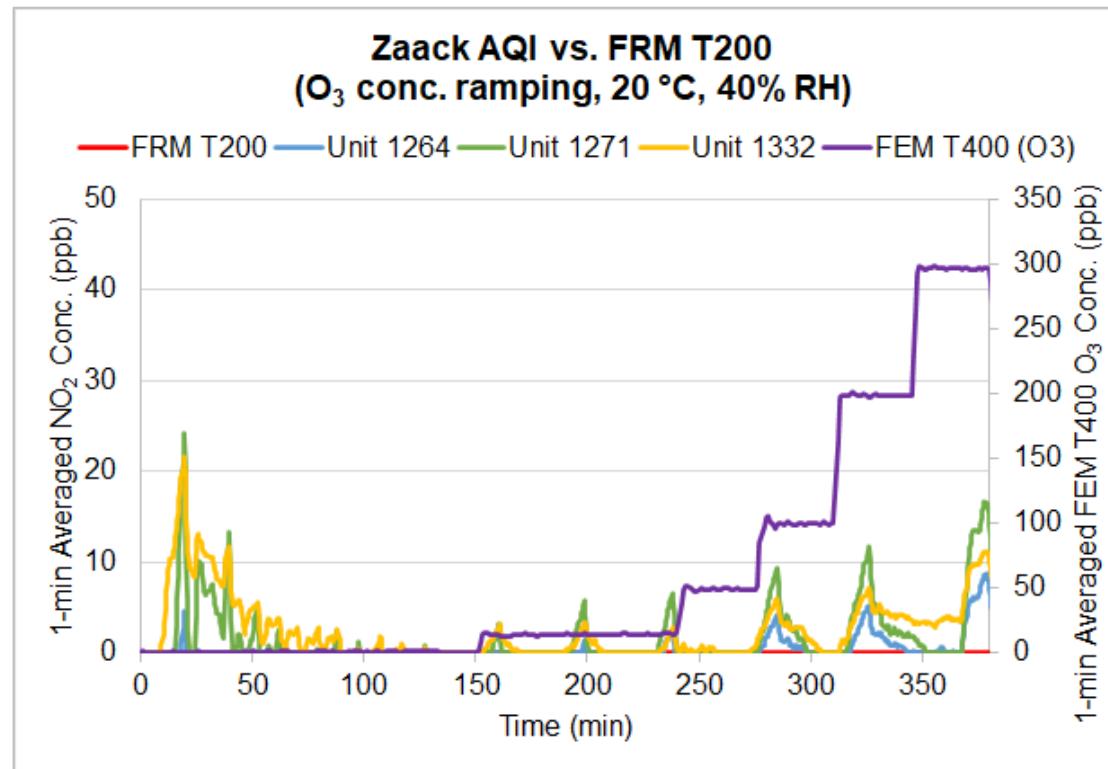


Low Temp-High RH

High Temp-High RH



# O<sub>3</sub> Interferent: Zaack AQI vs FRM T200 (NO<sub>2</sub>)



In the laboratory, the effect of O<sub>3</sub> interferent is evaluated by exposing sensors to increasing concentrations of O<sub>3</sub> at 20 °C and 40% RH. As shown in the figure, the FRM T200 maintained its baseline readings throughout the O<sub>3</sub> concentration ramping from 0 to 300 ppb, but the sensors showed spikes in reported NO<sub>2</sub> of ~ 5-20 ppb when there was no O<sub>3</sub> injected yet in the chamber, as well as every time the O<sub>3</sub> concentration was changed.

# Discussion: NO<sub>2</sub>

- **Accuracy:** The three Zaack AQI sensors showed accuracy ranged from 64.2% to 76.1%. (refer to slide 21).
- **Precision:** The three Zaack AQI sensors exhibited high precision during all tested NO<sub>2</sub> conc., T, and RH conditions. (refer to slide 22)
- **Intra-model variability:** Low to moderate NO<sub>2</sub> measurement variations were observed among the three Zaack AQI sensors at 20 °C and 40% RH. (refer to slide 21)
- **Data recovery:** Data recovery for NO<sub>2</sub> measurements was 99.8%, 99.9%, and 99.9% for Units 1264, 1271, and 1332, respectively (refer to slide 21)
- **Baseline:** At all conditions, FRM T200 NO<sub>2</sub> instrument baseline was ~ 1 ppb, while the sensors' baseline was ~ 5.5 ppb.
- **Response time:** Response time could not be studied due to the system design of the chamber system. With a 1.6 m<sup>3</sup> chamber volume and the max gas flow of 20 LPM, it was not possible to reach a high pollutant concentration within a short time.
- **Linear Correlation:** The three Zaack AQI sensors showed very strong correlation/linear response with the corresponding FRM T200 NO<sub>2</sub> measurement data ( $R^2 > 0.99$ ) (refer to slide 20)
- **Interferent:** The three Zaack AQI sensors were not inert to O<sub>3</sub> at 20 °C and 40% RH. When O<sub>3</sub> was increased from 0 to 300 ppb, the sensors showed apparent NO<sub>2</sub> spikes of ~ 5-20 ppb both when there was no O<sub>3</sub> injected yet, as well as every time the O<sub>3</sub> concentration was changed (refer to slide 24)

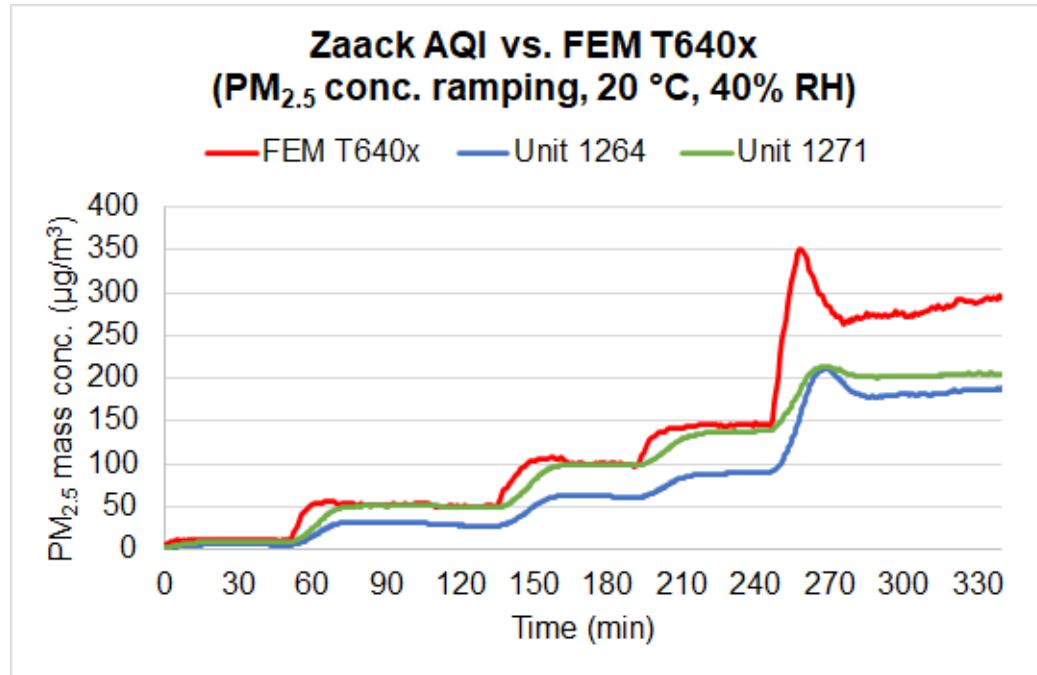
# Discussion: NO<sub>2</sub>

- **Measurement duration:** Zaack AQI sensors report 30-second averaged values.
- **Measurement frequency:** Zaack AQI sensors report 30-second averaged values. The obtained data was used as-is for calculation of statistics (e.g. data recovery, intra-model variability, mean, accuracy, precision), but condensed into 1-minute and 5-minute averages for linear correlation studies against the FRM T200.
- **Sensor contamination and expiration:** Prior to the laboratory evaluation, the Zaack AQI sensors were tested in the field for two months. The NO<sub>2</sub> laboratory studies lasted for about 8 days with intermittent non-operating periods and a storage period of ~ 11 months. For NO<sub>2</sub> measurements, all three Zaack AQI sensors maintained their functionalities and operated normally throughout the duration of the testing.
- **Concentration range:** 0-20 ppm NO<sub>2</sub> concentration as suggested by the manufacturer. During the laboratory evaluation, the Zaack AQI sensors were challenged with NO<sub>2</sub> concentrations up to 300 ppb. (refer to slide 20)
- **Climate susceptibility:** During the lab studies, temperature and relative humidity generally had little effect on the precision of NO<sub>2</sub> concentrations as recorded by the Zaack AQI sensors. Colder and drier conditions generally resulted in more underestimation, while hotter and wetter conditions generally resulted in better agreement of the sensors compared to the FRM T200. (refer to slides 22 and 23)
- **Response to loss of power:** Zaack AQI sensors were powered through the entirety of the lab tests.

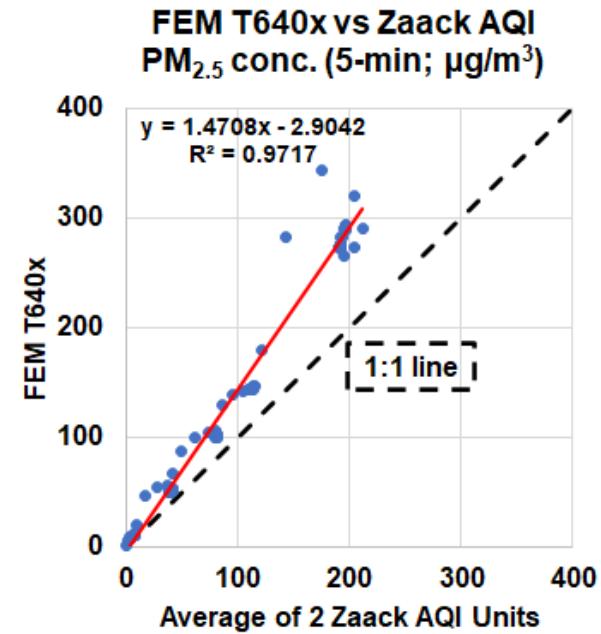
# **PM<sub>2.5</sub>**

- 1. FEM T640x vs Zaack AQI**
- 2. Accuracy, data recovery, and intra-model variability**
- 3. Precision**
- 4. Climate susceptibility**
- 5. Discussion**

# Zaack AQI vs FEM T640x (PM<sub>2.5</sub>)



## Coefficient of Determination



- The Zaack AQI sensors tracked well with the concentration variation but underestimated PM<sub>2.5</sub> concentration values compared to the FEM T640x in the concentration range of 0 - 300  $\mu\text{g}/\text{m}^3$ .

- The Zaack AQI sensors showed very strong correlations with the FEM T640x PM<sub>2.5</sub> mass conc. ( $R^2 > 0.97$ )

# Zaack AQI vs FEM T640x PM<sub>2.5</sub> Accuracy

- Accuracy (20°C and 40% RH)

Steady state #	Sensor Mean ( $\mu\text{g}/\text{m}^3$ )	FEM T640x ( $\mu\text{g}/\text{m}^3$ )	Accuracy (%)
1	7.72	11.33	68.1%
2	38.71	50.39	76.8%
3	80.38	100.01	80.4%
4	113.99	145.62	78.3%
5	196.22	291.82	67.2%

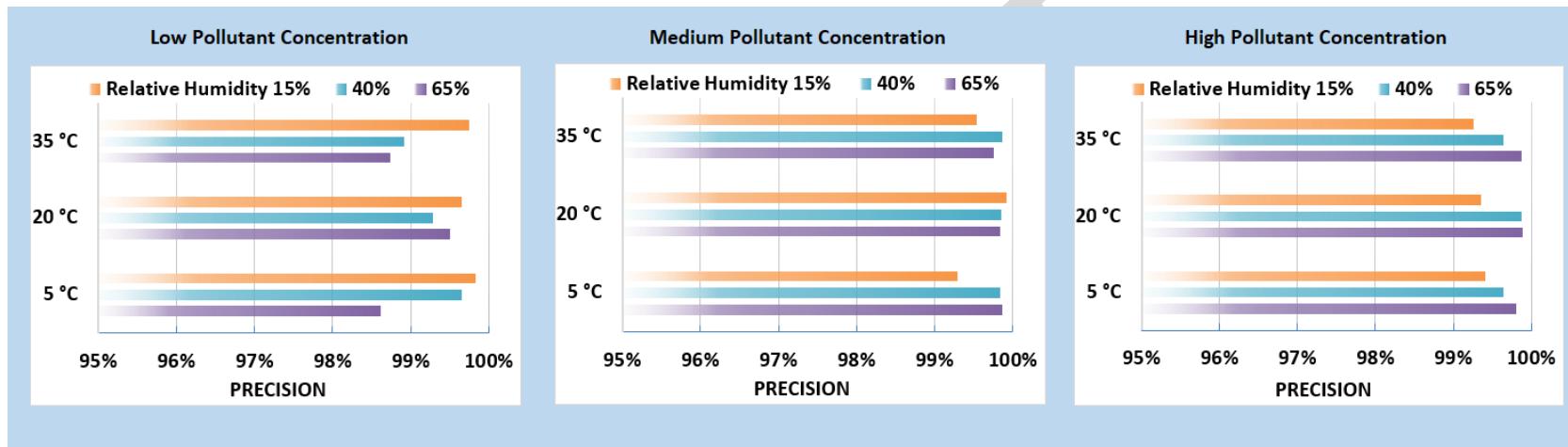
- The Zaack AQI sensors underestimated the measured concentration compared to the FEM T640x PM<sub>2.5</sub> mass concentration at 20 °C and 40% RH. The Zaack AQI sensors showed moderate accuracy (67.2% to 80.4%) for all tested PM<sub>2.5</sub> concentrations compared to the reference FEM T640x for the entirety of test.

## Zaack AQI Data Recovery and Intra-model Variability

- Data recovery for PM<sub>2.5</sub> measurements was 99.8% and 99.8% for Units 1264 and 1271 (Unit 1332 data was not analyzed due to PM sensor malfunction)
- Moderate PM<sub>2.5</sub> concentration variations were observed between the two units at 20° C and 40% RH, at 10, 50, and 150  $\mu\text{g}/\text{m}^3$  PM<sub>2.5</sub> as measured by the FEM T640x.

# Precision: Zaack AQI (PM<sub>2.5</sub>)

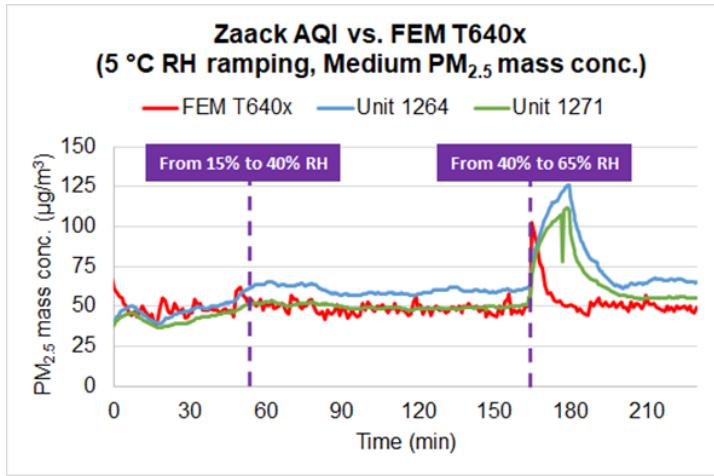
- Precision (Effect of PM<sub>2.5</sub> conc., temperature and relative humidity)



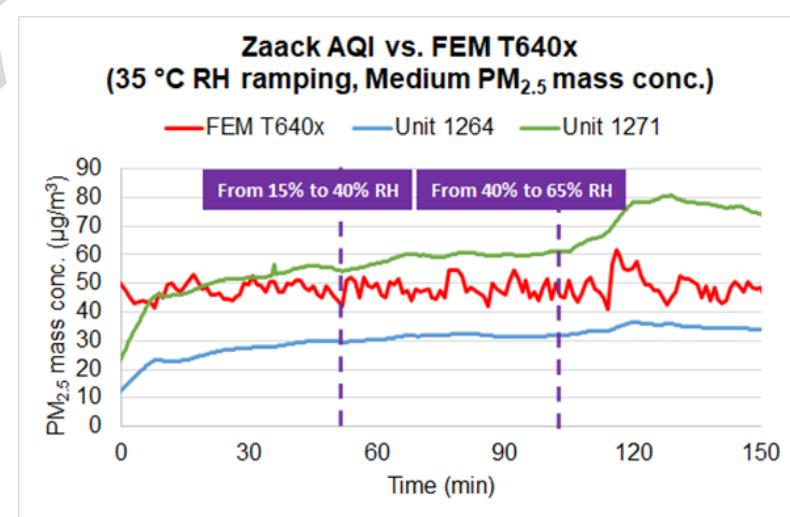
- Overall, the three Zaack AQI sensors showed high precision for all combinations of PM<sub>2.5</sub> conc., T, and RH.

# Climate Susceptibility: Zaack AQI (PM<sub>2.5</sub>)

Low Temp - RH ramping  
(medium conc.)



High Temp – RH ramping  
(medium conc.)



# Discussion: PM<sub>2.5</sub>

- **Accuracy:** The two Zaack AQI sensors showed accuracy ranged from 67.2% to 80.4%. (refer to slide 29)
- **Precision:** The two Zaack AQI sensors exhibited high precision during all tested PM<sub>2.5</sub> conc., T, and RH conditions. (refer to slide 30)
- **Intra-model variability:** Moderate PM<sub>2.5</sub> measurement variations were observed among the two Zaack AQI sensors at 20 °C and 40% RH. (refer to slide 29)
- **Data Recovery:** Data recovery for PM<sub>2.5</sub> measurements was 99.8% and 99.8% for Units 1264 and 1271, respectively. (refer to slide 29)
- **Bias:** N/A
- **Detection limit:** The detection limit cannot be estimated due to limitations in the chamber system design.
- **Response time:** Response time could not be studied due to the system design of the chamber system. With a 1.6 m<sup>3</sup> chamber volume, it was not possible to reach a high pollutant concentration within a short time.
- **Linear Correlation:** The two Zaack AQI sensors showed very strong correlation/linear response with the corresponding FEM T640x PM<sub>2.5</sub> measurement data ( $R^2 > 0.97$ ). (refer to slide 28)
- **Selectivity:** N/A for PM sensors test
- **Interferences:** N/A for PM sensors test
- **Note about PM<sub>1.0</sub>:** The field evaluation compared the PM<sub>1.0</sub> values reported from the Zaack AQI sensors against the field GRIMM and T640 that reported PM<sub>1.0</sub>. However, PM<sub>1.0</sub> was not compared in this lab evaluation because at the time of lab testing (before March 2022) the lab T640x firmware upgrade to report PM<sub>1.0</sub> was not finalized yet.

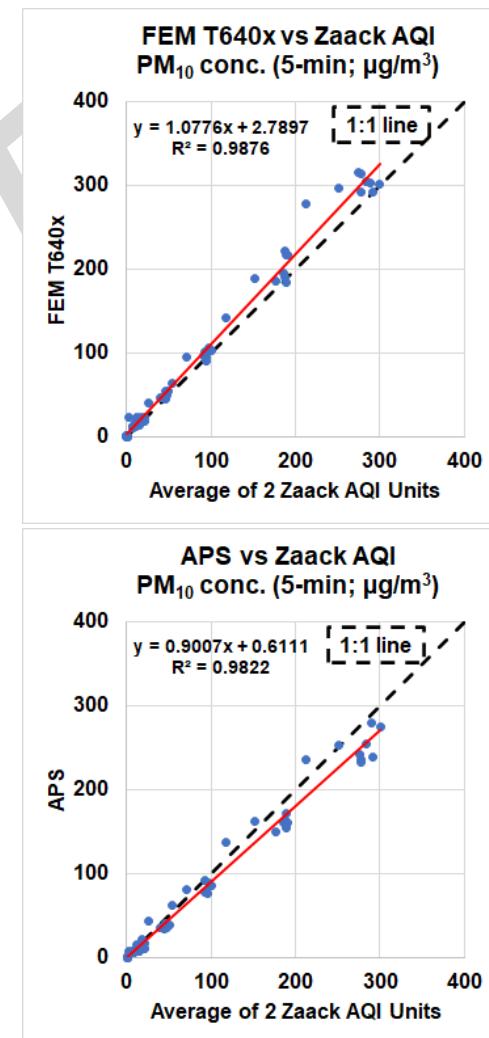
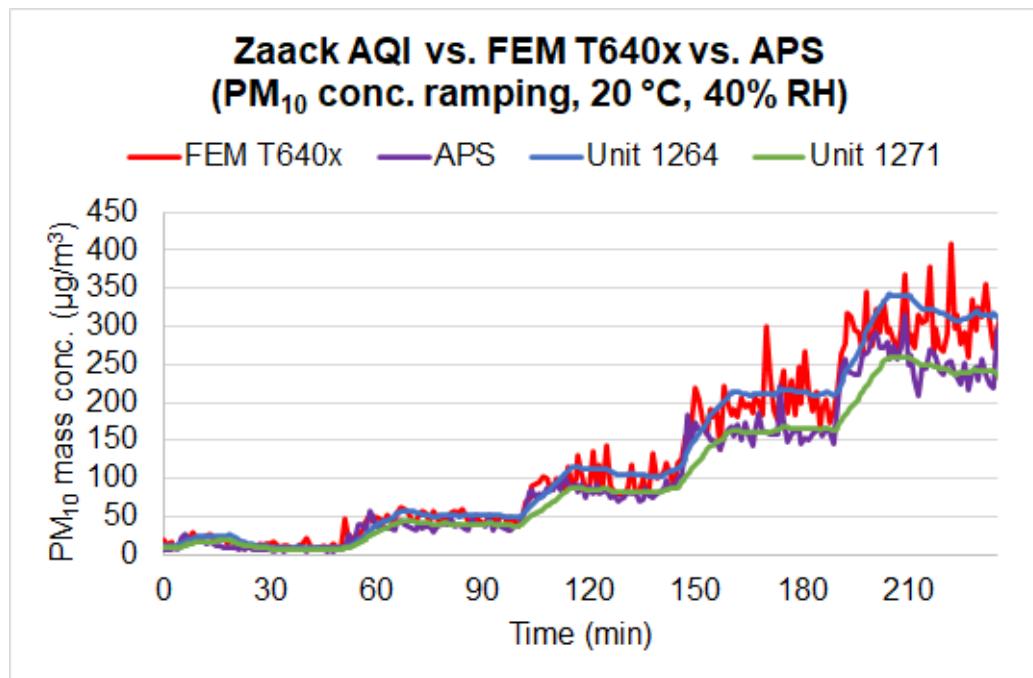
# Discussion: PM<sub>2.5</sub>

- **Measurement duration:** Zaack AQI sensors report 30-second averaged values.
- **Measurement frequency:** Zaack AQI sensors report 30-second averaged values. The obtained data was used as-is for calculation of statistics (e.g. data recovery, intra-model variability, mean, accuracy, precision), but condensed into 1-minute and 5-minute averages for linear correlation studies against the FEM T640x.
- **Sensor contamination and expiration:** Prior to the laboratory evaluation, the Zaack AQI sensors were tested in the field for two months. The PM<sub>2.5</sub> laboratory studies lasted for about 50 days with intermittent non-operating periods and a storage period of ~ 11 months. For PM<sub>2.5</sub> measurements, two of the Zaack AQI sensors (Units 1264 and 1271) maintained their functionalities and operated normally throughout the duration of the testing, while one of the sensors (Unit 1332) would only report either 0 or 1000 µg/m<sup>3</sup> during the laboratory studies and was thus excluded from analysis.
- **Concentration range:** 0.01 µg/m<sup>3</sup> to 1500 mg/m<sup>3</sup> PM<sub>2.5</sub> concentration as suggested by the manufacturer. During the laboratory evaluation, the Zaack AQI sensors were challenged with PM<sub>2.5</sub> concentrations up to 300 µg/m<sup>3</sup>. (refer to slide 28)
- **Drift:** N/A
- **Climate susceptibility:** During the lab studies, temperature and relative humidity generally had little effect on the precision of PM<sub>2.5</sub> concentrations as recorded by the Zaack AQI sensors. At low temperatures the sensors generally underestimated the PM<sub>2.5</sub> concentration, while at high temperatures the sensors diverged but on average overestimated the PM<sub>2.5</sub> concentration compared to the FEM T640x. (refer to slides 30 and 31)
- **Response to loss of power:** Zaack AQI sensors were powered through the entirety of the lab tests.

# **PM<sub>10</sub>**

- 1. FEM T640x vs APS vs Zaack AQI**
- 2. Accuracy, data recovery, and intra-model variability**
- 3. Climate susceptibility**
- 4. Discussion**

# Zaack AQI vs FEM T640x vs APS (PM<sub>10</sub>)



- The Zaack AQI sensors tracked well with the PM<sub>10</sub> concentration variations as recorded by the FEM T640x and APS in the concentration range of 0 - 300 µg/m<sup>3</sup>.
- The Zaack AQI sensors showed very strong correlations with both FEM T640x and APS PM10 measurement data ( $R^2 > 0.98$ ).

# Zaack AQI vs FEM T640x vs APS PM<sub>10</sub> Accuracy

- Accuracy (20°C and 40% RH)

Steady state #	Sensor Mean ( $\mu\text{g}/\text{m}^3$ )	FEM T640x ( $\mu\text{g}/\text{m}^3$ )	Accuracy (%)
1	7.90	11.95	66.1%
2	45.72	48.26	94.7%
3	94.95	98.26	96.6%
4	188.97	210.17	89.9%
5	279.06	306.70	91.0%

Steady state #	Sensor Mean ( $\mu\text{g}/\text{m}^3$ )	APS ( $\mu\text{g}/\text{m}^3$ )	Accuracy (%)
1	7.90	6.81	84.0%
2	45.72	38.54	81.4%
3	94.95	80.60	82.2%
4	188.97	161.67	83.1%
5	279.06	241.91	84.6%

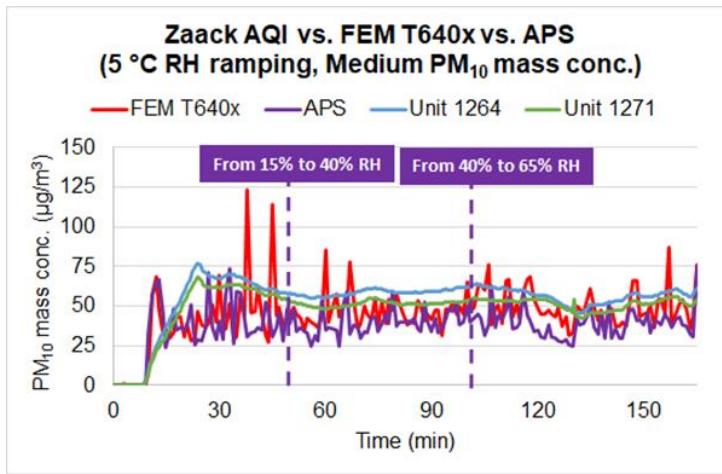
- The Zaack AQI sensors underestimated the measured PM<sub>10</sub> concentration compared to the FEM T640x, but overestimated the measured concentration compared to the APS, at 20 °C and 40% RH. The Zaack AQI sensors showed moderate to high accuracy (66.1% to 96.6%) for all tested PM<sub>10</sub> concentrations compared to the reference FEM T640x for the entirety of test. The Zaack AQI sensors showed consistently moderate accuracy (81.4% to 84.6%) for all tested PM<sub>10</sub> concentrations compared to the reference APS for the entirety of test.

## Zaack AQI Data Recovery and Intra-model Variability

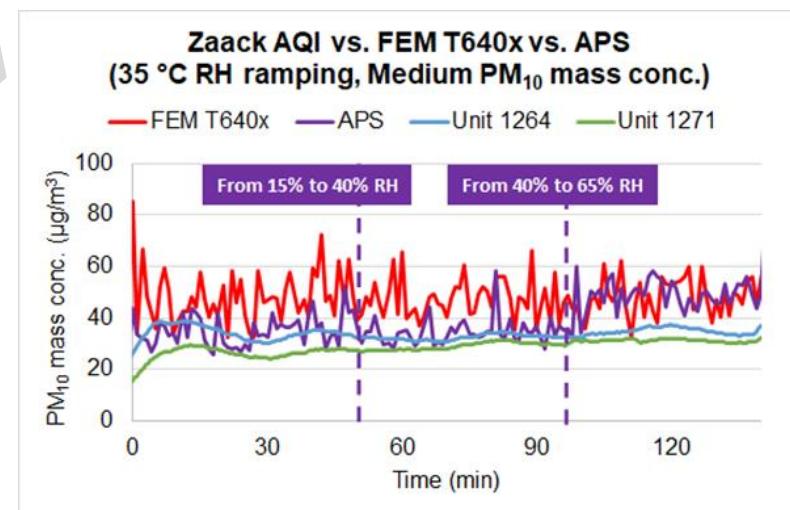
- Data recovery for PM<sub>10</sub> measurements was 99.9% and 99.8% for Units 1264 and 1271 (Unit 1332 data was not analyzed due to PM sensor malfunction)
- Moderate PM<sub>10</sub> concentration variations were observed between the two units at 20° C and 40% RH, at 10, 50, and 100  $\mu\text{g}/\text{m}^3$  PM<sub>10</sub> as measured by the FEM T640x.

# Climate Susceptibility: Zaack AQI (PM<sub>10</sub>)

Low Temp - RH ramping  
(medium conc.)



High Temp – RH ramping  
(medium conc.)



# Discussion: PM<sub>10</sub>

- **Accuracy:** The Zaack AQI sensors underestimated the measured PM<sub>10</sub> concentration compared to the FEM T640x, but overestimated the measured concentration compared to the APS, at 20 °C and 40% RH. The Zaack AQI sensors showed moderate to high accuracy (66.1% to 96.6%) for all tested PM<sub>10</sub> concentrations compared to the reference FEM T640x for the entirety of test. The Zaack AQI sensors showed consistently moderate accuracy (81.4% to 84.6%) for all tested PM<sub>10</sub> concentrations compared to the reference APS for the entirety of test. (refer to slide 36)
- **Precision:** Due to the nature of Arizona Test Dust dispersion, the aerosol concentration showed some variability, therefore, the precision cannot be fairly estimated.
- **Intra-model variability:** Moderate PM<sub>10</sub> measurement variations were observed among the two Zaack AQI sensors at 20 °C and 40% RH. (refer to slide 36)
- **Data Recovery:** Data recovery for PM<sub>10</sub> measurements was 99.9% and 99.8% for Units 1264 and 1271, respectively. (refer to slide 36)
- **Detection limit:** The detection limit cannot be estimated due to limitations in the chamber system design.
- **Response time:** Response time could not be studied due to the system design of the chamber system. With a 1.6 m<sup>3</sup> chamber volume, it was not possible to reach a high pollutant concentration within a short time.
- **Linear Correlation:** The two Zaack AQI sensors showed very strong correlation/linear response with the corresponding FEM T640x and APS PM<sub>10</sub> measurement data ( $R^2 > 0.98$ ). (refer to slide 35)
- **Interferences:** N/A for PM sensors test
- **Note about PM<sub>1.0</sub>:** The field evaluation compared the PM<sub>1.0</sub> values reported from the Zaack AQI sensors against the field GRIMM and T640 that reported PM<sub>1.0</sub>. However, PM<sub>1.0</sub> was not compared in this lab evaluation because at the time of lab testing (before March 2022) the lab T640x firmware upgrade to report PM<sub>1.0</sub> was not finalized yet.

# Discussion: PM<sub>10</sub>

- **Measurement duration:** Zaack AQI sensors report 30-second averaged values.
- **Measurement frequency:** Zaack AQI sensors report 30-second averaged values. The obtained data was used as-is for calculation of statistics (e.g. data recovery, intra-model variability, mean, accuracy, precision), but condensed into 1-minute and 5-minute averages for linear correlation studies against the FEM T640x and APS.
- **Sensor contamination and expiration:** Prior to the laboratory evaluation, the Zaack AQI sensors were tested in the field for two months. The PM<sub>10</sub> laboratory studies lasted for about 8 days with intermittent non-operating periods and a storage period of ~ 11 months. For PM<sub>10</sub> measurements, two of the Zaack AQI sensors (Units 1264 and 1271) maintained their functionalities and operated normally throughout the duration of the testing, while one of the sensors (Unit 1332) would only report either 0 or 1000 µg/m<sup>3</sup> during the laboratory studies and was thus excluded from analysis.
- **Concentration range:** 0.01 µg/m<sup>3</sup> to 1500 mg/m<sup>3</sup> PM<sub>10</sub> concentration as suggested by the manufacturer. During the laboratory evaluation, the Zaack AQI sensors were challenged with PM<sub>10</sub> concentrations up to 300 µg/m<sup>3</sup>. (refer to slide 35)
- **Drift:** N/A
- **Climate susceptibility:** During the lab studies, relative humidity generally had little effect on the stability of PM<sub>10</sub> as recorded by the Zaack AQI sensors. At lower temperatures the Zaack AQI sensors tended to overestimate the FEM T640x and APS, but at higher temperatures the Zaack AQI sensors tended to underestimate the FEM T640x and APS. (refer to slide 37)
- **Response to loss of power:** Zaack AQI sensors were powered through the entirety of the lab tests.